DEVELOPMENT AND STRUCTURAL PERFORMANCE ASSESSMENT OF LOW-CARBON CONCRETE USING RECYCLED CONCRETE AGGREGATES AND SECONDARY MATERIALS

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ABSTRACT

This thesis investigates the structural performance of low carbon concrete (LCC) developed with various proportions of recycled concrete aggregates (RCA) and supplementary cementitious materials (SCM's) as sustainable material alternatives to conventional concrete materials. Extensive materials testing and analysis of existing literature found that RCA sources possess up to 21% lower bulk specific gravity (BSG) and over 200% higher water absorption values relative to natural aggregate sources. The effect of RCA within experimental within mixtures was governed by the aggregate and mortar strength properties and relied significantly on the strength class of the resultant mixture with compressive/tensile strength reductions up to 41% observed.

Mixture design optimization of LCC mixtures was found to improve the alignment of actual and theoretical mixture free-water proportions and effectively improve the mechanical strength properties of LCC mixtures, with mechanical strength values up to 49.8 MPa achieved. Full-scale development and testing of 2-meter reinforced concrete beams subject to 4-point flexural testing found that LCC mixtures can achieve comparable and even superior flexural and serviceability properties (+3% higher) relative to conventional concrete mixtures, with 39 - 69% higher experimental values reported relative to CSA A23.3-14 factored strength empirical predictions. The cumulative findings from the thesis program confirmed that LCC mixtures could be utilized as a suitable concrete alternative within structural applications while also serving as a sustainable alternative.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Absorption Capacity (%)
AD	Air-Dry Condition
AC_2	2-hour absorption capacity (%)
AC_{24}	24-hour absorption capacity (%)
AM_{24}	24-hour absorbed moisture values (%)
A_s	Area of steel reinforcement (mm^2)
ASG	Apparent Specific Gravity
A_v	Area of shear reinforcement (mm^2)
b	Width of compression face (mm)
BSG	Bulk Specific Gravity
CED	Cumulative Energy Demand (MJ/m^3)
CO_2	Carbon Dioxide
CRCA	Coarse Recycled Concrete Aggregate
d	Depth of compression (mm)
DMA	Double-Mixing Approach
d_v	Effective shear depth (mm)
E_c	Modulus of elasticity of concrete
EMV	Equivalent Mortar Volume Method
ETWM	Equivalent Total Water Method
FA	Fly-Ash
f'c	Compressive Strength (MPa)
f'_{ct}	Splitting Tensile Strength
FM	Fineness Modulus
f_r	Modulus of rupture of concrete (MPa)
FRCA	Fine Recycled Concrete Aggregate
f_y	Yield Strength (MPa)
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GWP	Global Warming Potential (kg CO_2/m^3)
I	Moment of inertia of section about the centroidal axis (mm^3)
I_{cr}	Moment of inertia of cracked section transformed to concrete (mm^3)
I_e	Effective moment of Inertia (mm^3)
I_g	Moment of inertia for gross-section (mm^3)
ITZ	Interfacial Transition Zone
LCC	Low Carbon Concrete
L_n	Clear Span (mm)
MC	Moisture Content (%)
M_{cr}	Cracking Moment (MPa)
M-EMV	Modified Equivalent Mortar Volume
M_n	Nominal Moment (kNm)
MOE	Modulus of Elasticity (GPa)
M_r	Factored Moment resistance (kNm)
MRCA	Mixed Recycled Concrete Aggregates
Na_2SO_4	Sodium Sulfate
NCA	Coarse Natural Concrete Aggregate
NCA	Natural Coarse Aggregates
NFA	Natural Fine Aggregates
OD	Oven Dry Condition
OPC	Ordinary Portland Cement
OTM	Optimized Triple Mixing Approach

OVA	Original Virgin Aggregate
P_n	Nominal Load (kN)
PPM	Particle Packing Method
P_r	Factored applied loading resistance (kN)
RCA	Recycled Concrete Aggregate
RM	Residual Mortar/Adhered Mortar
RMC	Residual Mortar Content
s	stirrup spacing (mm)
SCM('s)	Supplementary Cementitious Material(s)
SF	Silica Fume
SP	Super-Plasticizing Agent
SSD	Saturated Surface-Dry Condition
STS	Splitting Tensile Strength (MPa)
TM	Triple-Mixing Approach
TSMA	Two-Stage Mixing Approach
V_c	Shear resistance attributed to concrete (kN)
V_n	Nominal Shear force (kN)
V_r	Factored shear resistance of concrete member (kN)
V_s	Shear resistance attributed to steel (kN)
V_x	Volume of X (per m^3)
W/C	Water-To-Cement Ratio
W/C_{eff}	Effective Water-To-Cement Ratio
W/C_{total}	Total Water-To-Cement Ratio
W_f	Final Weight (kg or g)
W_i	Initial weight (kg or g)
$W_{in\text{-}situ}$	In-situ weight (kg or g)
W_{OD}	Oven-dried weight (kg or g)
W_x	Weight Of X (kg/m^3)
α	(Shear design factor) inclination angle between inclined stirrups and the longitudinal axis of the member (rad)
α_1	(Flexural design factor) ratio of average stress in rectangular compression block to specified concrete strength
β_1	(Flexural design factor) ratio of depth of rectangular compression block to depth of neutral axis
γ_c	Concrete Density (kg/m^3)
$\Delta_{mid, pred}$	Predicted Midspan Deflection values (mm)
$\Delta_{mid, ult}$	Midspan Deflection at peak load (mm)
ε_c	Concrete Strain (μm/m)
ε_{cu}	Maximum strain at the extreme concrete compression fibre at ultimate (3500 μm/m)
ε_s	Steel Reinforcement Strain (μm/m)
θ	(Shear design factor) inclination angle of compressive stresses to the longitudinal axis of the member (rad)
λ	Modification factor for concrete density
ρ	Reinforcement ratio (%)
σ	Standard deviation
φ_c	Concrete material resistance factor (0.65 unless noted otherwise)
φ_s	Steel Reinforcement resistance factor (0.85 unless noted otherwise)
Ω	Resistance (ohm's)

1. INTRODUCTION

1.1. Background

The modernization of the construction industry and advancements within construction materials have given engineers and designers the ability to idealize, design and construct engineering marvels that were once beyond the scope of reality. The ability to continually strive and push the boundaries of our construction capabilities can largely be credited to reinforced concrete which has undergone extensive improvements over the years. Today, production volumes exceed 10 billion tons annually [1], making concrete the most used and arguably the most important construction material in the modern era.

Modern concrete uses various natural resources, specifically coarse and fine aggregates, water and cementitious materials, typically ordinary Portland cement (OPC) [2]. Natural coarse and fine aggregates have been sourced from various crushed stone and rock sources, while fresh potable water has been used as the primary water source. Many international codes and design guidelines provide provisions regarding the acceptable criteria for water and aggregate sources, with permitted usage based on material properties of the specific sources [34,5]. Policies have been provided regarding the use of various cementitious and pozzolanic-based materials, such as supplementary cementitious materials (SCM's) based on replacement ratios (i.e., % replacement). However, SCM usage is often governed based on regional availability, limiting the application and usage [3].

Given the exclusive use of natural resources, researchers have often labelled conventional concrete as a 'green material' and accepted as an ecofriendly construction solution [6,7]. Despite such perceptions, a growing number of researchers have challenged such notions and, through extensive study and investigation, have found that the excessive global demand, industry practices, material usage and "cradle-to-grave" lifecycle processes contribute towards the generation of significant global greenhouse gas emissions and pose a severe environmental threat requiring urgent corrective action [1,8–10]. Given the large production volumes, current concrete usage has placed extensive stress on the natural resource reserves of many global regions, given the overwhelming quantities of natural aggregates and freshwater required to support current concrete productions. Many regional ecosystems have sustained widespread degradation as they have struggled with the ever-growing aggregate volumes necessary to meet global concrete production demands given the associated quarry/mining operations, deforestation, material processing, greenhouse gas production and transportation processes [1,8–10] required for material extraction.

To mitigate the environmental repercussions of conventional concrete, emergent studies within the global research community have begun investigating eco-friendly low-carbon concrete (LCC) mixtures incorporating sustainable materials [9,11–17]. LCC mixtures utilize various alternative material sources enabling significant reductions in greenhouse gas emissions and reducing the carbon footprint associated with the concrete mix. The upcycling of concrete demolition waste (CDW) in recycled concrete aggregates (RCA) has often been studied as an eco-alternative aggregate source within LCC mixtures, while SCM's such as ground granulated blast furnace slag (GGBFS), fly ash, silica fume has been utilized to offset the carbon emissions associated with OPC. Calcium aluminate cement (CAC), geopolymer cement concrete (GCC) and limestone calcined clay cement (LC^3) have also been utilized given their lower GHG emissions relative to OPC [1,18]. Novel aggregate sources such as post-consumer glass, recycled tire/crumb rubber and recycled plastics have also been utilized within LCC. However, LCC usage has often been limited to experimental and small-scale case studies with limited implementation in large-scale industrial applications [1,19].

Despite the extensive sustainability (i.e., in terms of material upcycling and carbon emissions) and economic benefits, LCC has seen limited implementation within the construction industry given preliminary mechanical strength data from laboratory testing [1,20,21]. Several studies have found that LCC mixtures could achieve compressive strengths greater than 50 MPa [22–28] and present suitable durability (i.e., shrinkage, chloride/sulphate penetration, and freeze-thaw) properties [29,30]. However, despite such findings, most LCC studies have found that the use of increasing quantities of LCC materials often leads to significant mechanical strength reductions [1,16,37,26,30–36].

Previous laboratory experimentation has found that coarse RCA (CRCA) usage often presents significant compressive strength (f'_c), tensile strength (f'_{ct}) and concrete modulus of elasticity (E_c) reductions with significant reductions over 30% observed in select studies with mixtures comprised of 100% CRCA [14,16,41–47,24,25,27,30,32,38–40]. Further studies have also found that fine RCA (FRCA), CRCA and FRCA or RCA with SCM's often present similar mechanical strength reductions, often made more severe with increasing LCC material contents [14,25,30,35,36,48,49]. However, it should be noted that within the existing studies, RCA has primarily been limited to CRCA with SCM's, while limited studies have examined the use of FRCA or mixtures with CRCA and FRCA with SCM's.

To resolve the observed strength reductions in LCC mixtures, alternative mix design modification and optimization methods have been proposed and explored within various case studies [37,43,44,50–55]. Multiple studies have found that simple mixture proportion modifications, namely lowering the w/cm ratios and increasing cement content [55,56], may improve mechanical strength properties. However, results were often dependent on the quality of the CRCA source [22,55,56]. Emergent mixture proportioning and mixing methods have also been studied within recent literature, with preliminary testing indicating that such practices often lead to improved mechanical strength and microstructural characteristics for various LCC mixtures [43,44,50–54]. Despite promising findings, many such methods have often been limited, with minimal research conducted for LCC mixtures with the combined incorporation of CRCA, FRCA and SCM's.

There has also been very limited research on the use of LCC in large-scale structural applications, with few studies experimentally verifying the flexural and serviceability testing of large-scale reinforced LCC specimens. Of the few studies conducted, it has been found that the moment resistance, cracking behaviour, and resultant deflection characteristics of LCC mixtures differ from conventional concrete with extensive variability amongst various LCC mixtures [50,57–59]. Multiple studies have noted that the reduced mechanical strength findings observed within literature often translated into lower cracking moments (M_{cr}) and earlier crack propagations within reinforced LCC beams relative to conventional concrete specimens [57,60] [50,57,58]. Further studies have noted that in terms of flexural load capacities, similar ultimate bending moment (M_u), deflections (Δ) and reinforcement strain (ε_s) properties, LCC mixtures have often presented similar properties as conventional concrete members [58–60]. However, minimal investigations have been conducted for LCC mixtures comprised of high replacements of FRCA or mixtures with CRCA or FRCA and SCM's.

Despite considerable reductions within mechanical performance, comparison of LCC mixtures to conventional concrete from a life-cycle analysis perspective (LCA) has indicated that the use of LCC in new building construction can substantially lower equivalent CO_2 emissions relative to conventional concrete mixtures [61]. Conversely, RCA usage has been found to improve sustainability by avoiding the further extraction and depletion of natural aggregate reserves. The additional replacement and minimization of cement quantities through SCM incorporation has also been found to reduce embodied energy demands (MJ/kg) by roughly 25% and lead to embodied carbon (CO_2/kg) reductions of up to 38.7% [20,21]. Given that global concrete production currently exceeds 10 billion tons annually [1], the reduced consumption of OPC and natural aggregates through the substitution with LCC materials offers the ability to drastically minimize the environmental impact associated with conventional concrete materials extraction and minimize further ecological degradation. Therefore, the incorporation of RCA provides a viable solution to the overwhelming accumulation of the billions of tons of CDW threatening many global regions [9,10,65,12,38,51,54,61–64].

Canada and other developed nations such as the United States and many European countries have established concrete re-utilization regulations and design codes to encourage concrete waste and LCC usage such as those presented in CSA A23.1-14 [3] and ACI 555 guidelines [66]. However, despite these guidelines, the current standards within the CSA and ACI codes do not address the effect of RCA on the mechanical properties of concrete mixtures, present methods to minimize the adverse impact of RCA or provide effective mix design/proportioning methods for the production of concrete containing RCA with predictable fresh and hardened properties. As a result, the limited usefulness of existing standards has resulted in the lack of LCC industrial usage and RCA incorporation [13,35,67]. Given the limited studies and understanding of LCC mixture materials, further studies are required to investigate the structural characteristics of LCC developed with CRCA, FRCA and SCM's. The use of extensive mechanical and flexural strength testing of LCC mixtures can allow for further understanding regarding the cumulative effects of LCC materials and develop suitable mixture design methods to encourage and promote the use of LCC within the construction industry. Further testing is also required to evaluate the suitability of optimized mixture design methods in terms of the effect on the mechanical properties of LCC structural elements with higher replacements of LCC materials (i.e., CRCA, FRCA and SCM's) as well as gauge the applicability of current Canadian design standards (i.e., CSA A23.1-14, A23.2-14 [3] and A23.3-14 [68]) in terms of design accuracy, validation of current design assumptions and ensure adequate margins of safety in the design of LCC flexural elements.

1.2. Proposed Study

This thesis investigates the effect of the high percentage replacements of conventional concrete materials with alternative materials such as CRCA, FRCA and SCM's on the fresh and hardened properties of the resulting concrete. An extensive LCC mixture design program consisting of the systematic assessment of CRCA FRCA and SCM's was completed to evaluate the governing mechanical strength mechanisms for a low and high strength series of mixtures incorporating various mixture compositions of CRCA, FRCA and SCM's to quantify the effect of such materials on the fresh and hardened properties of LCC mixtures. Given the extensive variability of both the source and material properties of LCC materials, to allow for further comparison with the experimental findings, the research program also consisted of the development of a comprehensive literature database to analyze and identify trends and correlations across the larger body of global research findings.

The experimental program also investigated and evaluated the flexural strength performance of reinforced concrete beams produced with LCC incorporating various percentages of recycled and secondary materials. Based on the cumulative results of the study, reinforced concrete design considerations and suggested mix design revisions to current Canadian concrete mix design practices for LCC comprised of CRCA, FRCA and SCM's are also presented.

To achieve the program goals, the experimental program was divided into two sections: Section 1: Literature collection and establishment of an LCC literature database, and Section 2: Laboratory experimental research study. Section 1: Literature collection and LCC literature database assessment consisted of organizing previous empirical findings within literature into a comprehensive LCC database providing a state-of-the-art review of various LCC mix data, with a specific focus on the use of novel LCC mix design methods and their effects on the mechanical properties. The LCC literature database was also used to identify existing research gaps and analysis/establishment of trends regarding the use of novel mix design methods in terms of the effect on the mechanical properties of LCC.

Section 2: Laboratory experimental research study consists of a progressive 3-stage practical program consisting of Stage 1-Materials Assessment, Stage 2-Concrete and Mortar Mix Development and Testing and Stage 3-Flexural and serviceability analysis of reinforced concrete beams. The 3-stage laboratory investigation was used to compare the properties of various concretes produced with LCC and conventional concrete materials and further identify the governing strength mechanisms regarding LCC material usage on the mechanical strength properties of concrete mixtures for various strength designations. The analysis of reinforced concrete beams allowed for the flexural strength and resultant severability properties of LCC beams to be assessed and compared with conventional concrete beams. Such findings and conclusions within the experimental program were used to provide design recommendations regarding the effective design of LCC mixtures (mix design methods) and the effect of LCC materials on the structural capabilities of various structural design elements.

1.3. Research Objectives

In terms of research objectives, the completion of the thesis research program permitted the achievement of the following research objectives, stated below, broken down based on the section of the experimental investigation:

Section 1: Literature collection and establishment of an LCC literature database-Objectives

- Identification of research trends/gaps within existing LCC research.
- Assessment and comparison of existing research findings for various novel LCC mix design methods.
- Identification of any research gaps regarding the use of novel LCC mix design methods.
- Analysis/establishment of trends regarding the use of novel mix design methods and their effect on the mechanical properties of LCC.

- Assessment of the effectiveness of various novel LCC mix design methods.

Section 2: Laboratory experimental research study-Objectives

- *Stage 1-Materials Characterization*
    - Quantification of material properties for LCC (RCA and SCM's) and conventional concrete materials (NA and cement).
    - Identification of differences within various material properties (i.e., comparison of LCC materials with conventional concrete materials) and discussion of inter-property relations (i.e., the effect of RCA composition on aggregate properties: BSG, water absorption, etc.).
    - Preliminary assessment/conclusions regarding the influence of LCC material properties on mechanical properties (fresh and hardened) of LCC concrete mixtures.
- *Stage 2-Concrete and Mortar Mix Development and Testing*
    - Investigation and quantification of the influence of various LCC materials on the resulting mechanical properties.
    - Quantification of governing strength mechanism for various LCC mixtures for various concrete strength designations.
    - Assessment and verification of the effectiveness of current CSA concrete design practices for the design of LCC mixtures.
    - Assessment of novel LCC mix design procedures and comparison with results with findings with Section 1 and comparison with CSA mix design practices.
- *Stage 3-Flexural Analysis of Reinforced Concrete Beams Testing*
    - Assessment of flexural and serviceability properties of various LCC mixtures and comparison with those of conventional concrete mixtures.
    - Assess the applicability of existing CSA A23.3-14 reinforced concrete design methods (i.e., design assumptions, prediction accuracy, margin of safety).
    - Outline of suggestions regarding recommended design practices for the production of LCC.

1.4. Research Significance

The relatively short service life for typical concrete infrastructure (approximately 50 years) requires continuous use of concrete to replace, repair, or expand, further contributing to the progressive degradation of environmental systems [69]. Although existing CSA A23.1-14 [3] standards permit RCA usage within concrete, the limited use of RCA within further applications besides roadwork or backfill applications [35] prolongs the unnecessary disposal of suitable aggregate sources and continued extraction of natural resources. In terms of a holistic global perspective, many international nations lack the conditions required to sustain NA production demands or have the infrastructure/land availability to accommodate current CDW disposal volumes [10,32,54,64,70]. Many countries also lack the ability to re-purpose CDW in the form of RCA, given the limited codes and provisions developed to address the use of RCA and LCC materials. Canada, United States, Japan, and various European and other global nations have aimed to increase the viability and encourage LCC use by establishing concrete re-utilization policies [9,71–73] and design standards such as those outlined within CSA A23.1-14 [3] and ACI 555 [66]. However, while preliminary guidance is provided, the existing standards lack sufficient information and guidance regarding the effective use of RCA in LCC, further limiting RCA and LCC usage. Numerous research studies have also attempted to develop standardized mixture proportioning and design methods suited for LCC [43,44,50–54]. However, many of the presented findings and research methods have been limited to LCC mixtures which exclusively incorporate CRCA [51,53]. Studies assessing LCC mixtures containing the complete replacement of CRCA and FRCA [35,70] as well mixtures with RCA and SCM's are rare [28,35,54,70]. As a result, there is still a general lack of understanding regarding the material properties of LCC made with high replacements of LCC materials recycled and secondary materials.

Therefore, to develop suitable mixture design methods and achieve a comprehensive understanding regarding the effect of high-replacements of CRCA, FRCA and SCM's, concrete and mortar specimens were developed to systemically isolate and evaluate the effect of individual and combined use of various LCC materials. The tested specimens allowed for the identification of the governing failure mechanisms, the effect of various optimization methods in terms of mechanical properties, and the flexural characteristics of LCC elements. The research findings provided further validation regarding the suitable structural performance of LCC elements for further structural applications and the effective design of LCC with predictable fresh and hardened properties from a mixture proportioning perspective. Additionally, the findings from the experimental program provide further experimental findings to support the broader application of LCC as a reliable and structurally suitable alternative to conventional concrete mixtures while highlighting the notable equivalent CO_2 reductions given the use of alternative and secondary materials.

1.5. Thesis Outline

The following list provides a detailed breakdown of the chapter organization of the nine (9) chapters presented within this thesis:

Chapter 1 INTRODUCTION: presents the introduction and introductory commentary for the thesis body. Introduction statements briefly outlining the importance and significance of the thesis program, reasoning, and research contributions are outlined.

Chapter 2-LITERATURE REVIEW: presents an in-depth breakdown of the numerous LCC materials and the current state of practice within the field of low carbon concrete research. A detailed compilation and presentation of the findings from numerous existing LCC research studies are presented, outlining previous findings regarding the use of LCC materials and impact on concrete mechanical properties and structural implications and findings comparing LCC to conventional concrete mixtures. Emergent areas of LCC research are all presented and thoroughly discussed, consisting of the various LCC optimization methods ranging from various mixture proportioning methods to mixing methods and the effects of such methods in terms of structural properties of LCC mixtures. The literature review also outlines gaps within existing LCC studies and highlights areas requiring further research and analytical/numerical investigation.

Chapter 3-RESEARCH METHODOLOGY: provides a detailed breakdown of the organization of the research work undertaken during the thesis program. The organization, scope and goals of an extensive LCC literature database followed by a multi-stage progressive laboratory experimental research program are presented and explained.

Chapter 4- LCC DATABASE: provides a detailed overview and numerical analysis based on the research findings outlined within experimental literature from existing findings. The LCC database analysis is broken down based on the LCC material content (i.e., CRCA only, FRCA only, CRCA + FRCA, and SCM's in combination with RCA. A detailed assessment of replacement ratios, mixture proportions and further mixture relations such as water-to-cement (or water-to-cementitious materials) ratio (w/cm), cement: sand and further relations are presented. A detailed assessment and summarization of various optimization methods such as mixture proportioning and mixing methods are also presented in terms of the effect of such methods on the mechanical strength properties of LCC mixtures. The findings from the LCC literature database were used to evaluate trends within existing research, identify gaps within existing studies, and serve as a reference point to evaluate the experimental observations within further sections of the thesis program with those found within the existing literature.

Chapter 5: MATERIAL PROPERTIES TESTING: presents the material properties for the various LCC and conventional concrete materials utilized within the experimental program's concrete and mortar mix development/testing stages. Significant emphasis was placed on the coarse and fine aggregates with standard CSA A23.2-14 and ASTM aggregate testing methods conducted, as well as further qualitative and quantitative testing to further identify differences within the properties of the RCA and gauge the effect on further fresh and hardened concrete properties. The material properties observed were used to aid in the mixture development of the concrete and mortar mixture within further stages of the experimental thesis program.

Chapter 6: MIX DEVELOPMENT AND TESTING OVERVIEW: provides a detailed breakdown of the mix design aspects (mixture proportioning method, mixing method, material proportions) and reasoning for the selection and development of mixtures included within the thesis program. An overview of the fresh and hardened properties testing methods (i.e., procedures and standards) are also presented.

Chapter 7: MECHANICAL PROPERTIES ASSESSMENT: presents the experimental findings for the fresh and hardened properties of the developed concrete and mortar mixtures. Discussions of the observed mechanical properties, comparison with existing literature findings (i.e., from literature review and LCC database) and reasoning for the observed results are also provided. Optimized mixtures are also developed and presented based on the observed experimental findings from the initial concrete and mortar specimens.

Chapter 8: FLEXURAL EVALUATION OF REINFORCED CONCRETE BEAMS**:** A brief overview of the fresh and hardened properties of the select mixtures cast into beams is first presented, followed by a thorough analysis and comparison of the flexural and serviceability properties of various conventional concrete and LCC beams. Flexural properties such as peak load, nominal moment capacity, cracking moment, midspan deflection and cracking behaviour are presented along with a detailed discussion of the observed findings.

Chapter 9: CONCLUSIONS AND RECOMMENDATIONS: summarizes all of the notable findings presented within each of the experimental chapters of the thesis program. Implications of the presented research findings regarding academic and research contribution are outlined, while a detailed overview for follow-up research efforts and direction for general LCC research studies.

APPENDICES (Appendix A-F): An overview of the various appendices as well as a brief description of each are provided below:

APPENDICES

- Appendix A: Testing Standards
- Appendix B: Aggregate Properties from Literature
- Appendices C-E: Mix Proportioning Formulations and Sample Calculation
    - Appendix C: Absolute Volume Proportioning Sample Calculation
    - Appendix D: EMV Proportioning Sample Calculation
    - Appendix E: M-EMV (S=5) Proportioning Sample Calculation
- Appendix F: Moment Curvature Plots
- Appendix G: Trial Mixture Data

2. LITERATURE REVIEW

2.1. Low Carbon Concrete Materials Overview

To thoroughly understand and develop low-carbon concrete (LCC) mixtures, a detailed understanding of the materials, mechanical properties, and current practices must be achieved. Although LCC is an umbrella term encompassing a variety of eco-friendly concrete materials, for this research study, LCC will focus on the concrete comprised of recycled concrete aggregates (RCA) and supplementary cementitious materials (SCM's). The following chapter provides a detailed overview of the state-of-the-art of LCC materials and mixtures containing various combinations of RCAs and SCM's.

2.1.1. Recycled Concrete Aggregates

One of the most prevalent materials often used in LCC is RCA's. Originating after WW1 and WW2, the urgent need to rebuild and the inability to gather new resources saw post-war era researchers investigate the feasibility of re-utilizing the readily available supply of concrete waste as an alternative aggregate source to NA [61,74,75] (see Figure 1[76]).

Figure 1-Damage to Infrastructure in WWI and availability of concrete waste [76]

Derived from the crushing and processing of waste and demolished concrete, RCA has been used within LCC research as an alternative aggregate source to 'conventional' natural aggregates (NA) [77,78]. From the early pioneering studies post-WWI and WWII, it was found that from an economic perspective, compared with NA, RCA had various advantages based on their production methods and ease of availability [74]. However, it was also found that the high variability of RCA properties/composition resulted in poorer properties of the resulting new concrete limiting adoption and wide-scale implementation [74,75]. Early studies had also found that adequate quality of concrete produced with RCA required the limitation or complete removal of any deleterious materials to ensure suitable quality [74,75]. These initial studies provided the foundation of RCA research and introduced the concept of producing sustainable concretes, which are referred to today as low carbon concrete (LCC).

Current LCC and RCA research has gained significant traction around the globe, motivated by a variety of emerging issues stemming from depleting natural resource reserves, excessive concrete demolition waste (CDW) volumes, lack of landfilling sites, excessive GHG emissions from conventional concrete production and the increased importance of sustainable development and development practices [10,64,79].

Numerous studies have found that unlike natural aggregates (NA), the heterogenous nature of demolished construction and concrete waste often results in RCA sources containing impurities (i.e., deleterious materials) such as brick, tile, glass and asphalt [23]. To highlight the differences within the compositions of RCA and NA, a comparison of the coarse fraction for RCA (CRCA) and NA (NCA) are shown within Figure 2, while a comparison of the fine fraction for RCA (FRCA) and NA (NFA) are shown within Figure 3.

(a) *(b)*

Figure 2-Coarse Aggregates, (a) Coarse RCA (CRCA), (b) Coarse NA (NCA)

(a) *(b)*

Figure 3-Fine Aggregates, (a) Fine RCA (FRCA), (b) Fine NA (NFA), natural sand

Upon visual inspection, the heterogeneous nature of the RCA (coarse and fine fractions) can be identified relative to the NA sources (coarse and fine), given inconsistencies within materials (i.e., crushed concrete mortar, crushed rock, asphalt, brick and tile particles) as evident by variations within colours of the various particles within Figure 2. Previous studies have noted that the inclusion of deleterious materials further introduces higher variability within the RCA mechanical properties of the aggregates, resulting in significant variations amongst various RCA sources and relative to NA sources [16,22]. Appropriate precautions to limit quantities and hence the effect of deleterious materials have been suggested by researchers, such as the manual or automated removal of such materials through visual indicators or density-based sorting; however, such methods are often impractical or difficult to implement with large scale settings [16,22].

2.1.1.1. Production Methods and Material Life-Cycle

In terms of production methods and application, RCA and NA are produced using the same production methods (i.e., crushing operations), and within the overall material application, both serve as aggregates with concrete (i.e., LCC and conventional concrete, respectively). However, with regards to material lifecycle, RCA and NA differ significantly from one another. Conventional concrete practices and NA production generally follow a 'liner' process of which NA are sourced from industrial aggregate quarries and undergo a series of crushing/grading cycles until suitable for use within concrete as per CSA A23.1-14 guidelines [3] or other international guidelines as required (i.e., ACI, BS, IS, etc.…). Compared with the NA production, RCA used within LCC follows a 'circular closed-loop recycling process re-utilizing pre-existing concrete CDW [80–85]. Figure 4 and Figure 5 illustrate the differences within the production practices of the material lifecycles of NA and RCA concretes, respectively.

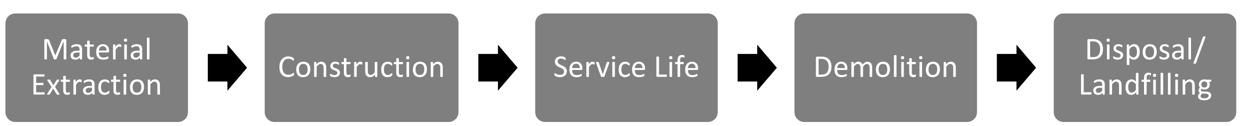


Figure 4-Material Lifecycle: Concrete containing natural concrete aggregates (NCA)

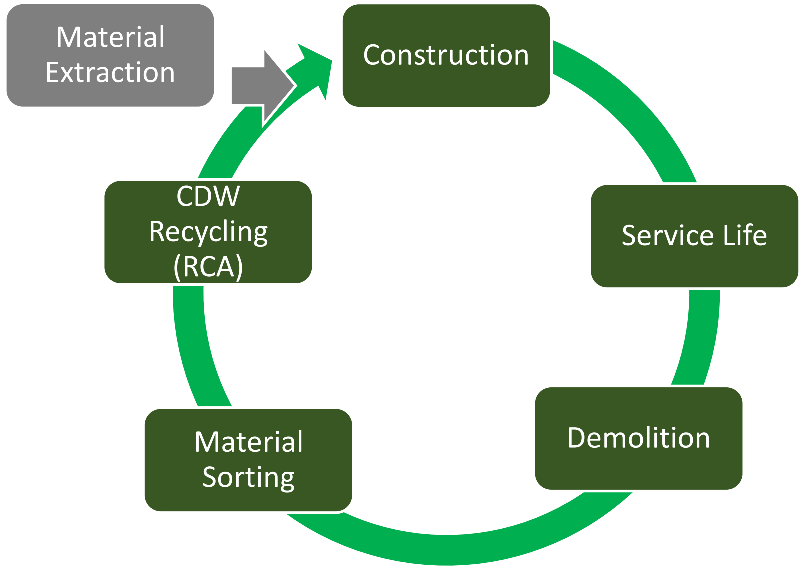


Figure 5-Material Lifecycle: Concrete containing RCA [85]

The linear production lifecycle of conventional concrete requires the continuous extraction of new materials (i.e., natural resources) and, in the case of reinforced concrete construction, includes recycling of steel reinforcement and the discarding of concrete rubble. In contrast, the closed-loop production lifestyle of RCA (Figure 5 [85]) takes advantage of the high quality and suitable material properties of concrete demolition and construction waste (i.e., CDW) while minimizing the extraction of natural materials (i.e., aggregates). Previous studies have commented that the closed-loop material lifecycle of RCA provides an alternative and environmentally sustainable source of new aggregates for the construction industry and enables the construction industry to work towards "zero waste" minimization objectives [11]. Further studies have also noted that the closed-loop material production of RCA would allow for minimized further exploitation/extraction of NA and provide additional benefits of reduced landfill waste and material transportation costs due to the local availability of RCA [12,80,81].

Preliminary sustainability studies have found that compared with conventional concrete, LCC made with partial CRCA replacements can lead to considerable reductions in Global Warming potential (GWP) (i.e., measured in terms of carbon emissions-kg CO_2/m^3) as well as the cumulative energy demand (CED) (i.e., energy demand-MJ/m^3) compared with NA [9,17]. Previous studies have noted that the use of CRCA content (i.e., 100%), FRCA or alternative binders such as supplementary cementitious material such as slag (GGBFS), fly ash, silica fume [86–88] in place of cement can considerably improve environmental savings, given the extensive environmental emissions generated by cement production, aggregate transportation and landfilling associated with conventional concrete [1,6,20,79,89]. Similar studies have also noted that the environmental savings in terms of GWP often have a high dependency on transportation distance, resulting in various magnitudes of environmental savings regarding RCA usage per application. To emphasis the dependency of GWP on Lifecycle transportation distance, Figure 6 highlights the associated GWP associated exclusively with various transportation distances, [61,90,91]. Based on Figure 6, locally available RCA offers considerable GWP savings relative to NA, although the GWP savings reduce or become non-existent with increasing transportation distances.

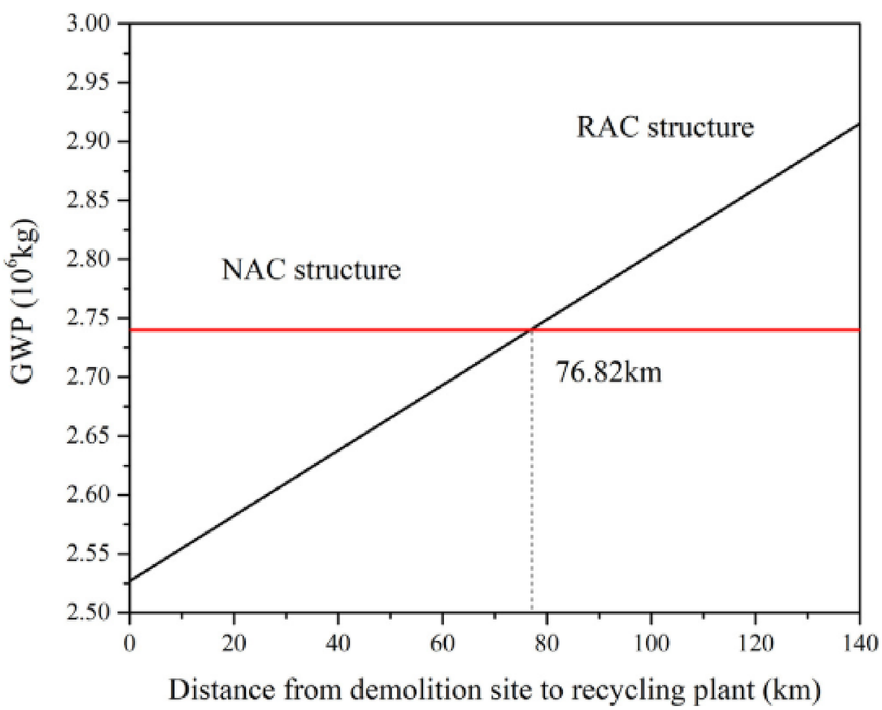


Figure 6-Relationship between GWP and distance from demolition site to recycling plant [61]
(Note: Values shown are specific to project within consideration [61]*, values may differ between various projects or applications)*

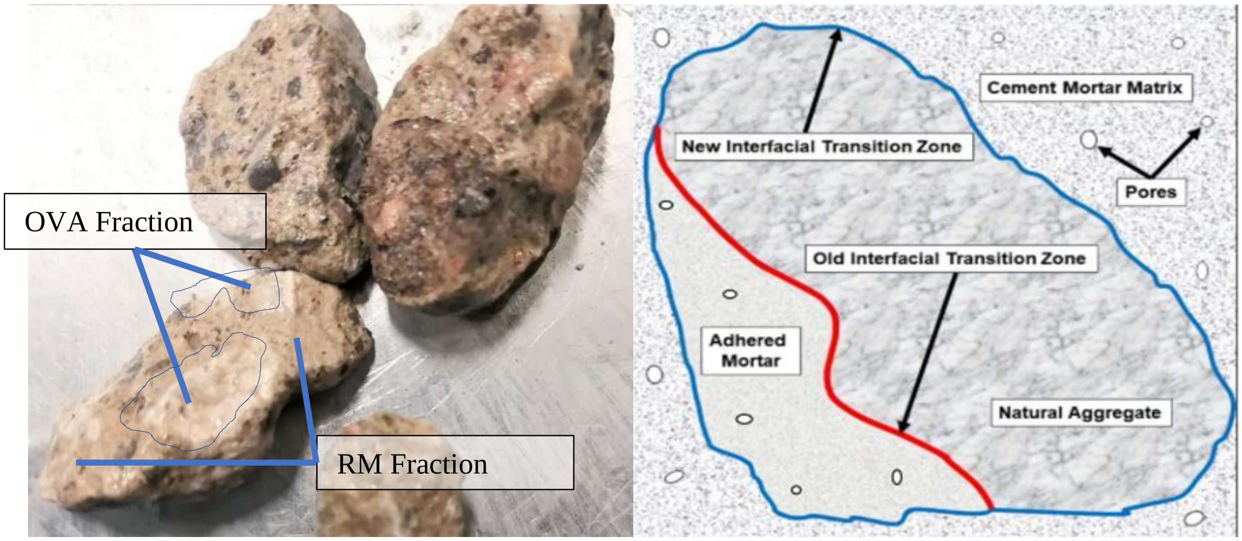
Therefore within future LCA and environmental assessments, environmental savings due to RCA usage should also include an evaluation based on the transportation distance to the project site to ensure an accurate assessment regarding the GWP of RCA and NA [90,91]. Efficient sourcing of RCA (e.g., through on-site production methods) may lead to significant environmental savings relative to NA. However, such cases may be challenging to achieve given site location, size limitations/restrictions and material availability (e.g., not possible in locations with new construction/ lack of pre-existing concrete demolition waste)[86–88]. However, given the readily available nature of RCA within various geographical areas, even in the case of limited or no on-site RCA production, locally available RCA is often available [86–88].

It should be noted that within the assessments presented above, the researchers have noted that further contributing factors associated with deforestation, mining/quarry operations, equipment/fuel usage and eco-system degradation (due to material extraction) were not included within the calculation of GWP given the assessment difficultly without making assumptions [61]. Therefore, although the aggregate production methods (i.e., crushing operations) may contribute towards the GWP for both RCA and NA, the further contributing processes associated with NA contribute towards the greater GWP and CED associated with NA, which are have not been reflected within many LCA conducted within literature [61].

2.1.1.2. RCA Properties and Microstructure

Regardless of similarities within production methods and applications, conventional LCC research has often utilized RCA and NA interchangeably without considering the differences within the aggregate structure or properties. Compared to NA, RCA can be classified as a multi-phase material consisting of a natural aggregate or "original" virgin aggregate (OVA) fraction, and a mortar fraction typically referred to as the residual mortar (RM) or adhered mortar (AM) fraction. Figure 7(a) illustrates that the OVA and RM fractions within the RCA structure (coarse RCA shown), while Figure 7(b) provides an idealized visualization of the multi-phase RCA structure. It should be noted that the terms residual mortar and adhered mortar haven be used interchangeably through existing LCC research, although for consistency, the term "residual mortar" or "RM" will be utilized throughout the remainder of the research program when permissible. Additionally, when referring to the OVA fraction within RCA, the term "natural aggregate fraction" has often been presented within existing LCC research. Although both terms are used interchangeably when referring to RCA, the terms "original virgin aggregate" or "OVA" fraction will be utilized throughout the remainder of the research program when permissible.

Additionally, although the OVA and RM fraction represent the two various fractions within the RCA structure, the boundary between the RM and OVA fraction referred to as the interfacial transition zone (ITZ) [54] is also of significant consideration. Within conventional concrete comprised of NA and cement mortar, the NA and cement mortar bond results in the development of a singular ITZ, which has generally been understood and extensively studied within literature [92,93]. It has been understood that within conventional concrete mixtures, the formation of bond cracking typically occurs at the ITZ at approximately 30-50% of the specified compressive strength of the concrete mixture and progressively increases within a stable manner with loading until the discontinuity limit (i.e., the onset of unstable continuous cracking) [92]. In the case of LCC, the introduction of RCA within the mixture introduces multiple ITZ's within the concrete matrix, as illustrated in Figure 7b, which can be classified as either "old ITZ" or "new ITZ". The "Old ITZ" refers to the RM-OVA interface (Figure 7b- red line), while the "new ITZ" refers to any interface with the fresh (newly mixed) concrete mortar such as the RM-new concrete mortar interface or the OVA-new concrete mortar interface (i.e., Figure 7b- blue line) [9].



(a) *(b)*

Figure 7-RCA Structure (a)Aggregate Composition, (b) Structural visualization [9]

Note: Adhered Mortar = Residual Mortar (RM), Natural Aggregate = Original virgin aggregate (OVA) (Terms used interchangeably within LCC research)

Various studies have examined the influence of the ITZ (i.e., both old and new ITZ) within the LCC structure on mechanical strength properties and have found that added complexity of the multiple ITZ interfaces often governs and limits the mechanical strength properties of LCC (and therefore LCC strength properties) [54,63,77,78]. Experimental findings have shown that the strength characteristics of the RCA are limited by the bond between the RM and OVA fraction (i.e., old ITZ), which in the case of high strength applications often limits concrete compressive strength [54,77,78]. Further investigations have found that under loading conditions, the weaker bond strength between the RM and OVA fractions (characteristic of many RCA sources) increases the propensity for fracture at the ITZ, which attributes to the significant differences within the material properties of RCA and NA sources such as aggregate crushing and abrasion values as well as amongst conventional concrete and LCC mixtures [22,54,77,78].

Various research studies have also shown that relative to NA (i.e., OVA fraction within the RCA), the RM fraction is much more porous and less dense than the OVA fraction with the RCA structure and often lead to 5 to 20 times higher water absorption values of RCA sources relative to NA [12,23,32,39,77,94]. Further aggregate testing has also demonstrated that the RM fraction is also of lower density than the OVA fraction, which often results in reduced bulk density and BSG values of the RCA sources compared with NA sources and significantly reduced hardened concrete density values when used in the LCC production [12,38,77,94].

A summary of aggregate properties collected from the literature highlights the differences between the NA and RCA sources based on differences between the respective coarse and fine fractions. It should be noted that the range of aggregate property values for the coarse and fine fractions of the RCA and NA are provided within Table 1 and Table 2, while a complete list of aggregate properties from extensive studies is provided within Appendix C: Absolute Volume Proportioning Sample Calculation, within Table 37-Table 40

Table 1-Summary of coarse aggregate properties *from literature review*

Aggregate Source	Aggregate Properties					
	Bulk Specific Gravity (BSG)	Absorption (%)	Bulk Density (kg/m3)	Aggregate Crushing Value (%)	LA Abrasion (%)	RMC (%)
NCA	2.53-2.93 (2.67)	0.20-2.40 (1.03)	1350-1733 (1529)	9.50-28.65 (20.31)	11.90-40.99 (23.65)	0
CRCA	1.94-3.11 (2.44)	0.35-11.3 (5.71)	1090-1568 (1433)	11.4-31.3 (23.50)	15.1-42 (33.10)	11.6-61.1 (38.50)
Notation: Minimum Value-Maximum Value (Average Value)						

Table 2- Summary of fine aggregate properties from literature review

Aggregate Source	Aggregate Properties			
	Bulk Specific Gravity (BSG)	Absorption (%)	Bulk density (kg/m3)	Fineness Modulus (FM)
NFA	2.54-2.69 (*2.62)*	0.24-3.00 *(1.07)*	1040-1607 *(1487)*	1.27-2.8 (*2.40)*
FRCA	1.91-2.45 (*2.21)*	5.03-13.10 (*9.56)*	1234-1466 (*1337)*	2.38-3.01 (*2.84)*
Notation: Minimum Value-Maximum Value (*Average Value*)				

In terms of coarse aggregate properties, the average values for CRCA and NCA are presented in Table 1. The influence of the residual mortar fraction on the resulting properties of the CRCA should be highlighted given the reduced BSG and bulk density values and significantly higher absorption capacity, aggregate crushing and abrasion values. Relative to the NCA sources, the CRCA presented 8.7% lower BSG, 6.2 % lower bulk density, 454.3% higher water absorption, 15.5% higher aggregate crushing value (ACV) and 39.8% lower abrasion resistance properties on average. Similar findings were also observed for the fine aggregate fractions with a 15.6% reduction in BSG, 10.1% reduction in bulk density and an alarming 793.5% increase within absorption capacity values relative to the NFA sources. It should be highlighted that within the results presented, the RM content for the CRCA was only found to be 38.46% (i.e., the total mass of aggregate attributed to residual mortar fraction), emphasizing the significant effect of the RM content on the mechanical properties of the CRCA as well as the FRCA. Note that the RM content of the FRCA was not presented (given the lack of RM testing methods developed within the literature for FRCA). To explain the differences within the properties of the NA and RCA sources, previous LCC studies have unanimously concluded that the significantly higher water absorption and lower bulk density and BSG values for the coarse and fine RCA sources can be attributed to the higher porosity and low-density properties of the adhered mortar [12,23,32,39,77,94]. While in terms of abrasion resistance and ACV for the CRCA, previous studies have reasoned that the reductions relative to NCA may be attributed to the formation of microcracks in the residual mortar and weaknesses within the ITZ interface resulting from RCA production [10,95].

It should be noted that given the material heterogeneity of the RCA sources, it can also be inferred that the differences amongst various RCA sources further increased the variability amongst the recorded aggregate properties evident by the higher ranges with the aggregate properties for the RCA sources as noted within Table 37 and Table 38. Various studies have noted that increased variability amongst the properties of various RCA sources can be attributed to differences within the source concrete properties, RMC values, and deleterious materials (e.g., tile, brick, asphalt, fibres as shown within Figure 2 and Figure 3) [56,96]. Many studies have also investigated alternative RCA processing and novel thermal, mechanical grinding and chemical treatment methods to enhance the physical and morphological properties and reduce the variability among various RCA sources [11,64,97]. Additional processing of RCA using various enhancement methods may significantly improve its mechanical and durability properties by reducing the adhered mortar compared with untreated RCA sources [11,64,97]; however, further research is required to assess the feasibility of such treatment options in large-scale industrial applications [1].

2.1.2. Supplementary Cementitious Materials (SCM's)

Cement production has been found to contribute in nearly 7% of the annual CO_2 emissions globally and a significant portion of the total greenhouse gases (GHG) emissions within the construction sector [79]. With cement usage projected to exceed 5 billion tonnes globally by 2050 [18], the enormous environmental repercussions have emphasized the need for sustainable alternative cement solutions [14] most often studied in the form of supplementary cementitious materials (SCM's).

By-products from various industrial processes, supplementary cementitious materials (SCM's) are compounds that possess pozzolanic/cementitious properties [87]. The most commonly used SCM's within the concrete industry include ground granulated blast furnace slag (GGBFS), fly ash (FA), silica fume (SF).

Various studies have also utilized other non-by-product materials such as metakaolin and limestone, although, for this research program, such materials are not within scope; however, they should be noted for completeness [10,18,98]. When incorporated in concrete mixtures, SCM's can improve long-term strength, durability, and fresh properties and offer economic benefits relative to OPC [14,87]; their utilization in concrete eliminates disposal requirements and improves the sustainability of concrete by minimizing the negative impacts on the environment due to the reduction in cement usage [61,87]. As per ACI 130R-19 [21], the use of GGBFS when used to produce 40 MPa conventional structural grade concrete to replace 50% OPC can reduce embodied energy (MJ/kg) by roughly 25% and embodied carbon (CO_2/kg) by 38.7% [21]. Similarly, the use of fly ash and other SCM’s can achieve similar energy and carbon reductions.

It should be noted that while the replacement of OPC with SCM’s can result in substantial reductions in embodied carbon and energy, many design standards (e.g., CSA A23.1-14 [3]) place limitations on the total allowable replacement of OPC with SCM’s [2,99,100]. Often SCM usage/OPC replacement is governed by exposure class restrictions or the specific application (i.e., mass concrete, prestressed concrete elements, footings, etc.) [2,99,100] as well as logistical restrictions due to regional availability. Additionally, given the differences in production, and physical and chemical properties compared with OPC, SCM’s use often results in significant changes compared to mixtures produced with OPC entirely [87]. Many studies have found that when combined with RCA, increasing contents of SCM’s such as silica fume, metakaolin, fly ash and GGBFS, often lowers the mechanical strength properties of the resulting concrete mixtures at 28 days; although less significant effects have been observed at 90 days [101]. It was found that the use of up to 50% GGBFS could be effectively used with <60% RCA content to achieved desired short-term strength properties. To improve the sustainability of the resulting concrete, it was found that higher amounts of RCA and GGBFS could be utilized for desired long-term properties; however, the effect of increasing RCA and GGBFS resulted in significant strength reductions with increasing replacement levels and greater variability within results [48]. It was also found that high replacement of fly-ash (50%) can effectively be used to produce LCC with similar compressive strengths to control specimens, although higher carbonation depths were reported relative to conventional concrete mixtures [87].

While many studies have investigated the optimal replacement amount for various SCM [48,70,101,102], as stated earlier, mixtures produced with SCM’s were generally found to improved sustainability aspects (i.e., carbon emissions and energy demands) given the lower embodied energy and carbon emissions per unit mass of SCM’s relative to OPC [21]. In addition to the use of SCM’s as an alternative to OPC within mixture proportioning, numerous emergent studies have also assessed the novel application of SCM’s within pozzolanic slurries, which has gained significant attention within LCC research studies [12,32,43,63,70,103–105]. It was found that the use of pozzolanic slurries within the mixing of LCC mixes containing RCA may significantly strengthen the ITZ's between the RCA and the new mortar due to the sealing of pores and voids inside the RM fraction of the RCA [12], further discussion provided in Chapter 2.2.3.2.

2.2. State of Practice

The increased importance of LCC amongst researchers, governments, and designers worldwide has resulted in increased research and implementation efforts of LCC on a global scale in recent years. The following sections provide an overview of existing laboratory studies' current state of practice for various LCC mixtures in terms of the effect of LCC materials on mechanical properties, construction practices and emergent research.

2.2.1.1. Fresh Concrete Properties

Given the heterogeneous nature of LCC, specifically RCA (CRCA and FRCA) combined with variations in mixture design methods, there has been a lack of consensus regarding the effect of such materials on the fresh properties of concrete mixtures.

2.2.1.1.1. Effect of CRCA

The use of CRCA generally tends to result in overall slump reductions relative to the conventional concrete mixtures [7,22,106–109,25,38,45–47,49,50,55]. Studies by Lv et al. [55] found that slump values steadily decreased with increasing CRCA contents up to 100%. It was found that slump values were reduced by 27% at 30% CRCA content (by volume), while 52% lower slump values were reported at 100% CRCA content (by volume) [55]. However, it should be noted that several experimental studies did not observe any significant changes in slump values regardless of CRCA content [38,110–112].

Multiple studies have attributed the reduced slump values for LCC produced with CRCA to the higher water absorption properties of the CRCA compared with NCA [38,82,110]. It has been reasoned that the increased water absorption of the CRCA (attributed to the porous RM fraction) leads to a reduction in the free-water content within the concrete mixture, resulting in the observed reduced slump values [38,82,110]. It has also been shown that within the first five minutes of mixing, approximately 90% of the maximum absorption potential occurred [109,113,114]. In addition, slump values with LCC produced with CRCA can also be attributed to the increased angularity and roughened surface texture of the CRCA, which leads to increased inter-particle friction in the fresh concrete mixtures, resulting in reduced slump properties [37,111]. It should be noted that given the variable production methods and composition of various RCA sources (i.e., amount of residual mortar), the effect of CRCA on the fresh properties of concrete is expected to differ amongst various research studies. However, given the reduced slump values often reported (regardless of magnitude), the effect of CRCA should be considered with further experimental testing.

2.2.1.1.2. Effect of FRCA

With regards to FRCA, due to the limited number of studies, the individual effect of FRCA on the workability of fresh concrete mixtures compared to mixtures comprised of NFA is quite inconclusive. Although slump reductions have also been reported within various research studies similar to CRCA, FRCA contents have often been limited to insignificant proportions (i.e., <50 %), leading to an inconclusive understanding regarding the influence of FRCA on the fresh properties of LCC mixtures. Initial studies by Kumar [32] have found that increasing FRCA content leads to reduced slump values with reductions up to 49% observed for mixtures developed with 100% FRCA [32]. Similar results have also been reported by Padmini et al. [56] studies, which reported significant slump reductions ranging from 42-58% for mixtures with 100% FRCA [56]. Similar to CRCA incorporation, the observed slump reductions for mixtures incorporating FRCA have been attributed to reduced free-water content of the mixtures given the increased water absorption characteristics of the RCA [38,82,110], as well as increased inter-particle friction within the fresh concrete mixtures due to the angularity and roughened surface texture characteristics of the FRCA compared with NCA [37,111].

Testing by Evangelista and de Brito [33] found that in order to achieve similar slump values as conventional concrete mixtures, LCC mixtures had to be proportioned with 16.1% increased water contents (+25.1 kg/m^3) for mixtures with 100% FRCA to compensate for the increased water absorption properties of the FRCA. Further assessments by Pedro, de Brito and Evangelista [26] also noted that given the increased water contents required for LCC mixtures with FRCA, the use of terms such as the effective water-to-cement ratio (w/cm$_{eff}$) may be used for LCC to highlight the differences from the total water content and emphasize the effect of absorption by the RCA (i.e., FRCA as well as CRCA). It was noted that the w/cm$_{eff}$ does not take into account the water absorbed by the aggregates during mixing; rather considers the free water available for cement hydration, of which the mechanical strength properties rely upon. The w/cm$_{tot,}$ however, considers the total water content of the mixture (absorbed + free-water) [26]. Therefore, while the w/cm$_{eff}$ may provide a greater level of mechanical strength production accuracy, use within LCC mixture proportioning relies upon an accurate assessment of the absorption properties of the RCA given the significant absorption capacities of the FRCA (and CRCA) and effect of free-water content on the resulting properties of the concrete mixtures, requiring additional assessments to accurately investigate the water absorption properties of RCA (FRCA and CRCA) [9,33,92,115]. Other experimental studies by Khatib [34], Kim et al. [64] and Pedro et al. [26] have reported that regardless of FRCA content (up to 100%), slump values remained relatively unchanged from the conventional concrete mixtures, in some cases increased by up to 31% for mixtures with 100% FRCA. In such studies, it should be noted that increasing free-water content values were often utilized to offset the water absorption properties of the FRCA (relative to NFA), leading to comparable or even increased slump values [26,34,64]. Although, it should be noted that such assessments do not consider the hardened properties of the mixtures; therefore, while increased mixture workability was observed, the effect of additional water contents on compressive strength, tensile strength and elastic modulus properties should be also be considered within LCC mixture designs.

2.2.1.1.3. Effect of Combined CRCA and FRCA

Regarding the use of FRCA and CRCA, although various studies have developed mixtures containing CRCA and FRCA, workability/slump values are often not reported, or CRCA/FRCA contents have been limited to insignificant values [26,46,116]. Although studies by Kim et al. [64], Corinaldesi et al. [70] and Pedro et al. [26] have reported the slump values for LCC mixtures developed with 100% CRCA and FRCA, and have found significant changes with regard to workability raltive to conventional concrete mixtures; further studies are required to extensively evaluate the effect of high volumes of CRCA and FRCA on the slump properties of fresh concrete mixtures given the lack of existing research studies.

However, despite the limited number of studies that have investigated the slump values for mixtures with high replacements of CRCA and FRCA, the general slump reductions often observed for mixtures utilizing RCA (i.e., CRCA or FRCA) have lead many studies to recommend the use of high-range water reducers, super-plasticizing admixtures or modified water compensation methods (such as the use of additional mixing water or the pre-saturation of RCA prior to mixing) to compensate for the increased aggregate absorption by the RCA and minimize observable slump reductions [25,30,36–38,69,117]. Further researchers have pre-cautioned against pre-saturation of the RCA before mixing as such methods may result in a lower ‘nailing effect’ resulting from a lack of penetration of the cement paste inside superficial pores of aggregate particles due to pre-saturation with water [118]. Other studies have observed that aggregate pre-saturation or use of aggregates within saturated surface-dry (SSD) moisture states may be ineffective [37] or even worsen the fresh and hardened properties due to the formation of a weaker ITZ between the cement paste and RCA [118]. It was found that LCC mixtures incorporating RCA at SSD moisture conditions exhibited lower compressive strengths and strength development rates compared to LCC mixtures incorporating RCA when used in an air-dried (AD) or oven-dried (OD) moisture conditions [109,110,119]. It was observed that bleeding of excess water or inadequate absorption of additional water by pre-saturated RCA during mixing resulted in increased w/c_{eff} ratios, reducing mechanical strength properties [109,110,119,120]. As a result, many researchers have given preference to the use of water compensation over aggregate pre-saturation methods, as it has been found to provide improved fresh properties without reducing the hardened mechanical properties performance due to the strengthening of the ITZ from the effective filling of the RCA surface pores with cement paste during mixing [118]. However, as for the case with light-weight aggregates (LWA), similar to the high-water absorption properties of RCA, precautions should be taken when additional water is proportioned to account for the absorption by the aggregates. Many LWA studies have utilized additional mixing water equal to the water absorbed by the aggregates after 24 or 48 hours of water submersion (i.e., AC_{24} or AC_{48}) [121]. Studies have noted that in many cases, the aggregates cannot absorb all the additional water during the mixing and setting period (i.e., 1-2 hours), resulting in higher w/c_{eff} than was assumed and lower strength and durability properties [121]. In terms of RCA, the high absorption of RCA and inadequate absorption by the aggregates during mixing [109,113,114,118] may also result in increased w/c_{eff} ratio reducing mechanical strength properties should excessive amounts of water be added during the mixing process [121]. As a result, guidelines similar to those of light-weight aggregates (LWA), which account for the water absorption 1 hour after water submersion [121], may also be applicable for use with RCA. It has been suggested that limiting additional mixing water to the amount of water absorbed by the aggregates after one hour may ensure that the aggregates effectively absorb the additional water added during concrete mixing, ensuring adequate workability without affecting the w/c_{eff} and resultant mechanical strength properties [119,120].

2.2.1.1.4. Effect of Combined CRCA, FRCA and SCM’s

With regard to SCM’s, the following analysis will be specific to LCC mixtures incorporating SCM’s with RCA (i.e., either CRCA or FRCA). As mentioned, the influence of SCM’s on the workability properties of fresh concrete (without RCA usage) has been widely studied and understood and is well established in design standards and publications [2,93]. However, as observed within literature, a limited number of studies have developed and assessed the effect LCC produced with RCA (i.e., CRCA or FRCA) and SCM’s. Although CRCA usage often led to decreased slump values, preliminary studies by Majhi [36] found that 100% CRCA with increasing slag content (i.e., GGBFS) led to increased slump values with slump values 64% higher at 100% CRCA and 60% GGBFS reported. While other studies by Cakir [111] found that for mixtures with 100% CRCA and up to 60% GGBFS or silica fume (SF), slump values remained relatively unchanged with respect to the control/conventional concrete mixtures. Other studies by Kou et al. [101] found that while increasing SCM content led to increased slump values, slump values remained relatively similar despite nearly 40% differences within SCM contents, regardless of the CRCA content values (i.e., 50 or 100%). Given the vast differences within the individual mixtures as well as the lack of systematic evaluation; while fluctuations within slump have been observed, further testing is required to systemically evaluate the influence of RCA and SCM's (when used in combination in LCC mixture) to thoroughly assess the impact that each material has on the slump properties of LCC mixtures given the lack of studies in the literature.

2.2.1.2. Hardened Concrete Properties

2.2.1.2.1. Effect of CRCA

Compared with conventional concrete mixtures, incorporating CRCA has often led to highly variable findings, given the heterogenous production nature and material sources [12,63,77,94]. Studies conducted by Hansen, [122] found that compressive, tensile, and flexural strength of LCC developed with CRCA may be equal to or higher than that of conventional concrete when the LCC mixtures with CRCA were made with the same or lower water-cement ratio than the original concrete. However, it was noted that while such cases were possible, the hardened mechanical properties of LCC made with RCA with similar proportions as conventional concrete mixtures may vary by as much as 50% or more depending on the quality of the RCA [122]. Other early studies by Ravindrarajah and Tam [123] found that replacing NCA with CRCA often led to reduced compressive strength, elastic modulus and increased shrinkage and creep values, however they noted that the quality of RCA had little effect on the resulting mechanical properties [123]. Recent research has reported similar findings despite several decades of improvements, stating that increasing RCA usage has often led to reduced mechanical strength properties relative to conventional concrete mixtures [16,26,30–36].

McGinnis et al. found that LCC mixtures incorporating 50% coarse RCA CRCA (by volume) presented 16.5% lower compressive strength values, while mixtures using 100% CRCA presented 26% reductions relative to conventional concrete mixtures [16]. Further studies by Ho et al. found similar results, observing that increasing CRCA content up to 100% led to incremental compressive strength reductions, although at w/cm ratios above 0.45, CRCA was found to have a negligible effect regardless of replacement content [31]. Experimental findings by Xiao et al. [112] also found that increasing CRCA content led to reduced compressive strength values (i.e., 25.6% reduction for 100% CRCA); however, even at 100% CRCA, compressive strength values over 20 MPa were achieved, indicating the possible usage of such mixtures in low-grade applications [112].

To further investigate the effect of CRCA, numerous studies such as those conducted by Fathifazl et al. [51], Ho et al. [31], González-Taboada et al. [77], Ryu et al. [54] and Mohammed et al. [78] have aimed to provide a detailed understanding of how CRCA influences the failure mechanisms of LCC. It was observed that the inclusion of CRCA and the effect on the mechanical properties was highly dependant on the w/c_{eff} ratios of the mixtures [31,54,77,78,92]. Extensive experimental testing has found that for w/c_{eff} ratios above 0.45, the effect of CRCA on the compressive strength was negligible. In contrast, at lower w/c_{eff} ratios (approximately 0.40) [92], the strength properties of the CRCA (due to the increased microstructural complexity) led to reduced mechanical strengths [31,54,77,78,92]. It was reasoned that under loading applications, the weak bond at the ITZ between the RM and OVA fractions within the CRCA led to an increased propensity for fracture, which was found to govern the resulting strength properties of the mixtures [54,77,78]. Previous studies have found that the reduced strength at the ITZ within the CRCA may be attributed to the current RCA production methods (i.e., aggregate crushing using impact or jaw crusher), which may result in the development of microstructural imperfections within the RM and OVA fraction of the RCA [47,69]. Such imperfections in the form of fractures and micro-cracks within the various phases of the RCA were found to form weak bonds and acting as a "weak link" within the concrete matrix, resulting in reduced compressive strength properties [69,116,117,124,125]. Further studies have concluded that alternative crushing operations may result in improved aggregate quality due to the use of alternative crushing mechanisms and the possibility for reduced fracture and micro-crack initiation, compared with the conventional jaw crushing production methods, although further testing and validation is required prior to wide-scale implementation [9]. An investigation by Duan and Poon [23] found that the hardened mechanical properties of LCC mixtures were highly dependant on the RM content values of the CRCA, with LCC produced with CRCA containing the highest amount of RM displaying the worst mechanical strength performance (up to 28% lower f'c values) [23]. It should be noted that while the RM heavily influenced the resulting mechanical strength properties, LCC with similar compressive strengths as well as splitting tensile strength and elastic modulus could be developed as conventional concrete mixtures while incorporating 100% CRCA [23]. Although compressive strength reductions have often been observed, numerous studies have also reported LCC mixtures incorporating 100% CRCA which achieved compressive strengths greater than 20 MPa [7,23,36,39,50,64,111,124–126], 30 MPa [22,40,47,49,52,63,116,127–129] and even between 40-60 MPa [23,25,41,101]. Although such findings highlight the suitable nature of CRCA within LCC in terms of f'c performance, the variable composition amongst various CRCA sources requires further investigation to ensure adequate structural reliability, especially in the case of CRCA derived from low strength sources concrete as such sources would result in the worst-case scenarios.

In terms of splitting tensile strength properties (f'_{ct}), various studies have observed that increasing CRCA replacement levels resulted in reduced tensile strength properties compared with control mixtures developed with NCA. Previous studies have noted that increasing CRCA content often led to progressive reductions within splitting tensile strength properties compared with conventional concrete mixtures [55,109]. Previous studies by Guo et al. [30], Duan and Poon [23], Kou et al. [101] and Pradhan et al. [63] found that at 100% CRCA, splitting tensile strength values were reduced by 20.5-39.6% compared with conventional concrete mixtures [23,30,63,101], however other studies found that reductions over 40% were observed within select studies [30,39,107,111]. Studies by Corinaldesi and Moriconi [70] found that for equivalent compressive strength values, LCC with RCA presented approximately 10% weaker splitting tensile strength values than conventional concrete mixtures containing NA. Further studies have found similar findings as well as attributing the reduced tensile strength properties of LCC mixtures developed with CRCA to the increased porosity of the CRCA relative to the NCA [26,33]. LCC research studies have found that unlike compressive strength the tensile strength (f'_{ct}) of LCC was inversely related to the open porosity of concrete (n^c_v), which is dependent on the open porosity of the aggregates and the volume of the paste in concrete as expressed in Equation 1 [10].

$$f'_{ct} = 6 * e^{-0.03*n^c_v}$$ Equation 1 [10]

Further studies have also found that the increased porosity of LCC mixtures containing CRCA is often attributed to reduced concrete density values, which was also found to lower the resulting splitting tensile strength values of the LCC mixtures compared with conventional concrete [36,46,51]. However, it should be emphasized that such experimental observations were derived for the 28-day f'_{ct} properties of LCC mixtures, as such additional studies have noted LCC mixtures with CRCA often display increased long-term f'_{ct} properties (i.e., >1 year) found to be higher than that of the control mixtures developed with NA [130]. It was reasoned that the improved long-term improvements within the properties of LCC with RCA can be attributed to the improved microstructure of the interfacial transition zone (ITZ) from the increased bond strength between the new cement paste and the original aggregate fraction within the RCA after continuous hydration due to residual cementing effects from fine RCA particles, not present within NCA [130]. In terms of existing concrete design standards, various studies have compared experimental f'_{ct} values with empirical modulus of rupture (f_r) predictions, such as CSA A23.3-14 Cl 8.6.4 and ACI 318-14 Cl 19.2.3 as shown within Equation 2 and Equation 3, respectively.

$$f_r = 0.6 * \lambda * \sqrt{f'_c} \quad (MPa)$$ Equation 2 [68]

$$f_r = 7.5 * \lambda * \sqrt{f'_c} \quad (psi)$$ Equation 3 [5]

Where:

f_r : modulus of rupture (MPa)
λ : concrete density modification factor
f'_c : concrete compressive strength (MPa)

It should be noted that while a direct comparison cannot be made between the splitting tensile strength properties and modulus of rupture for concrete mixtures given the fundamental differences within each of the properties, the relations provided in Equation 2 and Equation 3 allow for reasonable estimation of the splitting tensile strength properties of concrete mixtures. Previous studies by Mirza et al. [131] have found that f_r and f'_{ct} properties could be expressed with similar relations, although f'_{ct} were generally 75% of the f_r values [131]. Other studies by Hayles et al. [107] found that although a direct comparison was not appropriate for LCC mixtures, experimental f'_{ct} properties displayed a high degree of similarity to the f_r values predicted with existing CSA A23.3-14 equations shown within Equation 2 [107]. It should be noted that further testing did find that for lower quality CRCA, the f'_{ct} of LCC mixtures were significantly lower than anticipated compared with empirical predictions based on compressive strength values [107]. Based on such findings, it should be noted that given the variability within various CRCA sources, further modification factors may be required to effectively account for the differences within the properties of CRCA on the f'_{ct} properties of LCC mixtures. Although modification factors noted within Cl 8.6.5 of CSA A23.3-14 have been provided to account for the variable density of the concrete mixture and the effect of differences aggregates (i.e. density modification factor: λ), such factors do not explicitly account for RCA usage, rather vaguely address the use of low-density aggregate sources and lower density concrete (i.e., low and semi-low-density concrete) although quantifiable metrics for concrete density (i.e., γ_c = 1800-2000 kg/m^3) are not provided [68]. Similarly, ACI-318 also provides a modification factor to account for differences within f'_{ct} properties of non-conventional concrete, however, such factors are limited to light-weight concrete (refer to ACI 318-14 Cl 19.2.4.2) [5]. Given the extensive variability within existing findings as well as amongst various CRCA sources, further experimental testing is required to investigate appropriate relations to express the f'_{ct} properties of LCC mixtures and f_r properties with regards to the $\sqrt{f'c}$ given the lack of standards presented within existing CSA A23.3-14 [68] and ACI-318 [5] concrete design standards for LCC mixtures.

Regarding the modulus of elasticity (MOE) findings, although various studies have utilized and tested LCC mixtures with various combinations of CRCA, few studies have reported elastic modulus values for LCC mixtures containing CRCA. Preliminary studies have found that increasing CRCA contents up to 100% results in progressive reductions within modulus of elasticity values [43]. Studies by Kim and Yang [44] found that the use of 100% CRCA led to MOE reductions up to 20.2%, with similar results also found within further experimental testing by Yang [52], Pedro et al. [26], Chang et al. [129], which reported reductions ranging up to 27.8% [52], 9.21% [26], 14.1%[129] respectively. Several studies have reported MOE reductions over 40% for LCC with 100% CRCA in select cases [7,23,39,50,52,70,107], although such findings can largely be attributed to reduced compressive strengths of the mixtures. In terms of equivalent compressive strengths, previous studies have found that compared with conventional concrete mixtures, the reduced performance of LCC produced with CRCA may be attributed to the fact that the MOE properties depend on the stiffness of the paste well as that of the aggregates [26,126]. Studies have noted that RCA sources are more susceptible to deformations than NA, given the reduced MOE of RCA, which results in lower stiffness properties for LCC mixtures when incorporating CRCA [126].

Previous studies by McGinnis et al. [16] found that gradation of RCA also heavily influences the resultant stiffness properties of the mixtures, with smaller RCA sources resulting in improved MOE values compared with large sizes aggregates. Further testing indicated that the absorption and deleterious material content of the CRCA (i.e., RCA) were also primary characteristics that negatively impacted concrete strength and the resulting stiffness properties of the mixtures [16]. Studies by Mobili et al. [132] found that the reduced elastic modulus for LCC mixtures with CRCA can be attributed to the reduced density of resulting concrete mixture, caused by the increased total porosity and higher porosity of the residual mortar fraction within the RCA sources (both coarse and fine fraction) [132]. However, it was noted that the reduced MOE of LCC mixtures due to the use of CRCA might also be beneficial such that the reduced stiffness properties may decrease the probability of cracking due to the lack of tensile or shear stresses development [132].

In terms of existing design equations and empirical relations, current CSA A23.3-14 (i.e., Cl 8.6.2.3 and Cl 8.6.2.2) and ACI 318-18 (Cl 19.2.2.1 a/b) design standards provide empirical relations to calculate the modulus of elasticity properties of conventional concrete mixtures as expressed within Equation 4, Equation 5, Equation 6 and Equation 7.

$$E_c = 4500\sqrt{f'_c} \qquad \textit{(MPa)}$$ Equation 4 [68]

$$E_c = 3300\sqrt{f'_c} + 6900 * \left(\frac{\gamma_c}{2300}\right)^{1.5} \qquad \textit{(MPa)}$$ Equation 5 [68]

$$E_c = w/c^{1.5} 33\sqrt{f'_c} \qquad \textit{(psi)}$$ Equation 6 [5]

$$E_c = 57000\sqrt{f'_c} \qquad \textit{(psi)}$$ Equation 7 [5]

Where:

E_c *: Modulus of Elasticity of Concrete (MPa or psi as specified)*

f'_c : Concrete Compressive Strength (MPa or psi as specified)
γ_c : Concrete Density (kg/m^3)
w/c : water-to-cement ratio

It should be noted that the presented empirical relations were developed for use with conventional concrete mixtures and do not account for the effects of RCA or SCM's on the MOE properties for LCC mixtures. While provisions are outlined for variations within concrete density or the water-to-cement ratio of the mixture (i.e., Equation 5 and Equation 6) given the reduced stiffness properties of RCA relative to conventional concrete aggregates, such design equations may lead to over-estimation of the MOE properties for LCC mixtures and result within significant deviations relative to the experimental MOE values for LCC mixtures. Previous studies by McGinnis et al. [16] established empirical relations based on regression analysis for previous LCC mixtures developed with CRCA to model the MOE of LCC produced with CRCA, as shown within Equation 8 [16].

$$\frac{E_{LCC}}{E_{NA}} = 1.02213 - 0.01556\frac{AC_{34-crca}}{AC_{24-NCA}} - 0.00947D - 0.0374R - 0.00316Grade - 0.000029f'_{c-target} \text{ (MPa)}$$ Equation 8 [16]

Where:

E_{LCC} : Modulus of elasticity for the LCC made with RCA (MPa)
E_{NA} : Modulus of elasticity for the conventional concrete made with NA (MPa)
D : deleterious material percentage (by % weight)
$AC_{24\text{-}crca}$: CRCA Absorption Capacity (%)
$AC_{24\text{-}NCA}$: NCA Absorption Capacity (%)
R-Percentage of CRCA (by % volume),
Grade: average size of the coarse aggregates (mm)
$f'_{c\text{-}target}$: target compressive strength of conventional concrete mixture made with NA (MPa)

It was observed that within such studies, the use of Equation 8 accurately predicted the elastic modulus properties of LCC mixtures with an R^2 value of 0.74. However, such equations were developed based on mixtures of which CRCA is being used to replace NA and is ideally suited for LCC mixtures with partial incorporation of NCA and CRCA, as noted within the study. Therefore, mixtures incorporating 100% CRCA or LCC mixtures not modelled after existing NA mixtures may not be suited for use with Equation 8, given the lack of applicability to such mixtures due to the lack of NA properties (i.e., A_{NA}, $f'c_{target}$).

While existing design studies have indicated that the use of CRCA leads to significant fluctuations within hardened mechanical properties, findings relative to conventional concrete mixtures indicate that further research efforts are required to further the understanding regarding the influence and mechanism of CRCA impacts the properties of LCC mixtures. While existing design standards are often used to evaluate the properties of LCC mixtures incorporating LCC, the significant differences within the aggregate properties of CRCA and NCA sources has led to significant variations within predicted, and empirical values further made complicated by the increased material variability (i.e., composition) of CRCA (i.e., RCA) sources. As a result, further research is required better to understand the influence and account for the CRCA properties and develop empirical relations to accurately express the mechanical properties of LCC mixtures while accounting for the differences and effects of CRCA.

2.2.1.2.2. Effect of FRCA

Compared with CRCA, far fewer studies have investigated the mechanical strength properties of LCC mixtures incorporating FRCA. Similar to conclusions found for CRCA usage, existing experimental studies have reported that increasing FRCA usage often leads to reduced mechanical strength properties [26,30,32–35]. Mechanical strength testing of LCC mixtures with 0-100% FRCA (by volume) within studies by Kumar et al. [32], Evangelista and de Brito [33] and Khatib [34] found that increasing FRCA content often led to significant compressive, tensile and elastic modulus reductions with increasing FRCA content, with mechanical strength reductions of over 30% observed at FRCA replacements of 100%. Investigations by Guo et al. [30] found that limiting FRCA to 30% presented no significant effect on mechanical strength properties; however, further FRCA replacements led to increased mechanical strength reductions [30]. It should be noted that various studies have commented that the water absorption properties of FRCA may also significantly impact the hardened mechanical strength properties of the mixtures given the increased water absorption of FRCA relative to NFA sources, as shown within Table 2 [26,32–34].

Experimental testing conducted by Leite [115] found that during typical concrete mixing durations (i.e., up to 30 minutes), FRCA absorption stabilizes, reaching around 50% of its maximum absorption capacity [115]. Other studies have found that despite the increased absorption capacity of RCA (coarse or fine), the inclusion of cement and SCM's during the mixing period limits the water absorption of RCA as the binder materials act to seal pores/voids within the aggregates resulting in partial water absorption [92]. Other studies by Xie et al. [119] have also found that the moisture state of the aggregates (i.e., oven-dried, air-dried, or saturated surface-dry) further influences the absorption capabilities of RCA, which may also impact the resulting mechanical strength properties [119]. Despite the lack of consistency amongst literature, the inability for LCC mixtures to reach SSD conditions given the lack of absorption (i.e., absorbing less than 100% of the aggregate absorption capacity) during concrete mixing have often been found [9,33], which as noted by Pedro, de Brito and Evangelista often leads to increased free-water content, higher w/cm_{eff} values and resulting reductions in mechanical strength properties [26]. It should be noted that despite the variability due to the absorption characteristics of FRCA, compressive strengths exceeding 25 MPa were still achieved while using 100% FRCA in numerous studies [30,32,64,133] and even 50 MPa [26,33]. Despite the suitable mechanical strength properties of LCC mixtures with 100% FRCA, further research is required to develop suitable mixture proportioning methods to improve the accuracy for LCC mixtures incorporating FRCA

2.2.1.2.3. Effect of multiple LCC materials

Minimal studies have utilized and investigated the influence of multiple sustainable constituent materials such as RCAs and SCM's on the hardened properties of LCC. In terms of compressive strength, with regard to LCC developed with CRCA and FRCA, studies by Guo et al. [30] conducted extensive testing of 18 different LCC mixtures incorporating both CRCA and FRCA with various replacement ratios and w/cm ratios. It was concluded that increasing CRCA and FRCA would "seriously jeopardize" the mechanical performance of LCC with compressive strength reductions up to 42.2% relative to control mixtures observed regardless of w/cm ratio. It was observed that in some cases, LCC mixtures comprised of CRCA and FRCA with higher w/cm ratios presented higher compressive strength values than similar LCC mixtures with lower w/cm values; however, compressive strengths were often dramatically reduced with an increase in the CRCA and FRCA content [30]. Other studies by Dapena et al. [46] found that the use of 100% CRCA with minor FRCA replacements (i.e., up to 10%) did not affect the compressive strength properties of LCC mixtures at 28 days, with similar compressive strengths observed for all mixtures (i.e., varied between 47.1 MPa and 52 MPa) [46]. Similar results were also reported by Kou and Poon [35] and Guo et al. [30], which found the compressive strengths of LCC mixtures with 100% CRCA and FRCA replacements ranging from 30-50% were not negatively affected by CRCA and FRCA incorporation. Testing by Guo et al. [30] found that early age compressive strengths (i.e., ≤ 7 days) were reduced as FRCA content increased from 50 to 100%, while after prolonged curing (i.e., 28-90 days), compressive strengths for mixtures with 100% CRCA and FRCA ranging from 50-100% was also reduced by up to 10% [35]. Studies by Kou and Poon [35] found that for LCC mixtures with 100% CRCA and 100% FRCA, compressive strengths were steadily reduced with increasing CRCA and FRCA contents with reductions up to 42.2% observed. Several other studies have also reported similar compressive strength reductions when utilizing 100% CRCA and FRCA, up to 23.8% [26,64,70].

Regarding the effect of RCA and SCM's, limited studies have investigated RCA and SCM's effect on the hardened mechanical properties. Preliminary studies by Majhi et al. [14] have found that LCC mixtures with increasing CRCA and SCM contents often present reduced compressive strength reductions relative to conventional concrete mixtures with up to 37.5% lower compressive strength values observed for LCC mixtures comprised with 100% CRCA and 60% GGBFS [14]. Other studies have also reported significant reductions in the early-age compressive strength properties and attributed to the slower strength development properties of GGBFS relative to cement [36]. Studies Dodds et al. [48] presented similar findings, observing 12.9 to 37.9% lower compressive strength values for LCC mixtures with CRCA contents up to 100% and GGBFS contents up to 65% [48]. It was noted that the compressive strength properties of the LCC mixtures appeared unaffected by GGBFS incorporation up to 50% as similar compressive strength values were observed regardless of slag content [48]; however, increasing CRCA contents were observed lower compressive strength values for uniform GGBFS contents [48]. Cakir [111] found that 100% CRCA and 60% GGBFS resulted in up to 48% lower compressive strength values, while the use of 100% CRCA and 10% silica fume resulted in reductions up to 16%. Further studies found that the observed mechanical strength reductions for mixtures with SCM’s can be partially attributed to typical the slower strength development properties of SCM particles (especially GGBFS) compared with cement [14,36,134], with similar finings also cited within literature and well-known for mixtures containing fly-ash and other SCM’s [2,93]. It was observed that in some cases, the use of minor replacements of SCM’s with RCA led to minor improvements in mechanical strength and durability properties attributed to improved pore structure and reductions within pore size due to smaller particles size of SCM’s relative to cement [70].

In terms of further mechanical strength or durability properties, few studies have reported on the additional mechanical properties besides compressive strength, limiting the experimental findings and understanding regarding the combined effects of LCC developed with CRCA and FRCA or RCA and SCM’s. As a result, further mechanical properties such as splitting tensile strength, modulus of elasticity and durability properties have only been reported within select studies, however generally limited within discussion or reasoning regarding the observed properties [10,27,104,111,116,129,135,28,30,35,36,46,49,70,101].

Preliminary studies by Guo et al. [30] have found that the use of 100% CRCA and FRCA results in upwards of 45% reduced splitting tensile strength properties, while studies by Pedro et al. have observed reductions up to 38.2% [26]. Other studies have found similar reductions, concluding that increasing CRCA and FRCA content often leads to significant reductions within splitting tensile strength values compared with conventional concrete mixtures [35,70]. Existing studies have also found that increasing replacements of SCM’s with RCA also leads to reduced splitting tensile strength values, although the use of SCM’s has been observed to improve the chloride penetration/migration resistance properties, cracking resistance and corrosion initiation [35,102]. Studies by Majhi and Nayak [14] found that the use of GGBFS with RCA led to improved resistance to sulphate attack (i.e., mass and strength loss) attributed to reduced calcium hydroxide content in the bulk hydrated cement paste, increased fineness of the GGBFS particles and reduced pore size of the resulting concrete structure [14]. Similarly, other studies have found that the use of FRCA within LCC mixtures leads to improved resistance to chloride-ion penetration with increasing FRCA content, which has been attributed to filler effects due to the smaller particles size of the FRCA relative to NFA [35]. It was also found that drying shrinkage of the LCC mixtures increased with an increasing FRCA content due to the residual mortar fraction of the FRCA sources contributing to an increase in the paste volume (i.e., cumulative volume of water + cement/binders + residual mortar), although it was reported that the use of lower w/cm ratios could overall shrinkage effects of FRCA [35].

While minor durability and mechanical strength improvements have been observed within select studies, the vast majority of the studies have reported that the use of increasing LCC materials often leads to reduced or inferior mechanical strength properties relative to conventional concrete mixtures. As noted earlier, many studies have reasoned that the reduced mechanical strength performance of LCC mixtures with increasing CRCA and FRCA content can be attributed to the cumulative effects of the increased aggregate porosity, poor strength of the residual mortar fraction and propensity for fracture at the ITZ of the RCA (CRCA and FRCA) [30,70]. Other studies have also noted that the reduced strength values may be attributed to the higher water absorption of recycled aggregates and the resultant effect on the w/c ratio of the mixture. Kou and Poon [35] observed that as the FRCA content increased, increased water content was added into the mixtures to compensate for the higher water absorption of the fine recycled aggregate (as the recycled aggregate were not saturated prior to mixing), which resulted in progressive increases within the slump values of the mixtures. Further testing found that after 10 min of immersion, the water absorption of the FRCA reaches only 51% of the AC_{24} with further investigation reasoning that part of the additional water was not be taken up by the aggregate particles during mixing; hence contributing to the increased slump properties [35]. Other studies have also reasoned that the increased free-water content may lead to lower f'c, tensile strength and MOE values due to an increase in the w/cm ratio of the mixture [30].

It should be noted that few studies have reported that the use of RCA with SCM's or even the use of 100% CRCA and 100% FRCA with LCC mixtures has resulted in similar or even improved compressive strength properties for LCC mixtures with CRCA (or FRCA) and SCM's with compressive strength improvements of 10.4-25.5% reported within select studies [49,70]. However, given the overwhelming majority of research studies reporting significant reductions, various studies have advised against the use of high replacements of conventional concrete materials with LCC material alternatives, citing that such material usage may not be practical given the significant reductions and increased variability in their material properties [115,133,136,137]. It should be noted that while lower SCM and RCA replacements may result in improved or even comparable compressive strength properties compared with conventional concrete mixtures, the use of reduced SCM and RCA (CRCA or FRCA) content or omittance of such materials reduces sustainability benefits and embodied carbon savings [61,87]. However, despite the observed reductions, compressive strengths exceeding 50 MPa [35], 40 MPa [26,35], 30 MPa [10,35,70,116] and 20 MPa [30,35,64,70,116,138] have still been achieved within multiple studies for LCC mixtures utilizing 100% CRCA and 100% FRCA, while comparable tensile strength [35,36,101,111,116] and MOE properties [10,49,70,116,135] have also been presented within existing LCC research studies, although it has recommended that higher-quality RCA sources be utilized (i.e., similar aggregate properties as NA and with low RM content values) [22,24–26,53].

In terms of design methods and empirical design standards, based on the experimental data observed within previous compressive strength testing, Guo et al. [30] proposed an empirical relation to calculate the compressive strength of LCC mixtures with CRCA and FRCA based on non-linear regression analysis as shown within Equation 9 [30].

$$f'_c = \frac{k1}{k2}\left(\frac{w}{cm}\right)(1-k3)AC_{24-CRCA}R_{CRCA} - k4AC_{24-FRCA}R_{FRCA}$$ Equation 9 [30]

Where:

$AC_{24\text{-}CRCA}$: CRCA Absorption capacity (%)
$AC_{24\text{-}FRCA}$: FRCA Absorption capacity (%)
R_{CRCA} : CRCA Replacement ratio-by volume (%)
R_{FRCA} : FRCA Replacement ratio-by volume (%)
k1, k2, k3 and k4: Empirical constants based on experimental results, (k1 = 68.52, k2 = 4.96, k3 = 5.39 and k4 = 2.64)

It should be noted that Equation 9 considers the differences of the aggerate properties of the RCA sources and impact on the mixture properties (i.e., the effect of water absorption on compressive strength properties); however, it does not provide any guidance regarding the attainment of desired w/c_{eff} values given the absorption properties of RCA sources or consider the effect of SCM's. Additionally, while the empirical constants may be utilized to provide an accurate prediction of the compressive strength properties of the mixture, the provided values were specific to the results of the specific experimental program; therefore, such empirical constant values may apply for further mixtures without calibration of the empirical constants. Therefore, further testing methods are required to provide accurate predictions of compressive strength values for LCC mixtures and develop empirical relations to express further mechanical strength properties such as splitting tensile strength and modulus of elasticity properties of LCC mixtures. Although various studies have utilized high replacements of LCC materials such as RCA (CRCA or FRCA), the lack of extensive studies investigating the effect of such materials (specifically use of multiple materials) has led to a lack of established design standards specific, resulting in increased caution from researchers s regarding the increased use of LCC materials within industrial applications. Although mixture optimization has recently emerged within existing LCC research studies, such methods have often been limited to LCC mixtures incorporating CRCA only without any research or further provisions aimed towards the use of combined LCC materials (i.e., combined use of CRCA with FRCA and SCM's).

2.2.1.3. Impact of LCC materials in Reinforced Concrete Applications

Despite the reduced mechanical strength properties often observed for LCC mixtures incorporating various arrangements of CRCA, FRCA and SCM's within existing LCC research studies compared to conventional concrete mixtures [7,26,33,40,41,46], LCC mixtures often display suitable mechanical and durability properties required for use within a wide variety of structural applications [102,139,140]. As a result, many studies have built upon initial research investigations and have conducted extensive experimental testing to evaluate the structural characteristics and suitability of LCC/LCC. In existing studies, reinforced LCC beams' flexural and serviceability properties have often been the focal point for existing structural assessments [50,58,59,141–147].

Numerous studies have found that the ultimate flexural capacities (M_{ult}) of reinforced LCC beams produced with RCA are often similar to conventional concrete regardless of coarse or fine RCA incorporation, with minimal differences compared with conventional concrete mixtures [58,141–144]. Further studies have found that the flexural behaviour of LCC beams were governed primarily by the reinforcement ratio (ρ), rather than the compressive strength (f'c) properties of the concrete mixtures when the ductility properties of the beam were dominated by the reinforcement ratio/reinforcement properties (i.e., beams designed for under-reinforced behaviour using existing design standards) [59]. As a result, it was found that the behaviour of under-reinforced LCC beams could accurately be predicted using the existing design codes with minimal modifications to consider differences within the properties of the LCC mixtures (i.e., reduced MOE and tensile strength values) [59,146]. Various studies have also found that in terms of serviceability properties, reinforced LCC beams exhibit reduced cracking moment (M_{cr}) values, ranging in 10-28% reductions compared with conventional concrete beams [58,142,144]. Further studies have also found that compared with conventional concrete, LCC beams displayed increased deflections (+5-22%) at serviceability (Δ_s) and ultimate loads (Δ_{ult}) [58,142,145,146]. Other studies have also noticed LCC beams exhibit similar crack prorogation and failure mode behaviour as conventional concrete beams regardless of RCA replacement [59], while further studies have noted that LCC beams often exhibit increased crack widths and smaller crack spacing [144–146]. Various studies have attributed the differences in LCC beams' serviceability and cracking behaviours (i.e., M_{cr}, Δ_s, Δ_{ult}) to the reduced MOE and f'_{ct} properties of the LCC beams relative to conventional concrete [145], stemming from the increased microstructure complexity of the RCA [142].

As noted earlier, various studies have noted that the crushing of source concrete required for the production of RCA (CRCA and FRCA) often results in the undesirable and unpredictable formation of microcracks throughout the RCA structure, which may weaken the bond strength at the ITZ between the RM and OVA fraction, resulting in the increased possibility of pre-mature fracture under loading conditions. As a result, many studies have reasoned that the increased deflections and cracking of LCC can be attributed to the weakened ITZ and the reduced MOE and f'_{ct} properties of the LCC mixtures [10,95,139,142,145]. It should be emphasized that regardless of the increased deflections and earlier cracking initiation within LCC beam elements, such studies found that despite reductions relative to conventional concrete mixtures, such properties were still within acceptable guidelines for use with structural applications [58,142,145,146].

Regarding further experimental testing of additional structural elements such as columns and slabs, although various studies have tested such elements [117,129,148,149], by comparison, far fewer studies have investigated the structural characteristics of such elements. As a result, although the structural suitability of beams has been investigated and found to be suitable for many structural applications, further research testing is required for additional structural elements prior to the implementation of LCC within large-scale industrial/structural applications as an alternative to conventional concrete.

2.2.2. Industrial Usage of Low Carbon Concrete

Despite the comparable flexural and serviceability properties observed for LCC reinforced concrete beam members observed within various experimental testing [58,141–144], as well as the environmental and potential economic savings; industry utilization of LCC and the implementation of wide-scale concrete recycling practices has proved to be a very challenging task in many global regions [14,81]. The idea of recycled concrete re-utilization and natural aggregate conservation has been largely ignored by many regions, especially in nations such as Canada, United States and Britain, even though aggregates make up 70-80% of a concrete mix by volume [16,48,70,109]. Various studies have assessed the current conditions and accepted practices within various international construction industries to understand further the cause lacking implementation of concrete reuse and recycling practices. Studies have found that despite additional regulations encouraging concrete recycling, designers and contractors are not incentivized enough to re-use RCA as a replacement material in structural concrete applications, given the relative abundance of NCA found that regions such as Canada, United States and the UK [11,12,38,43,48,51,61,63,64]. It was also concluded that while certain situations may arise where it is desirable to use RCA and implement concrete recycling practices, the use of RCA has mainly been limited to low-grade or non-structural applications [9,15,16,45,48,50,51,105,107]. While Canada, the United States and the UK may have an abundance of natural resources and large reserves of natural aggregates, many regions around the world suffer due to the lack of natural resources and lack of designated landfill disposal sites, emphasizing the need for alternative sources of construction materials and change with concrete recycling practices [32,64,70].

2.2.2.1. Case Studies

Despite the extensive use of RCA in the production of LCC mixes and the demonstrated success in laboratory studies (within select studies), LCC with RCA in practical industrial applications has generally been limited in application [23]. Although comparable properties have been achieved within lab-based studies, further research investigations have found that a lack of technical data, mix specifications, and quality control (QC) / quality assurance (QA) policies and guidelines, are amongst the main reasons why RCA or LCC have not been widely encouraged within new structural concrete construction [15,16,48,50,51,81,105] regardless of the potentially good RCA quality and laboratory success of LCC mixes [45]. It should be noted that such conclusions do not apply for LCC mixtures incorporating SCM's (without the inclusion of RCA) given the wide-scale usage of SCM's and mix design specifications and standards already implemented within many global construction regions (i.e., such as clauses outlined within CSA A23.1-14 [3] as well as ACI 130 [21], ACI 233 [99], ACI 234 [150] and ACI 2114 [151], as well as other relevant standards)

However, despite the overarching industry hesitancy to implement LCC or concrete recycling practices, preliminary projects have begun experimenting with the limited inclusion of LCC comprised with RCA to investigate the suitability of LCC and RCA within the construction industry. In 2015, a dual commercial building complex in Shanghai began construction on two 12-story reinforced concrete frame structures, with one structure was made using LCC comprised of CRCA (Tower A, west) while the other was made with conventional concrete (Tower B, east). Construction of the dual building complex was completed in 2017 and is shown in Figure 8 [61].

Figure 8-Profile of the demonstration project buildings [61]

Considering the scant experience in applying LCC within large-scale construction endeavours, the use of CRCA within the project was limited to a replacement percentage of 30%, while FRCA was omitted in favour of NFA for safety considerations [61]. Additionally, conventional concrete was used for components under the ground to abide by required safety considerations [61]. Despite the limited quantities of CRCA and LCC, lifecycle analysis of the project demonstrated that the recycling of concrete demolition from existing infrastructure in the form of CRCA within LCC production has the potential to improve the sustainability of reinforced concrete structures by reducing the GWP potential and CED relative to conventional concrete made with NA [16,61]. An extensive lifecycle analysis (LCA) completed for two-identical buildings found LCC (with 30% CRCA) resulted in a reduction in GWP (-7.93%) and lowered cumulative energy demand (CED) by approximately -12.79 %, compared with the building constructed using conventional concrete (NA) [61]. However, it should be noted that while such environmental savings were relatively minor. On a global scale, such savings from LCC will translate into exponential energy and carbon emission savings, which can further be improved by the use of increasing LCC materials (i.e., increasing CRCA, FRCA and SCM contents).

However, despite such savings and relatively similar mechanical performance within various studies, the use of LCC as an ecofriendly alternate concrete solution [86] requires further investment, financial support and establishment of technical and performance standards to ensure greater application of LCC and LCC material usage with the construction sector [11]. Despite global incentives and various international governments urging the need for sustainable development/development practices, limited countries have adopted policies or developed technical standards recognizing the added value of re-using construction materials in the form of RCA and LCC within construction applications [15]. As a result, construction waste/ concrete recycling facilities, practices and procedures vary considerably between global nations [7,13,43] despite the recognized added value provided by RCA and LCC [117].

2.2.2.1.1. Current Practices and Barriers to Adoption

The large volumes of concrete waste generated annually coupled with the limited re-utilization by many global nations had led to the excessive and unnecessary landfill disposal for the vast majority of the concrete waste in many regions around the world. Despite increased pollution generation and the reduction in landfilling space caused by the unnecessary disposal of CDW [10,54,64], the rate of concrete recycling varies considerably around the world [12,54,61,64,80]. Several countries in Europe, such as the Netherlands and Belgium, have achieved concrete recycling rates of over 90% and have well-established concrete waste management and recycling procedures. In comparison, other European countries such as Italy and Spain have achieved concrete recycling rates below 10% and have not established an extensive concrete recycling network [7,54].

To understand the difficulties that countries have in establishing concrete recycling practices re-utilization practices, researchers have analyzed the differences of the practices established within leaders such as Japan to the limited establishment of practices such as those within Australia [11]. In Japan, the construction material recycling law enacted in 2000 requires contractors to sort out and recycle waste generated in building & demolition work, resulting in materials such as concrete, asphalt and wood being reused from demolition projects. While Australia, similar to many other countries, has yet to establish effective procedures or concrete recycling practices. As a result, the lack of implemented waste management infrastructure (i.e., facilities and equipment) due to the significant initial investment has limited the recycling rates and practices [11]. Researchers have concluded that unique to the Japanese construction sector, the recycling industry is profitable due partly to the construction material recycling laws, which enforce continued recycling of concrete and other wastes within new construction projects [11]. Many regions worldwide have opted to implement legislation to pursue waste minimization objectives/strategies, including ‘zero waste’/’near zero waste’; however, based on current progress, such strategies have proved ineffective due to the lack of consistent enforcement, governmental support and financial burden to contractors [11].

Various studies have also summarized several fundamental difficulties, outlining the limitations that many countries face in the establishment of CDW recycling practices, namely: the high cost of the investment, limited management skills, lack of experience with usage of recycled products, and the lack of support [9,11]. It should be highlighted that the most prevalent factor that limits the use of recycled materials within the construction industry has been found to be the lack of experience and material unfamiliarity amongst contractors [11]. Despite the continued recycling and production of recycled aggregates from the considerable generation of concrete CDW, the industry lacks the experience to adequately re-use these recycled materials, forming a severe problem of balancing the demand and availability of recycled concrete products [11].

Within North America, countries such as Canada have limited the re-utilization of concrete waste to one-off minor roadwork construction projects [35], despite establishing various federal and provincial policies aimed to promote the usage and re-utilization of concrete waste materials [71–73]. Various studies have reasoned that the limited use of recycled concrete in further applications can be attributed to concerns over material quality, mechanical properties and long-term performance [13,15,23,48,105,107]. Within Canada, the current production methods used for concrete recycling and RCA production have further limited the use of RCA within applications besides roadworks (i.e., structural concrete). Many RCA producers have commonly sold RCA within sub-base gradations (i.e., Granular A or Granular B) containing both coarse and fine RCA; not suited for use within structural concrete without further processing [16,43].

Furthermore, due to the limited recycling/re-utilization of RCA within the North American construction sector, governing bodies within Canada/United States (i.e., ACI, CSA) have failed to establish detailed design standards for the production of concrete incorporating LCC incorporating RCA [9,81,105]. While ACI 555-01 has developed preliminary guidelines for the re-use of concrete [66], as commented by many studies, such guidelines included does not give specific mix design methods for achieving desired fresh and hardened properties for LCC mixtures comprised of RCA [51] and are not extensively developed from large data sets [9]. While other international LCC/ RCA standards have been developed, many standards do not provide detailed information required to effectively develop LCC [9], further emphasizing the lack of urgency amongst global nations/organizations to establish standards promoting the use of LCC and RCA, despite the increasing demand for suitable aggregate sources and the growing concerns regarding the lack NA resource availability [9,14,17,32].

Researchers have found that the limited implementation of RCA, LCC and establishment of LCC design standards within the construction sector can be summarized within a circular degenerative cycle [11]. The study found that many countries and organizations fail to establish recycled concrete mix design guidelines and utilize RCA/ LCC within the construction sector due to a degenerative cycle limiting recycled concrete implementation. The cycle shown in Figure 9 outlines the process limiting the recycled concrete usage and hence the adoption of LCC [11].

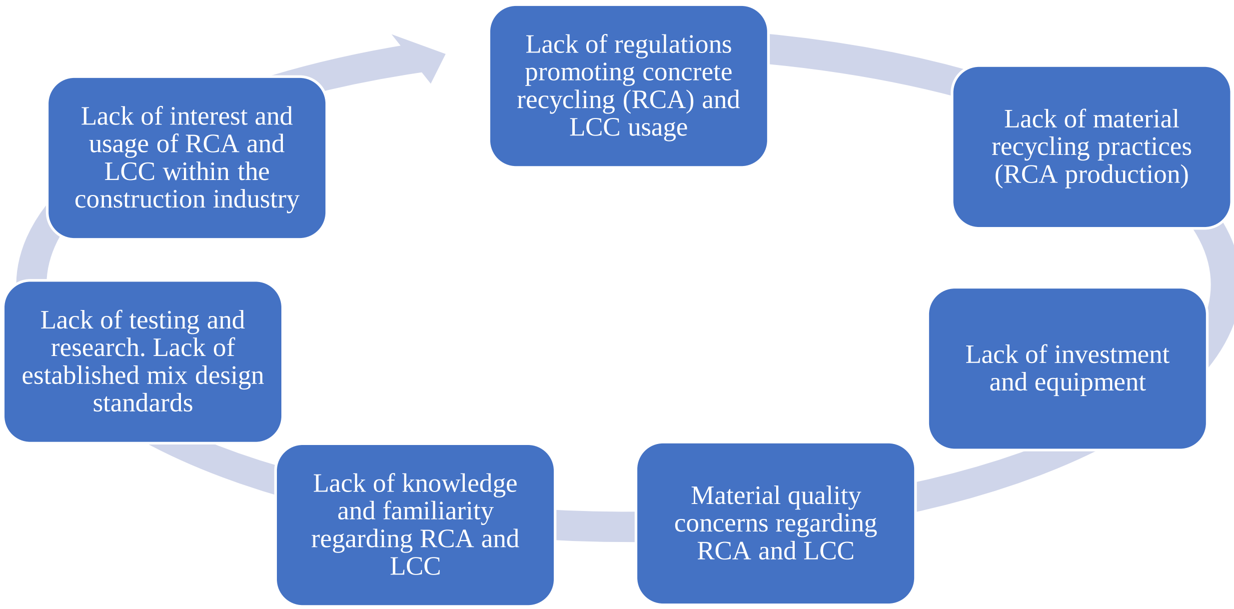


Figure 9-RCA and LCC barriers of adoption degenerative implementation cycle [11]

As summarized within Figure 9, it can be reasoned that the lack of LCC interest/ lack of concrete recycling program implementation starts with the limited regulations enforcing concrete recycling. Limited governmental legislation leads to the lack of concrete recycling practices, stemming from a lack of investment and equipment given concerns over material quality due to unfamiliarity and knowledge of such materials [9,81,105]. The limited knowledge and familiarity within the industry can be attributed to the limited testing and poor mechanical properties of LCC mixtures, given the lack of established design standards stemming from the lack of interest within the construction sector [11]. It is important to note that the information found in Figure 9 is general and intended to be applied to the construction sector broadly. Various regions and countries may have additional restrictions or limitations not listed, which may also limit the implementation and utilization of recycled concrete within the construction sector.

However, despite the limitations hindering the implementation of concrete recycling practices and the use of LCC and RCA, numerous research studies have encouraged RCA and LCC usage by developing LCC optimization techniques and dedicated mix design practices to develop LCC mixtures with predictable mechanical properties. As mentioned in Chapter 2.2.1.2.1, the current CSA mix design standards do not account for the material differences within LCC materials [100], often resulting in inferior properties of the

LCC mixtures. As a result, various novel mix designs and optimization methods specific for LCC have been investigated by various researchers to account for the differences within the properties of LCC materials to ensure the effective development of LCC mixtures. Therefore, to determine the appropriateness of the various novel mix design and optimization methods as well as further examine the suitability of the current CSA concrete design practices within the production of LCC with RCA, Chapter 2.2.3 examines the effect of these alternative mix design and optimization methods and their suitability for use with LCC.

2.2.3. Emergent Research-Optimization of Low Carbon Concrete Properties

Given the differences within the aggregate properties and the effect on the concrete mixture, various studies have noted that simple equivalent weight or volume replacement/proportioning methods do not effectively account for differences within the properties of various LCC materials (RCA/SCM's) [51,53]. Although various studies have proven that LCC with comparable mechanical properties as conventional concrete can be developed [22,24–26,53], given the sizeable mechanical strength reductions often observed within previous studies, researchers have attempted to produce LCC mixtures of comparable structural aptitude as conventional concrete mixtures through the utilization of various optimization methods and practices.

Within previous literature, various optimized mixture design methods such as mixture proportioning, mixing methods, water compensation methods and aggregate pre-treatment methods have been developed and found to improve the mechanical strength properties of LCC mixtures relative to existing concrete design methods (i.e., CSA, ACI, etc.) commonly utilized in LCC research. Although emergent within recent LCC research, the use of various optimization methods has been found to considerably improve the mechanical strength properties of LCC mixtures in some cases by effectively account for the differences within the aggregate properties of LCC materials, not considered within existing mix design standards (CSA, ACI, etc..).

This sub-chapter reports the state-of-the-art findings regarding the optimization of LCC mixes using various optimization methods presented within the literature and presents a detailed overview regarding the methodology/procedure for each method and comparison against conventional mixture design methods. The various optimization methods presented for the research program will be limited to mixture proportioning and mixing methods. Further methods such as aggregate pre-treatment and water compensation methods will not be discussed, given their variable nature and high dependency on the specific aggregate sources (i.e., aggregate properties) utilized within the various literature.

2.2.3.1. Mixture Proportioning

Commonly, research studies have utilized simple mix proportioning methods to develop LCC mixes containing various arrangements of CRCA, FRCA or CRCA and FRCA. Based on the data collected from numerous research articles, the most common proportioning method for the development of LCC mixtures with RCA has been equivalent volume replacement, with 335 LCC mixes (54.7% of all entries), followed by equivalent weight replacement with 128 LCC mixes (20.9% of all entries). Such methods treat RCA as homogenous materials, similar to the proportioning of NA within conventional concrete mixtures, with minor variations due to differences within aggregate properties [51].

While equivalent weight/volume mix proportioning of LCC proves convenient and straightforward, various studies have noted that such mix proportioning methods are invariably ineffective and result in inferior workability and mechanical properties and higher variability than the concrete proportioned using NA [14,16,133,139,152,26,34,36,48,112,122,129,130]. Further studies have also found that the resulting workability and variability within the mechanical properties are highly dependent on the moisture conditions of the RCA prior to mixing [40,109,153] (i.e., dry, air-dried, SSD) as well as the moisture conditions used for curing the concrete specimens [25,154].

However, it was also found in several studies, contradictory to previous findings, equivalent workability and compressive strength values can be achieved using equivalent weight/volume proportioning methods to produce LCC mixes containing RCA [7,23,133,139] [55] through the use of incremental adjustments to the w/cm ratio and total water content of the LCC mixtures [139] [55]. It has been noted that within these studies, the use of several RCA sources often leads to increased variability within the resultant mechanical properties. Many studies concluded that the properties of the LCC mixes were highly dependent on the properties of the RCA used within the mixtures [7,23,133,139], with various LCC mixtures found to present varying mechanical properties despite the identical/similar mix proportions given the variations within the aggregate properties of the RCA sources. Studies also found that the use of various RCA sources resulted in batch-specific mix adjustments (i.e., water content and w/cm ratio), which varied between LCC mixtures due to the high dependency on the properties of specific RCA sources utilized [139]. However, despite several promising studies, the inherent variability and lack of consistency regarding the use of RCA, limited by the lack of standardized guidance on creating mixture designs with predictable mechanical property and durability performance, has further limited the widespread usage of RCA in industrial settings [9].

To find suitable mix proportioning methods specifically for LCC produced with RCA, various researchers have sought to develop novel mix proportioning methods to address the differences within properties of RCA specifically. Preliminary mix proportioning methods such as the "Particle Packing Method" (PPM)

[63,69], modified Bolomey (three equations) method [7,17,70,81,126,155] and Equivalent Mortar Volume (EMV) method [44,45,49–52,94,104,107,108] have been developed and utilized in several research in effort to produce RCA concrete mixes with suitable properties.

The PPM mix proportioning relies on the attainment of the maximum packing density using a specific gradation of coarse and fine aggregates. Optimal packing density used by the PPM method is achieved through appropriate grading of the coarse and fine aggregates to allow smaller particles to fill up the voids between large particles [63]. Bolomey mix proportioning method, on the other hand, determines the strength of the concrete based on various equations using a variety of parameters and coefficients, which depend largely on the degree of hydration as well as other aggregate considerations [17,156]. Despite additional considerations regarding the use of RCA and RCA properties, both the PPM and Bolomey methods have had been infrequently implemented within experimental research (<4% of all mix entries within the LCC database), while preliminary results have also not resulted in significant improvements to the mechanical properties.

The EMV method however, has been increasingly studied in recent years and gained significant research attention as a possible solution for the effective mix proportioning of LCC mixes containing RCA [1,50,69,80,107,119]. Developed by Fathifazl et al. [51] in 2009, the EMV method was developed specifically to address the two-phase material composition of RCA (i.e., residual mortar and original aggregates (OVA)) [51]. The EMV method modifies the mixture proportions of concrete produced with NA and conventional mix proportioning methods, using a variety of equations based on differences within the aggregate properties of RCA [51]. Unlike conventional mix proportioning methods (i.e., volume/ weight replacement), the EMV method considers the residual mortar portion of the CRCA as part of the total mortar (TM) volume (i.e., residual plus fresh mortar volume), allowing for the proportioning of RCA concrete mixes with the same TM volume as a companion 'control' mix produced entirely with NCA [51]. It should be noted that the EMV was not originally developed for use with FRCA; as a result, for mixtures proportioned with the EMV methods and FRCA, the RM volume fraction within the FRCA sources has not been included within the TM volume given the lack of standardized RM testing methods for FRCA sources. Equation 10 outlines the governing equations pertaining to the EMV method and the calculation of the equivalent TM content.

$$V^{NAC}_{TM} = V^{LCC}_{TM} = V^{LCC}_{NM} + V^{LCC}_{RM} = V^{LCC}_{RM} + V_w + V_c + V_{Fine\ agg.}$$ *Equation 10*

Where:

V^{NAC}_{TM} *: Volume of total mortar fraction within conventional concrete mixture (per* m^3*)*

V^{LCC}_{TM} : Volume of total mortar fraction within LCC mixture (per m^3)
V^{LCC}_{NM} : Volume of new mortar fraction within LCC mixture (per m^3)
V^{LCC}_{RM} : Volume of residual mortar fraction within LCC mixture (per m^3)
V_W : Volume of water within mixture (per m^3)
V_C : Volume of cement within mixture (per m^3)
$V_{Fine\ Agg.}$: Volume of fine aggregate within mixture (per m^3)

A comparison of the proportions of various LCC mixtures proportioned with equivalent volume, equivalent weight and EMV method are shown in Table 3. It should be noted that the values presented within Table 3 were not modelled after a specific mixture presented within literature rather developed by the authors based on the guidelines/ design criteria for a conventional concrete mixture with a compressive strength of 30 MPa (w/c of proportioned mixtures: 0.58) and was developed for the sake of mixture comparison. Sample calculations regarding mixtures proportioned with the absolute volume method are presented within Appendix C: Absolute Volume Proportioning Sample Calculation, along with additional aggregate properties of the NA and design assumptions.

In terms of the LCC mixes made with RCA, as shown in Table 3, mixtures proportioned in accordance with conventional mix proportioning methods (i.e., equivalent volume/weight replacement) methods, the resulting mixes contain larger TM volume (V_{TM}) compared to the control concrete mixes ('Control') proportioned with NCA (calculated as the sum of $V_{water,}$ $V_{cement,}$ and $V_{fine\ Agg.}$). Studies have found that the higher TM content of LCC proportioned with conventional mix proportioning methods is generally responsible for its previously reported inferior properties compared to the NCA concrete, while the extent of mechanical strength inferiority depends partly on the volume fraction of the RM in the RCA concrete [51]. As shown in Table 3, LCC mixtures proportioned with the EMV method ensure the proportioned mixtures have uniform V_{TM}, with the goal of achieving identical/similar specified mechanical properties as the conventional concrete mixtures [51]. For clarity, samples calculations for the proportioning of LCC mixtures using the EMV and M-EMV method (S=5) are presented within Appendix D: EMV Proportioning Sample Calculation and Appendix E: M-EMV (S=5) Proportioning Sample Calculation, respectively.

Table 3-Comparison of Mixture proportions of various mix design methods

	CSA (control)	Volume Replacement	Weight Replacement	EMV	M-EMV (S=2)	M-EMV (S=5)
W_{water}	177.00	177.00	177.00	112.80	140.95	151.91
W_{cement}	305.17	305.17	305.17	194.49	243.02	265.36
W_{NCA}	1012.11	0.00	0.00	0.00	0.00	0.00
W_{NFA}	830.04	0.00	0.00	530.16	662.48	728.99
W_{CRCA}	0.00	888.52	1012.11	1416.46	1173.47	1071.02
W_{FRCA}	0.00	612.29	830.04	0.00	0.00	0.00
% NCA	100	0	0	0	0	0

%CRCA	0	100	100	100	100	100
V_{NM}	0.59	0.59	0.70	0.37	0.47	0.52
V_{RM}	0.00	0.14	0.16	0.22	0.19	0.17
V_{TM}	0.59	0.73	0.87	0.59	0.66	0.69
Mass RMC*	0.0	244.3	278.3	389.5	322.7	294.5

Note: Mixtures and mixture proportions presented developed by authors for comparison purposes.
Proportions shown for 1 m^3 of concrete.
*Based on CRCA sources with 27.5% RMC by mass

It should be noted that mix proportioning based on the EMV method requires the proper determination of residual mortar for the CRCA sources. While a standard test method for the determination of the residual mortar content (RMC) of the CRCA sources has not been developed thus far, various thermal, chemical, abrasion, image analysis and empirical methods have been developed and effectively used to accurately determine the RMC of CRCA sources to varying degrees of success [7,15,157,16,22,23,39,45,52,108,138]. Further information regarding the testing and determination of the RMC of the CRCA sources is provided within Chapter 5.3.1.1.

Additionally, as stated within the initial EMV development studies, the EMV method assumes the use of CRCA [51], while the further use of FRCA have been omitted entirely in favour of NFA. As a result, for the EMV mixtures within Table 3, the proportioning of the FRCA sources was achieved using equivalent volume replacement methods. It should be noted that, as mentioned earlier, the residual mortar fraction of the FRCA sources was not considered as part of the residual mortar volume (i.e., V^{RAC}_{RM}) for mixture proportioning. Additionally, it was assumed that within the development of the EMV method, differences within strength or densities of the RM and the fresh mortar or differences between the OVA and NCA (assuming partial replacements) would have minimal or negligible effects on the resultant properties on the properties of the resultant LCC mixes [51]. It is also assumed that severely deteriorated or damaged mortar in recycled concrete will generally not survive the crushing forces during RCA production and will indirectly assure the quality of the RM [51].

Using the EMV method, various studies have found that compared with conventional mix proportioning methods, the EMV method provides considerable improvements to density, flexural strength, elastic modulus properties and comparable/improved compressive strengths properties [49,51,94,107,158]. Additionally, it was also found that the LCC mixtures proportioned with the EMV method, as indicated within Table 3, allowed for significant reductions in the water, cement and fine aggregate contents, enabling improved sustainability and greater environmental savings compared with LCC mixtures proportioned with conventional mix proportioning methods [20,44,107].

However, despite the observed benefits, a variety of studies have commented on various shortfalls of the EMV method. Various studies have reported that the use of the EMV method for mixture proportioning method is appropriate for rich concrete mixtures (i.e., >800 kg/m^3 of fine aggregates), as the EMV method proportioning results in a significantly lower quantity of fine aggregate materials, which many studies have demonstrated results in reduced mixture amounts and lower workability properties [44,50,52,107]. Further testing also found that the reduced workability of the LCC mixtures proportioned with the EMV method led to significant reductions within compressive and tensile strength properties (up to 55.6% and 53.4% reductions) as well as reduced elastic modulus values (up to 53.1% reductions) as well. Many studies have commented on the consideration of the entire residual mortar within the CRCA sources as a part of the mortar volume rather than the aggregate volume within the EMV method. As outlined within research studies, high RMC values within various CRCA sources may not allow for the proportioning of LCC concrete with CRCA as the primary coarse aggregate sources as the specified volume of CRCA (i.e., V^{RAC}_{CRCA}) required by the EMV method may exceed the dry-rodded unit volume of the CRCA sources (i.e., the upper limit to CRCA volume proportioning for unit volume of concrete). As a result, many studies using the EMV method have utilized partial CRCA replacements, as NCA may be needed to compensate for the total OVA deficiency provided by the CRCA sources as per the EMV proportioning guidelines [51]. While this is not a concern for CRCA sources with low RMC values, as indicated within Table 3, the average RMC values for CRCA sources within numerous studies was found to be >38%, which often exceeds the maximum allowable RMC content (as per EMV proportioning), not allow for the complete replacement of NCA with CRCA.

Numerous studies have also found that the residual cementing properties of RCA are significantly lower compared with conventional OPC [159]. When crushed at early ages (i.e., up to 28 days), studies have found that the RCA are weak (due to lack of cement hydration and strength development of the RM); however, as outlined in Figure 10, rapidly gain strength over time given the further hydration of the residual cement particles within the recycled aggregates (i.e., RM) [39,159,160]. Despite aggregate strength development over time [159], studies have found that the substitution of cement with recycled concrete fines/aggregates decreases compressive strength properties when used in LCC production and does not provide supplementary filler effect and nucleation sites, similar to the substituted cement [160]. As a result, consideration of the RM as a part of the mortar volume instead of the aggregate volume within the EMV mixtures poses problems, as the residual cementing properties of the RM are not equivalent to the pozzolanic/ strength development properties as OPC. Especially for aggregates crushed at later ages (i.e., years after initial construction-as in most cases), the EMV method lack of residual cementing over-estimates the residual cementing capabilities and limits the volume of new mortar (i.e., cement, water and fine agg.) added to the concrete mixture, resulting in reduced mixture amounts, lower workability and reduced mechanical strength properties [39,44,50,52,107,159,160].

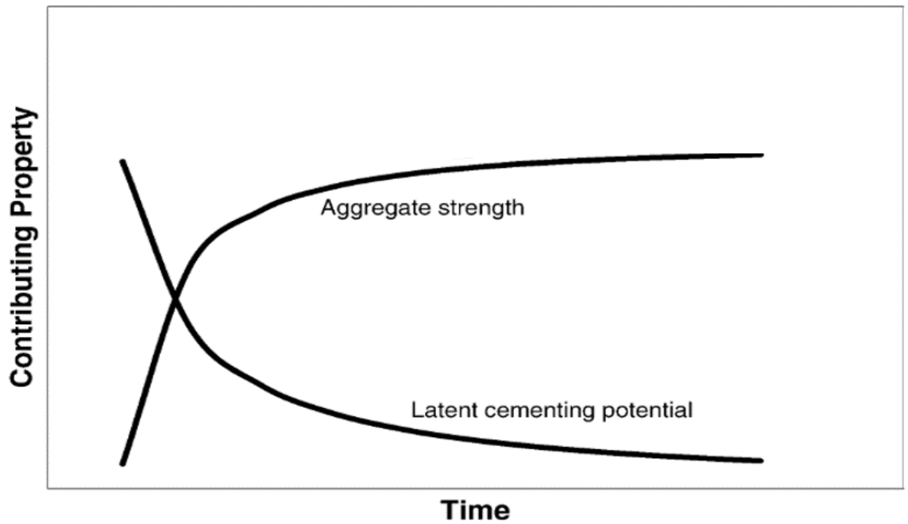


Figure 10-Visualization of cementing potential and strength of the RCAs [39]
Contributing property refers to contributing property within the strength of hardened LCC mixture, latent cementing potential refers to RM fraction within RCA

To alleviate some of the inherent shortfalls of the originally proposed EMV method, many research studies have investigated the potential of a modified equivalent mortar volume method (i.e., M-EMV) [44,45,49,50,52,107]. While various M-EMV research studies have been conducted, for clarity, the M-EMV method discussed in the following chapters will be the modified method developed and widely used by Yang and Kim [44,45]. The modified equivalent mortar volume method (M-EMV) introduces a scale factor (i.e., “S-factor”) to further subdivide the residual mortar portion of the CRCA [45], as shown in Figure 11. Unlike the original EMV method, the modified EMV method considers a portion of the RM (governed by S-factor) as part of the total mortar (TM) volume and the remaining portion as part of the total coarse aggregate volume (i.e., TCA as shown in Figure 11) [44,45,50].

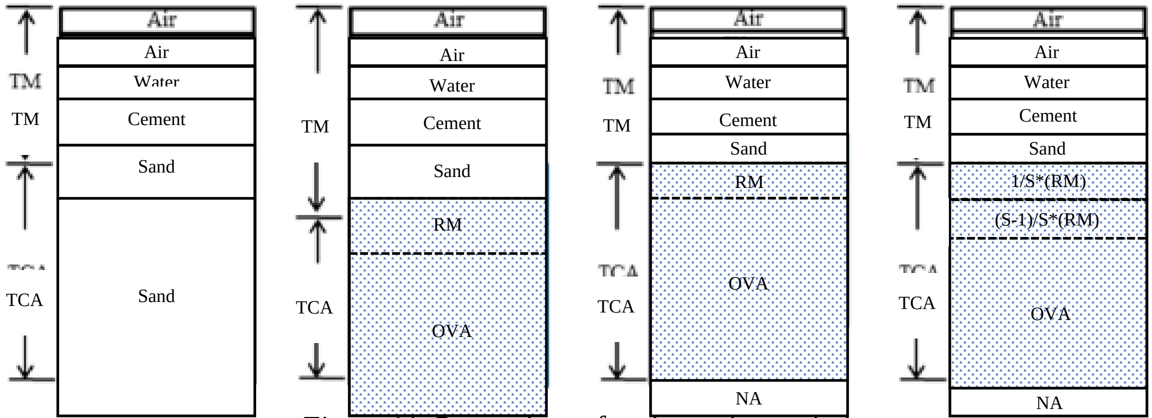


Figure 11-Comparison of various mixture designs

(Left-Right: Conventional NA concrete, Equivalent volume replacement, EMV method, M-EMV method).

Note: *For EMV and M-EMV method shown, NA may be omitted based on RMC values of CRCA.* [50]

Preliminary testing using this modified EMV method indicated that the workability of concrete mixes was improved compared with the original EMV method within numerous studies [45,52,108]. Yang and Lee [108] found that for control mixes with slump values of 150 mm, M-EMV mixes proportioned with S-factors of 2 and 3 resulted in slumps ranging from 110-140 mm, which was significantly improved compared with the original EMV method, which showed slump values of 80 mm [108]. Additional studies also found that similar workability could be achieved for both the EMV and M-EMV proportioned mixtures when using super-plasticizers; however, increased amounts of super-plasticizer were required for the EMV mixes compared with M-EMV mixes [50,52]. However, it was also found that when modelled after control mixes with low workability (i.e., slumps below 40 mm, such as paving concrete), both the EMV and M-EMV displayed significant slump reductions with slump values ranging from 0-11 mm [45].

In terms of mechanical properties, various research studies have found that the use of the M-EMV mix proportioning method results in considerable improvements to the compressive strength values compared with the EMV method. It was found that mixes proportioned with S-factors of 2 and 3 resulted in 11% and 10.8% higher 28-day compressive strength values, while the original EMV method only resulted in a 3.1% increase in 28-day compressive strength values [108]. Further studies found that the M-EMV method could be used for CRCA replacement levels up to 100% to produce concrete with similar or higher compressive strength at 28-days to the control mixes [44,52]. Further testing has also shown that while the use of RCA generally results in reduced elastic modulus values, the use of the modified EMV/EMV mixture proportioning method in this study will result in elastic modulus values, even for paving concrete, comparable or even superior to those of similar mixes made with natural aggregate [7,44,45,52,107,108]. Such improvements using the M-EMV method can be attributed to the volume fractions and the elastic moduli of the aggregate and the mortar used within the M-EMV method [50].

2.2.3.2. Mixing Procedures

As mentioned in the preceding chapter, the use of specialized mix proportioning methods such as the EMV and M-EMV methods often rely heavily on the quality and strength of the RCA sourced for LCC production [56,82,96]. As a result, specialized mixing procedures have also been extensively studied in numerous studies to improve the microstructure characteristics as well as the mechanical and durability properties of LCC mixtures [43,53,54,127,161,162].

The mixing procedure refers to the order of addition of the concrete materials (i.e., water, cementitious materials and aggregates) and duration of mixing during mechanical mixing of the concrete mixtures. Within LCC research studies, the standard procedure outlined within the CSA A23.2-2C [3] and ASTM C192 [163] standards is referred to as the "normal mixing procedure or normal mixing approach" (NMA). The NMA method, summarized in Table 4, provides a standardized mixing procedure for concrete laboratory specimens and has been utilized extensively by a majority of LCC research studies (477 entries, 77.9% of all studies) as outlined further within Chapter 4.

Table 4-Normal Mixing Approach (NMA) [100,163]

Step #	Description
1.	With no rotation, add coarse aggregate, some mixing water and admixture (if applicable).
2.	(If practical*) Start the mixture and add fine aggregate, cement and water with the mixer running.
3.	Mix all ingredients for 3 minutes.
4.	Stop the mixer, cover opening to prevent evaporation and let sit for 3 minutes.
5.	Remix all ingredients for 2 minutes and then discharge contents from the mixer.

**Refers to safe mixer operations; if unsafe to add materials while mixer running, stop mixer then add materials*

Despite extensive usage within literature, the NMA outlined with the CSA and ASTM standards does not provide any specific provisions or modifications pertaining to use with RCA [100,163]. Minor advisory warnings are listed for the use of lightweight aggregates due to concerns over the aggregate absorption characteristics and the effect on the fresh/hardened properties (i.e., slump, compressive strength, and resistance to freezing and thawing) [100,163]. However, the use of RCA are not explicitly addressed [100,163]. Various researchers have examined the NMA in various studies and have commented on the lack of specialization and inability to produce adequate quality LCC when incorporating RCA [12,29,53,54]. Unlike NA comprised entirely of a singular aggregate, the multi-phase material characteristics of RCA (as highlighted within Figure 7) have been found to significantly influence the quality and strength of the RCA, which governs the mechanical and durability properties of the resulting concrete [12,29,53,54]. Therefore, to strengthen the ITZ of RCA and improve the microstructural characteristics and LCC produced with RCA, innovative mixing methods such as double-mixing (DMA), two-stage mixing (TSMA) and other novel mixing methods have been developed and gained increasing research attention within recent years [43,53,54,127,161,162].

The concept of these novel mixing methods revolve around specific separation and strictly timed incorporation of mixture ingredients (namely water) during concrete mixing allowing for the production of a pozzolanic slurry [53], which coats the surface of the RCA, filling cracks, pores and voids within RCA allowing for strengthening of the ITZ and improving the microstructural characteristics of the RCA [12,53]. The TSMA procedure as developed by Tam et al. [53] is provided within Table 5. It should be noted that while the TSMA was originally developed with steps 1-8, steps 9-10 were also added to the mixing process during the preparation of the laboratory specimens during this study as it was deemed upon completion of steps 1-8, additional mixing be undertaken as the concrete mixture lacked uniformity and uniform consistency.

Table 5-Two-Stage Mixing Approach (TSMA) [53]

Step #	Description
1.	With no rotation, add coarse aggregate and fine aggregates.
2.	Turn on mixer and let run for 60 seconds
3.	(If practical*) Add ½ of the water (by weight) into the mixer with mixer running
4.	Mix ingredients for 60 seconds.
5.	(If practical*) Add all cementitious materials with mixer running
6.	Mix ingredients for 30 seconds.
7.	(If practical*) Add remaining other ½ of the water (by weight) into the mixer with mixer running
8.	Remix all ingredients for 2 minutes and then discharge contents from the mixer.
9.	**Stop the mixer, cover opening to prevent evaporation and let sit for 3 minutes.
10.	** Remix all ingredients for 2 minutes and then discharge contents from the mixer.

*Refers to safe mixer operations; if unsafe to add materials while mixer running stop mixer then add materials
**Additional steps often added to the original TSMA (step 1-8) ensure adequate mixing time and consistency

Preliminary findings in various research studies have found that the use of TSMA, as well as the DMA mixing procedures, can lead to significant improvements in LCC mechanical properties [53,54], with various studies findings 17% higher 28-day compressive strengths and up to 21.8% higher flexural strengths compared to similar LCC mixes developed with the NMA mixes and >50% CRCA [43,54]. Studies have also found that incorporating fly-ash and silica fume can effectively fill pores and voids within the RCA and further react with calcium hydroxide to form C-S-H gel. It has also been reported that incorporation of SCM's within TSMA, DM procedures also results in a denser RCA microstructure and an improved ITZ due to the SCM's greater fineness compared with the standard NMA [12,53,162,164]. Additional studies have built upon the concepts introduced by the DMA and TSMA and have developed further specialized mixing approaches for LCC and RCA, such as the Triple Mixing Approach (TMA) 132, as outlined in Figure 12 and Equation 11.

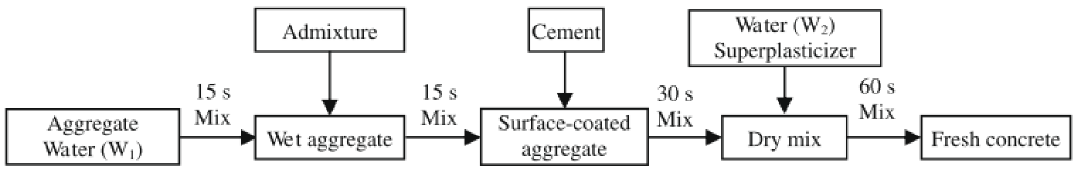


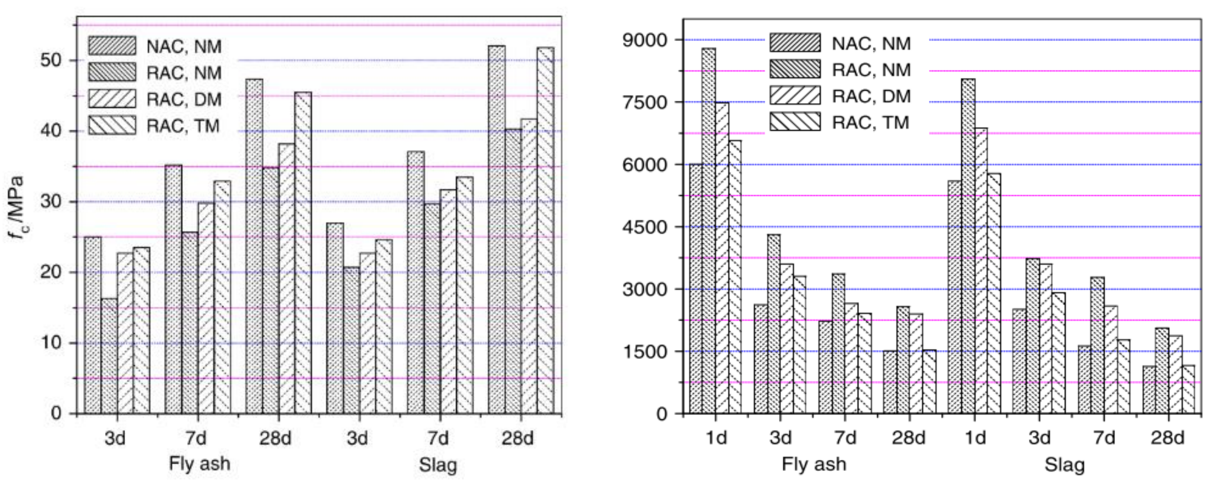
Figure 12-Triple Mixing Approach Overview (with the addition of admixtures/SCM's) [127]

$W_1 = 1.2 * (W_t - W_f)$ $\quad$ $W_2 = W_t - W_1$ $\quad$ Equation 11 [127]

Where:

W_t : Total water within mixture (kg/m^3)
W_f : Free-water content (kg/m^3)
W_1 and W_2: Water Fraction 1 and 2- refer to Figure 12 (kg/m^3)

The TMA has been examined by numerous studies and compared against conventional concrete; LCC mixtures comprised of 100% CRCA have demonstrated that the TMA can effectively improve compressive strength and chloride resistance properties, comparable to conventional concrete mixtures as shown within Figure 13 [127].



(a) (b)

Figure 13-Effect of mixing methods on mechanical properties of concrete mixtures [127]

(a) Effect f'$_c$, (b)Effect on chloride ion penetration resistance. Note: NM-Normal Mixing Approach (NMA), DM-Double Mixing Approach (DMA), TM-Triple Mixing Approach (TMA)

Based on extensive testing and analysis, additional studies have also worked to optimize the mechanical strength and durability resistance improvements provided by the TMA approach and have developed the optimized triple mixing (OTM) approach [28]. Similar to the TMA approach, the OTM approach utilizes various SCM's; however, further separates the mixing of materials into additional components allowing for optimization of the mixing methods and further improved properties of the resultant concrete compared to use with the NMA, DMA and TMA mixing procedures [28]. However, despite preliminary findings, the OTM, as well as the TMA, have not been extensively used or further verified by numerous researchers, limiting the applicability based on the lack of extensive testing. Additionally, given the extensive quality control measures and extensive testing required to constantly ensure accurate use of the OTM, methods such as the TSMA or DM provide a much more simplistic advantage given the simplicity of such methods relative to the OTM, as well as the benefits of improved mechanical strength properties relative to NMA.

2.2.3.3. Effect on Structural Properties

Although used extensively within numerous small-scale cylindrical or cubic specimen testing, in terms of structural elements, limited studies have employed various optimized mix proportioning and mixing methods in order to improve the structural characteristics (i.e., flexural and/or serviceability properties) of large-scale LCC structural elements (i.e., beams, columns, slabs) while using partial or near-complete replacements of LCC materials (i.e., combinations of CRCA, FRCA and/or SCM's) [33,47,50,82,108,120,12]. Apart from small-scale testing, various studies have found that in addition to the improved microstructural and mechanical strength (MOE, f'_{ct}) properties, the use of optimized mix design methods such as EMV based mixture proportioning and/or optimized mixing methods can further modify and impact the cracking behaviour and deflection characteristics of large scale LCC structural elements as impact the resultant flexural capacities.

In terms of serviceability properties, preliminary studies have found that the LCC beams proportioned with the EMV method displayed similar cracking and yielding behaviour to control beams (i.e., yielding followed by concrete crushing at failure) [50]. Further testing also indicated that the use of EMV proportioning led to similar deflection values regardless of RCA content [50], which relative to other studies which observed that 9% higher deflections within LCC beams relative to conventional concrete beams provide an indication of the serviceability improvements provided by mixture optimization through EMV proportioning [5]. Additionally, in terms of cracking moments (M_{cr}), various studies have observed that while EMV proportioning leads to minor improvements, reductions up to 28% relative to conventional concrete mixtures were still observed [143]. As noted earlier, the reduced M_{cr} for LCC mixtures has been attributed to the increased microstructural complexity (i.e., presence of RM, OVA and ITZ) and reduced strength characteristics of the RCA given the propensity for fracture/cracking at the ITZ under loading/stress conditions [143–145]; as a result, although EMV proportioning and mixing optimization methods have demonstrated the ability to improve microstructural characteristics [43,53,54], representative improvements were not observed within M_{cr} properties. It should be highlighted that in some cases, the use of optimized mix design methods did lead to increased cracking moments were observed in some cases (26% higher) [143].

In terms of flexural properties, various studies have noted that the use of EMV mixture proportioning has led to LCC beams with comparable or minor flexural strength reductions (4%) relative to conventional concrete mixtures [50]. Other studies have also noted that in terms of ultimate moment capacity, the use of EMV proportioning has led to LCC with 5-8% higher values relative to conventional concrete mixtures regardless of RCA source tested (i.e., different source concretes) [143]. However, within such studies, LCC beams were designed (using existing design standards) such that ductile behaviour was to be expected (assuming comparable behaviour as conventional concrete beams); as a result, the failure of the beams was primarily dependant on the strength properties of the reinforcing steel.

Regardless of the use of optimization methods, further studies have reasoned that the comparable flexural strengths properties observed for LCC and conventional concrete mixtures were affected primarily by the reinforcement ratio rather than the compressive concrete strength properties of the respective concrete mixtures [58,59]. Other studies have also concluded similar findings, stating that compared to conventional concrete beams, LCC beams with the same water-to-cement ratio with CRCA replacement ratios up to 100% (i.e., 100% CRCA) have comparable flexural capacity values as corresponding conventional concrete beams [142].

As a result, based on the experimental observations, although the benefits provided by optimization methods are apparent with regards to mechanical properties of concrete specimens (i.e., f'_c, f'_{ct}, MOE), the use of optimization methods has less of an effect on the flexural and serviceability properties for reinforced concrete beam elements. Therefore, although encouraging findings have been observed, existing research efforts regarding the influence of optimization methods on the flexural and serviceability properties of LCC beams are significantly limited, requiring further research to understand such effects. Combined with the lack of experimental investigations regarding the structural properties, the limited information and understanding regarding LCC mixtures has not provided a sufficient volume of findings or confidence amongst contractors/designers to use such materials within further applications or industrial applications. Additionally, it should be noted that many of the observations presented have been limited to LCC beams utilizing CRCA and EMV proportioning methods, while further materials such as FRCA, SCM's and mixing optimization methods such as TSMA, DM, or further methods such as water compensation have not been utilized or investigated within existing LCC studies.

2.2.4. Summary

Based on the extensive literature review regarding the current state-of-the-art of LCC research, a summary of the over-arching observations obtained are presented below:

- In terms of production methods, the circular production nature of RCA presents a much more sustainable alternative relative to NA, although the use of concrete and demolition wastes is often highly variable and introduces unknown quantities of undesired deleterious materials within the resultant RCA.
- RCA can be classified as a multi-phase material consisting of an "original" virgin aggregate (OVA) fraction and a residual mortar (RM) fraction, with the boundary between each fraction classified as the interfacial transition zone (ITZ).
- Various studies have examined the microstructure properties of RCA and have found that the added complexity due to the ITZ often governs/limits the mechanical strength properties when used in LCC [54,63,77,78]. It was found that the RM fraction is much more porous and less dense than the OVA fraction, which significantly modified the aggregate properties of RCA relative to NA.
- An assessment of existing literature found that coarse RCA (CRCA) have an average 8.7% reduction in BSG, 6.2% lower bulk density, 454.3% higher water absorption, 15.5% higher aggregate crushing value (ACV) and 39.8% lower abrasion resistance properties than natural coarse aggregates (NCA). While FRCA was found to have a 15.6% reduction in BSG, 10.1% reduction in bulk density and an average 793.5% increase within absorption capacity values relative to the natural fine aggregate (NFA) sources.
- An assessment of existing LCC mixtures with the literature found that CRCA was often the primary LCC material used (79.2% of all mixtures), while FRCA (17.3% of all mixtures), CRCA + FRCA (11.3% of all entries) and SCM's with RCA (12.1% of all entries) were significantly understudied within the existing literature.
- In terms of fresh properties, the use of RCA often led to significant variations within slump, attributed to increased water absorption values of RCA and lack of accurate water compensation

methods for RCA, leading to inaccuracies within mixture contents (i.e., free-water and w/cm ratio of the mixture).

- In terms of hardened properties, the use of LCC materials was often found to reduced f'_c, f'_{ct} and MOE values with increasing replacements. Reductions within mechanical properties were attributed to weak bond at the ITZ and propensity for fracture under loading, existing cracks within the RCA micro-structure, porous nature of the RM and reduced pozzolanic properties of SCM's relative to OPC. Although various studies had noted that the reductions were dependent on the w/cm of the ratio, requiring further research investigation.
- Numerous existing research studies have also investigated the use of novel optimization methods to improve mechanical strength properties of LCC by strengthening the properties of LCC materials. Methods such as EMV/M-EMV proportioning and TSMA mixing methods were found to lead to considerable improvements within small-scale specimens, although further testing was required to assess such effects in large-scale structural elements.

3. RESEARCH METHODOLOGY

As noted earlier, the research program was divided into two sections consisting of (1) LCC Literature Database Analysis and (2) LCC experimental assessment. Within the LCC literature database analysis, the experimental findings from over 100 peer-reviewed LCC research papers (mixture proportions, mix design procedures and concrete properties) were collected and analyzed in terms of the usage of materials, impact of LCC materials replacement on concrete properties and effect of various design methods on concrete properties. It should be noted that the literature analysis and collection were limited to LCC research papers that investigated the use of RCA or SCM's, while further materials (i.e., geopolymers, limestone calcined clay cement, etc.…) were not included within the analysis. Further information regarding the breakdown and organization of the database analysis is presented in Chapter 3.1.

Based on the findings from the LCC literature database analysis, a detailed experimental program was developed to address the identified research gaps. As a result, a multi-stage experimental program was devised within the LCC experimental assessment of the research program, consisting of three progressive subsections: 1-Materials assessment and characterization, 2-Concrete Mixture Development and Concrete Properties Testing and 3-Flexural Response and Serviceability Assessment of Steel-Reinforced Low Carbon Concrete Beams. The materials assessment and characterization subsection consisted of the materials testing of the coarse and fine fraction of RCA and natural aggregate (NA) sources, including absorption capacity (AC_{24}), bulk specific gravity (BSG), bulk density, micro-Deval abrasion resistance, particle size distribution, and fineness modulus (FM) based on the CSA A23.2-14 testing standards [3]. Further testing was also conducted to assess the residual mortar (RM) content of the coarse RCA (CRCA) sources as well as the total absorbed moisture values of the fine RCA (FRCA) sources. Additionally, the properties of the water (potable water) and binder sources (cement and GGBFS) used within the experimental program were also measured. The purpose of the materials assessment and characterization stage of the experimental program was to investigate the properties of the various material sources and aid in the understanding of how the properties of the various LCC material properties impact the fresh and hardened concrete properties observed within further chapters of the experimental program. The second stage of the experimental program consisted of the concrete mix development and testing of various LCC mixtures designed within various LCC materials compositions and various mix design methods found within the literature database. The purpose of this stage of the experimental program was to investigate and better understand the effect that various LCC materials have on the governing strength mechanisms for different grades of structural concrete and mortar mixtures, as well as systematically evaluate the effect of LCC materials on the resulting fresh and hardened LCC properties using both conventional and novel mix design methods. Additionally, based on the preliminary findings within the concrete mix development and testing stage, LCC mixtures were developed using the governing strength mechanisms presented during the initial findings and optimized to achieve comparable mechanical strength properties as the control mixtures through the use of optimized mix design practices. Lastly, based on the findings from the concrete mix development and testing subsection, the final section of the experimental program consisted of the flexural and serviceability assessment of steel-reinforced low carbon concrete beams. Through the testing, the influence of LCC materials in terms of their impact on the flexural properties (nominal strength, steel yielding) as well as severability (deflections, cracking) were assessed relative to control mixtures through the use of 4-point flexural testing. A detailed overview of methodologies followed for each of the experimental program subsections is provided within chapter 3.2.

3.1. LCC Literature Database Analysis Overview

Given the extensive volume of experimental findings, the first part of the research program consisted of the development and analysis of existing LCC research findings through the establishment of an extensive LCC research database. The database consisted of the collection and organization of the experimental findings from over 100 peer-reviewed LCC research papers (materials proportions, mix design methods and concrete properties), while the analysis was based on 1) usage of LCC materials within LCC mixtures, 2) impact of LCC materials replacement on concrete properties and 3) the effect of emergent optimization practices/methods on the mechanical properties. A detailed breakdown of the various material subcategories and emergent optimization practices analyzed is provided below

1- Usage of LCC Materials
    - CRCA usage and replacement content
    - FRCA usage and replacement content
    - CRCA and FRCA usage and replacement content
    - SCM and RCA (CRCA or FRCA) usage and replacement content

2- Emergent Optimization Practices/Methods
    - Mixture Proportioning Methods
        - Equivalent Mortar Volume (EMV) and Modified EMV (M-EMV) proportioning
    - Mixing Methods
        - Two-stage mixing approach (TSMA), double mixing approach (DMA)

In terms of the optimization methods, while various methods have been presented throughout existing literature, for conciseness given the limited research studies for many of the various methods, the database analysis was focused on mixture proportioning methods such as the equivalent mortar volume (EMV) and modified EMV method (M-EMV) and mixing methods such as two-stage mixing approach (TSMA) and double mixing approach (DMA). Further optimization methods based on water compensation, water proportioning or additional mixture proportioning/mixing methods (with the exception of the EMV/M-EMV proportioning and TSMA) were not included within the LCC database given the lack of extensive research findings and lack of conclusive findings.

In terms of the database analysis, while various mechanical properties and quantifiable metrics have been presented within existing research studies, for conciseness, the analysis was limited to the fresh and hardened properties to keep in line with the further stages of the experimental program, while metrics such as fracture energy, bond strength, carbon footprint/ equivalent CO_2 were not evaluated. Extensive focus was placed on the following mechanical properties: (1) workability/slump, (2) compressive strength (f'_c), (3) splitting tensile strength (f'_{ct}) and (4) modulus of elasticity (MOE). It should be noted that self-consolidating concrete (SCC) mixtures were omitted within the database analysis. The flexural and serviceability properties of reinforced LCC elements were not evaluated within the database; however, were discussed within the literature review shown in Chapter 2.2.3.3.

The results from the database analysis were used to further investigate the experimental findings within subsequent sections of the experimental program by allowing for a comparison of experimental findings with those found within literature. The results from the initial database analysis were used to assess the effectiveness of various optimization practices/methods used throughout literature, and the use of LCC materials on the mechanical properties of LCC mixes obtained within the experimental program to those found within existing literature.

3.2. Experimental Program

Following the establishment and analysis of the LCC literature database, a detailed three-phase laboratory experimental program was planned to address the gaps and areas of limited research identified within the LCC database analysis. As noted, the experimental testing program consisted of three progressive subsections consisting of 1-Materials assessment and characterization, 2-Concrete Mix Development and Testing and 3-Flexural Response and Serviceability Assessment of Steel-Reinforced Low Carbon Concrete Beams. An overview of each of the various experimental sections is provided in the subsequent sections.

3.2.1. Materials Assessment and Characterization

The initial stage of the experimental program consisted of a detailed materials assessment of the various concrete materials used throughout the experimental program. Emphasis was placed on the assessment of the coarse and fine aggregate properties of both the natural and RCA sources due to their large impact on the resulting concrete mixtures. Water sources were also while the cement and SCM's were not tested as their properties were provided by the respective manufactures prior to use within the experimental program. Additionally, it should be noted that the same aggregate, water and binder sources were utilized throughout the entirety of the experimental program. Ground granulated blast furnace slag (GGBFS) was utilized as the primary SCM throughout the experimental program.

In terms of materials testing, all testing was conducted as per CSA A23.2-14 standards [3], while further references were also made to ASTM and OPSS (Ontario) as required. A summary of the aggregate properties tested and the corresponding testing standards is provided in Table 6. It should be noted that while the CSA A23.2-14 standards were primarily used for the testing (primary testing standard), additional testing standards were also referenced during the testing (secondary assessment standards) for completion purposes or used in the absence of non-existent CSA A23.2-14 standards as provided within Table 6.

Table 6-Aggregate Properties Tested and Corresponding Testing Standards

Material Property	CSA Assessment Standard	Secondary Assessment Standard ***
Coarse Aggregates		
Bulk Specific Gravity (BSG)	CSA A23.2-12A [3]	ASTM C127 [165]
Absorption (AC24)	CSA A23.2-12A [3]	ASTM C127 [165]
Bulk Density	CSA A23.2-10A [3]	ASTM C29 [166]
Gradation/Sieve Analysis	CSA A23.2-2A [3]	OPSS MTO LS-602 [167,168]
Micro-Deval Abrasion Resistance	-	ASTM D6928 [169], OPSS MTO LS-618 [170]
Residual Mortar (RM) Content		*, **
Fine Aggregates		
Bulk Specific Gravity (BSG)	CSA A23.2-6A [3]	ASTM C128 [171]
Absorption	CSA A23.2-6A [3]	ASTM C128 [171]
Gradation/Sieve Analysis	CSA A23.2-2A [3]	OPSS MTO LS-602 [167,168]
Total absorbed moisture/absorption rate		*

*No Existing Standard
**Testing procedure used from existing studies
***Use of additional assessment standard, if applicable. Used for further reference

It should be highlighted that while the corresponding CSA, OPSS or ASTM standards (refer to Table 6) were used for the majority of the aggregate testing, further aggregate testing such as total absorbed moisture/absorption rate of the FRCA and residual mortar (RM) content of CRCA were based on modified testing procedures provided within existing literature (no existing CSA, ASTM, OPSS testing standards). An overview of the modified RM testing procedures is provided in Chapter 5.3.1.1**.**

3.2.2. Concrete Mix Development and Testing

The second stage of the experimental program consisted of the mechanical properties testing of three series of concrete mixtures (Series A, B, and C) for two target concrete compressive strength (f'_c) classifications (30 MPa and 50 MPa). Within the Series A mixtures, six different mixtures were developed, based on the current mixture design, proportioning and mixing methods outlined within the current CSA A23.1-14 standards. Control mixtures were proportioned using natural coarse and fine aggregates and cement, while the remaining LCC mixtures within the Series A mixture set were developed using various arrangements of LCC materials, intended to systematically assess the effect of LCC materials on the fresh and hardened mechanical properties of concrete. Additionally, the Series A mixtures were proportioned to assess the sole and combined influence of LCC material usage (i.e., coarse RCA, Fine RCA and SCM's-GGBFS) on the governing strength properties (i.e., governing strength mechanisms) through the use of both concrete and mortar specimens. Series A mixtures were developed using the absolute volume method as specified within the CSA A23.1-14 [3] standards for both the control and LCC concrete/mortar mixes. CSA A23.1-14 [3] concrete mixing methods standards were also followed during the preparation of the Series A mixtures. When specified with the various Series A mixtures, RCA (coarse and fine fraction) was used to replace the entire NA fraction with an equivalent volume, while the use of GGBFS with select series A mixtures was used as 50% of the total binder materials by weight. It should be noted that the Series A mixtures were also used to assess the effectiveness of current concrete mixing practice and the applicability for use with LCC materials.

The Series B mixtures were developed to investigate the mechanical properties of LCC mixtures designed with the highest percentage replacement of LCC materials designed with novel optimization methods reported in the literature as discussed in Chapter 2.2.3.2. Mixture proportioning methods such as the EMV/M-EMV mixture proportioning [45,51] and TSMA/DMA [53] were used for the design of the Series B mixtures to maximize the LCC material content (by % weight) and improve mechanical strength properties/ minimize mechanical strength reductions due to LCC material usage. It should be noted that the mechanical properties of the Series B mixtures were compared with those reported in the LCC database analysis as well as with those found within the Series A mixtures to gauge the effectiveness of the various mix design methods in terms of the effect on the mechanical properties (fresh and hardened properties) of LCC mixtures.

Based on the cumulative findings obtained from the Series A and B mixtures, Series C mixtures consisted of the optimization of two LCC mixtures to achieve comparable properties to those of the control mixes (conventional concrete). The Series C mixtures were designed using specific mix design practices and LCC material restrictions such that the equivalent fresh and hardened properties as those of the control mixtures could be obtained. An overview of the mixture characteristics (i.e., mix design and material composition) of the various mixtures within the Series A, B and C mixtures is provided within Table 7. It should be noted that the Series A and B mixtures were developed for two-target concrete compressive strength (f'c) classifications (30 MPa and 50 MPa), for a total of 20 mixtures, while the Series C mixtures were only designed for one of the target concrete strength classes (30 MPa target strength class: RNS-C, 50 MPa target strength class: NRS-C).

Table 7-Series A, B and C Mixture Characteristics-Mix Design and Material Composition

Series	Mix	Mixture Characteristics				
		Coarse Agg.	Fine Agg.	Binder	Mix Proportioning	Mixing Method
A	NNC-A *	NCA	NFA	OPC	Absolute Volume Method**	CSA Standards**
	RNC-A	CRCA	NFA	OPC		
	NRC-A	NCA	FRCA	OPC		
	RRC-A	CRCA	FRCA	OPC		
	NNS-A	NCA	NFA	50% OPC, 50% GGBFS		
	RRS-A	CRC	FRCA	50% OPC, 50% GGBFS		
B	RNC-E-B	CRCA	NFA	OPC	EMV	TSMA/DMA
	RNC-M-B	CRCA	NFA	OPC	M-EMV	
	RRC-M-B	CRCA	FRCA	OPC	M-EMV	
	RRS-M-B	CRCA	FRCA	50% OPC, 50% GGBFS	M-EMV	
C	RNS-C	CRCA	NFA	50% OPC, 50% GGBFS	Absolute Volume Method **,***	TSMA/DMA
	NRS-C	NCA	FRCA	50% OPC, 50% GGBFS		

Note: target strength (MPa) to be indicated for each mixture (i.e., -30 or -50, example: NNC-A-30),
*Control Mixture
**Based on CSA A23.1-14 standards,
***Modifications made to the w/cm ratio and water proportioning-optimized for highest compressive strength values

A detailed overview of the mix design methods/ mixture devolvement of the Series A and B mixtures is provided within Chapters 6.1.1 and 6.1.2. While the mix design methods/ mixture devolvement of the Series C mixtures is provided in Chapter 6.1.3.

3.2.3. Flexural Response and Serviceability Assessment of Steel-Reinforced LCC Beams

Based on the mixture proportions developed (i.e., Series A, B and C mixtures), the final stage of the experimental program consisted of the flexural response and serviceability assessment of LCC beams developed with various arrangements of LCC materials (CRCA, FRCA and GGBFS) and mix design methods. The Series-A mixtures (NNC-A) for both the 30 and 50 MPa mixtures were used when designing the control beam specimens. Four LCC mixtures were chosen for use within the flexural and serviceability properties of reinforced concrete beams. The LCC beams were developed using the RRC-M-B and RRS-M-B mixtures with target strengths of 50 MPa to assess the effect of the complete replacement of coarse and fine RCA (RRC-M-B) and further partial replacement of 50% GGBFS (RRS-M-B) on the flexural and serviceability of reinforced concrete beams. The RRS-M-B-50 and NRS-C-50 mixtures were also chosen to assess the further flexural, and serviceability testing of reinforced LCC beams with the highest incorporation of LCC materials (by % weight) and further evaluate the effect of optimized mixture design methods and on the flexural and serviceability properties of reinforced concrete beams. Duplicate beam specimens were constructed for each concrete mixture providing a total of 12 beams. It should be noted that the mixture characteristics (i.e., mix design and material composition) of the selected mixtures chosen for use within the development/testing of the reinforced concrete beams are the same as those outlined in Table 7.

In terms of the test setup, the reinforced concrete beams were tested under 4-point flexural testing through a uniaxial testing frame, with a clear span length of 2000 mm (total length of 2250 mm) with a rectangular cross-section of 150 x 225 mm (width x height). It should also be noted that four (4) strain gauges were mounted at the mid-span of each of the beams (2 on the top concrete surface and 2 on the reinforcing steel bars embedded within concrete at mid-span) to further investigate the strain behaviour of the tested beams (top concrete strain and steel yielding) as well as generate strain distributions for each of the tested beam specimens. Further details regarding the longitudinal and transverse reinforcement arrangement, test-frame set-up, instrumentation overview, cross-sectional profiles, and further design details are provided within Chapter 8.

4. LOW-CARBON CONCRETE DATABASE

Extensive research and experimental studies have assessed the possible substitution of conventional concrete materials with LCC mixtures, namely RCA and SCM's. Given the existing research volume, various assessments have been conducted to summarize the key findings presented within past studies.

Previous reviews by Xie et al. [119] have summarized previous studies dealing with the mechanical properties of LCC produced with CRCA and the parameters affecting mechanical performance. Extensive analysis regarding the effect of various aggregate properties of the CRCA, the influence of w/c ratios and preliminary assessments regarding mixing methods and the effect on the mechanical performance of LCC were presented [119]. However, while preliminary guidance is provided regarding moisture states of aggregates and mixture methods, limited guidance is provided regarding the proportioning of the mixture contents. At the same time, the omittance of the FRCA fraction limits the lack of applicability of the research findings. Similarly, Shi et al. [12] have examined the mechanical strength enhancement of LCC mixtures through various RM strengthening methods and removal methods [12]. While an extensive summarization of enhancement methods such as aggregate pretreatment, carbonation treatment and pozzolanic slurry methods are presented, the findings shown are exclusive for LCC with CRCA[12] and ideally suited for small-scale mixture applications. The applicability of the presented methods or methods suitable for FRCA usage are not presented, while the consideration of such methods in large-scale applications or from an economic perspective are not provided [12].

Similarly, state-of-the-art summarizations provided by McNiel and Kang [60] and Pacheco et al. [86] also lack further applicability with regards to mixtures prepared with FRCA. Although extensive numerical summarization regarding the effect of CRCA on the mechanical strength properties of LCC flexural elements [60] and the applicability of the bias factor within Eurocode 2 and ACI 318-14 flexural resistance models of reinforced concrete beams are presented [86], such studies have provided limited information regarding the effect of FRCA and provide limited relations concerning material properties and mixture design development of LCC mixtures. Existing summarizations provided by Silva et al. [65] have examined the factors affecting RCA's physical, chemical, mechanical, permeation, and compositional properties for both CRCA and FRCA sources [65]. Classifications were also outlined based on material composition and contaminants to ensure the effective usage of CRCA and FRCA within LCC; however, such analysis has focused primarily on the characterization of aggregate properties, with little guidance regarding mixture proportions and mixture development.

Numerous researchers have also gone to a higher degree and developed LCC literature databases to organize and present the experimental findings from past studies and conducted thorough empirical analysis [9,77,87]. Database assessments by Carević et al. [87] have examined the carbonation resistance properties of conventional concrete, LCC and high-volume fly-ash concrete (HVFAC) mixtures and the application of fib Model Code 2010 predictions. It was observed that the existing fib Model Code 2010 relations presented a linear relationship between the carbonation depth and square root of time ($t^{0.5}$) for conventional concrete and LCC mixtures but not HVFAC with fly-ash (FA) contents exceeding 35% of the total cementitious materials. Further analysis found that modified relations (i.e., $t^{0.78}$) correlated better with the experimental and numerical carbonation depth predictions. The results from the study indicate that the use of SCM's (i.e. FA) modified the microstructural characteristics of the resultant concrete mixture, while RCA had a limited effect concerning the applicability of existing fib Model Code 2010 predictions [87]. Other databases such as those developed by González-Taboada et al.[77] and Adams et al. [9] have proposed design methods for structural grade LCC, based on the physical-mechanical properties of recycled concrete coarse aggregates studied using the database [77]. As well as utilized statistical analysis methods from the database collections to improve the mechanical strength predictions of LCC mixtures [9]. Such databases have concluded that the mixture proportions can significantly influence the resultant mix properties, especially with w/c ratios over 0.6, as in such cases, the low quality of the new cement paste is more significant than the presence of the CRCA [9],[77]. Further analysis found that the correlation between aggregate to cement proportions (i.e. aggregate: cement ratios) was also statistically significant (at 95% confidence intervals) regarding the influence on the compressive strength of LCC systems [9]. Further guidance regarding mixture design methods was also provided within such databases, presenting findings that supported that aggregate pre-soaking methods (to avoid loss in workability) negatively affected f'_c due to the bleeding effect through the ITZ [77].

While the findings from the various data summarizations and databases provide valuable experimental insight supported by extensive literature findings, the results presented within such studies, the applicability of the studies are limited to LCC comprised with CRCA and geared to f'_c properties exclusively. The limited use of FRCA and SCM's within the presented research has limited the applicability of the presented findings, with little information provided regarding the effects of FRCA or SCM incorporation. The limited data presented on the f'_{ct} and MOE properties and the structural implications of LCC in terms of flexural and serviceability properties also require further research investigation and data analysis to promote further the use of LCC or CRCA, FRCA and SCM usage as suitable construction alternatives.

In terms of guidance on mix design, while the effects of CRCA are well documented, the existing databases provide limited guidance regarding the effective mixture proportioning of LCC mixtures to ensure the minimization of the adverse effects of CRCA. While methods to reduce the negative impacts of CRCA on the mechanical properties or improve the strength characteristics of CRCA (i.e., strengthening of the ITZ and microstructural characteristics) have not been discussed within the existing research databases. Although Adams et al. [9] González-Taboada et al.[77] present extensive guidance regarding strength-based w/cm ratio design for LCC with CRCA replacements to minimize the effect of CRCA as well as achieve target compressive strengths, such findings are limited to mixtures with target compressive strengths ≤ 40 MPa as well as do not consider the use of additional LCC materials (FRCA and SCM's) despite the improved mixture sustainability from their incorporation. Although FRCA has been mentioned briefly within a few existing state-of-the-art reviews and databases studies [77,137], a thorough discussion and analysis regarding the use of higher replacements of FRCA, combined usage of both CRCA with FRCA and SCM's have not been presented. Additionally, the influence of further mixture design optimization methods presented within recent literature, such as the optimized mixture proportioning and mixing methods, have not been presented despite increasing use and mechanical strength benefits provided as found within existing literature-refer to Chapter 2.2.3.

Therefore, based on the assessment of the existing databases and research, a detailed literature database comprised of the research findings from over 100 various LCC research studies was developed further to analyze the effect of combined LCC materials usage (i.e., CRCA, FRCA and SCM's) in terms of mechanical strength properties. While further assessment of emergent mixture proportioning and mixing optimization methods presented within literature was also conducted to identify trends and their influence on the resulting properties of LCC mixtures.

4.1. Database Scope

The scope of the database is limited to the analysis of existing gaps within existing literature and preliminary statistical analysis and identification of trends within the mechanical properties of the presented data. A comparison of various LCC mix data produced using various LCC materials, ranging from individual materials such as CRCA and FRCA to combined material incorporation (i.e., CRCA + FRCA, SCM's + RCA) was conducted. Optimized mix proportioning methods and mixing methods and current mix design practices were also included and analyzed separately to assess the effectiveness and identify any trends regarding the use of the various optimization techniques as well as gaps within existing research studies.

The database includes the input of LCC mechanical properties, aggregate properties and mix design extracted from over 100 peer-reviewed research articles. Although various mechanical properties have been reported in numerous articles such as compressive strength (f'_c), splitting tensile strength (f'_{ct}) and elastic modulus (MOE or E_c), to streamline the database investigation, the primary focus of the database investigation will focus on the 28-day compressive strength (f'_c) properties of the various mixtures. For completion, the f'_{ct} and MOE values for the various mixtures are presented in the complete database as listed within Appendix H: Low Carbon Concrete Database along with the mixture proportions (i.e., cement content, water content, aggregate content), mixture design information (mixture proportioning method and mixing method) corresponding to each of the various mixtures, and country of origin for further statistical and analysis purposes.

To eliminate further variability within the database analysis, the following eligibility criteria, data requirements and modifications were applied to the database inputs:

- Use of concrete specimens only (coarse aggregates, fine aggregates, water and cementitious materials) excluding mortar or cement paste specimens.
- Mixture proportions must be provided within the research article and in units of kg/m3, with incomplete, partial, missing or absolute material proportions concrete not included. The criteria are also applicable to aggregate proportions containing coarse and fine aggregates which the percentage (%) of either coarse or fine within the total aggregate proportions is unspecified (i.e., X kg/m3 of coarse and fine aggregates combined).
- Minimum of one mechanical property consisting of compressive strength (7 or 28 day required, 56 and 90 days optional), splitting tensile strength at 28 days or modulus of elasticity at 28 days.
- Standardization of the material test specimens to 100 x 200 mm cylinder or equivalent. The following factors were used as suggested by previous literature [172] for the conversion to equivalent 100 x 200 mm cylinder strength:
    - Cubic Specimens and Prisms: 0.8
    - 150 x 300 mm Cylinders: 0.95
- Conversion of mechanical property data to metric units. All units converted to MPa (compressive or tensile strength testing) or GPa (modulus of elasticity testing) if provided in alternative units (i.e., imperial). Any LCC mechanical property data with units not explicitly provided or missing within the research study were omitted.

4.2. Overview and Organization

The database was split into two major sections consisting of (1)-Mixture proportions (CRCA, FRCA, and SCM's) and (2)-Optimization methods (mix proportioning method, mixing method and combined optimization methods). Although the primary focus on the database assessment was on the 28-day compressive strength properties, further properties such as splitting tensile strength (f'_{ct}) and modulus of elasticity (MOE) were also discussed within each section. However, it should be noted that given the limited database observations reported for splitting tensile strengths (f'_{ct}) and MOE properties, a detailed statistical analysis was not conducted.

A description of each section and the various subsections for each section of the database analysis are provided below:

Database Analysis Part 1: Effect of Mix Proportions

- Effect of RCA
  - Effect of CRCA
  - Effect of FRCA
  - Effect of CRCA + FRCA

- Effect of SCM + RCA content:
  - Effect of CRCA + SCM's
  - Effect of FRCA + SCM's
  - Effect of CRCA + FRCA + SCM's

Note: Mixtures utilizing optimization methods were omitted within this section

Database Analysis Part 2: Effect of Mixture Design Optimization Methods

- Effect of mix proportioning methods
- Effect of mixing methods

For each section, the objective of the database analysis was to (1) establish relations between each of the resultant mechanical properties of the concrete mixtures and use of various materials, proportions or optimization methods as applicable, (2) incrementally assess the influence of increasing amount of RCA content to ensure suitable usage within structural applications, (3) (specific to optimization methods) asses the influence of various optimization methods in terms of mechanical strength changes relative to conventional mixture design methods (i.e. CSA, ACI, etc…) and (4) aid in the establishment of effective design practice recommendations for LCC mixes.

The results from the first section of the database analysis (effect of mixture proportions) were used to quantify the effects of RCA and SCM's on the resulting LCC properties, identify trends within existing research, identify research deficiencies and possible areas of future research efforts based on limitations within existing research studies. The results from the analysis will be used to further guide the following sections of the experimental program by serving as a reference point for further analysis. The results from the initial database analysis will be used to assess the effectiveness of various optimization methods used throughout literature, specifically optimized mix proportioning (i.e., EMV) and mixing methods (i.e., TSMA or TMA) and their effect on the mechanical properties of LCC mixes. The results from the database analysis will guide the mix design development used throughout the experimental testing program regarding the use of RCA (CRCA and FRCA), SCM's and optimized mix design methods (i.e., mix proportioning, mixing and water compensation).

4.3. Database Analysis Part 1: Mixture Materials

In terms of material incorporation, while various LCC materials have been utilized throughout existing LCC studies, a detailed assessment regarding LCC material usage with past studies have not been complied within existing research summarizations or database assessments. Previous studies have noted that limited understanding of the effects of further materials such as FRCA has resulted in limited research studies and experimental assessments [132]. Similar conclusions can also be applied to LCC mixtures with RCA and SCM's. Therefore, to further understand the current state of LCC mixtures in terms of material characterization, Figure 14 provides a breakdown of the mixture composition of 612 LCC mixtures published in over 100 global experimental studies, broken down based on mixture composition (i.e., materials usage: CRCA, FRCA, SCM's).

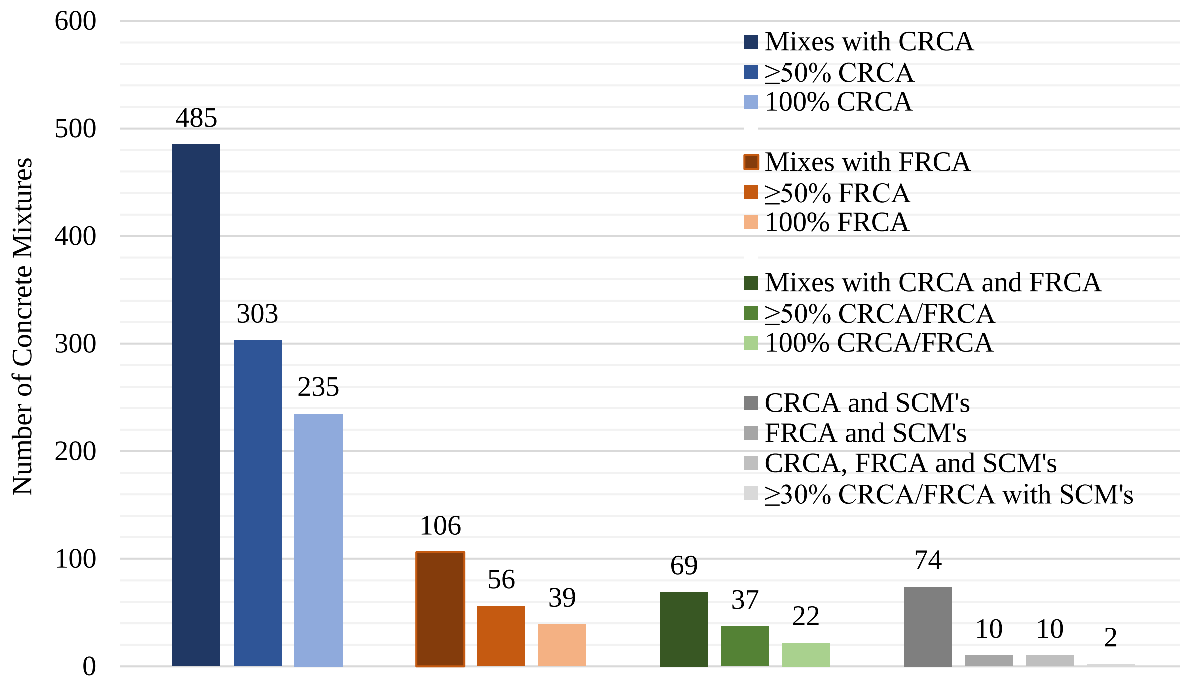


Figure 14-LCC mixtures according to recycled materials content based on the literature. Total number of mixtures = 612 (Note: Mixtures may be classified as part of more than one sub-category)

Based on the findings presented in Figure 14, it can be observed that the coarse aggregate fractions (i.e., CRCA) comprised the largest portion of LCC mixtures included with the assessment. Out of the 612 total LCC mixes presented, 485 mixes accounting for 79.2% of all mixtures were produced with CRCA (i.e., 1-100% CRCA content), with progressive decreases at higher percentage replacements of CRCA (≥50% or 100%). Further analysis indicates that FRCA has been limited to a fraction of the number of mixtures compared with CRCA (106 mixtures, 17.3%), while significantly decreases observed with increasing replacements. Similarly, the results also indicate that the combined incorporation of CRCA and FRCA with existing LCC mixtures (shown in green) has also been significantly limited, with an insignificant number of studies using 100% replacements of CRCA and FRCA (by weight or volume). In terms of SCM's usage, the findings indicate that although only a portion of the total mixtures, a significant number of LCC mixtures have utilized CRCA with SCM's (74 mixtures, shown in grey). However, further examination of SCM's with materials such as FRCA or with the combined usage of CRCA and FRCA indicates that only a handful of studies (i.e., ≤10 mixtures, respectively) have been conducted to examine the combined effects of CRCA, FRCA and SCM's with LCC mixtures.

It can be reasoned that the limited research studies with FRCA or the combined use of various LCC materials can be attributed to differences within RCA properties such as the water absorption, microstructural properties, BSG and density values (especially in the case of FRCA relative to NFA) and the observed unpredictability in fresh and hardened concrete properties [69,95,109,137,173,174]. Various studies have noted that while the partial use of SCM's or increasing RCA contents can improve the sustainability aspects o of the concrete mixtures [48,107,174], increasing SCM and RCA content has often lead to significant f'_c and f'_{ct} reductions [14,36,134], with previous studies, recommended limited to marginal replacements (e.g., < 50%) [42,102,175]. Adams et al. [9] found that, in a broad sense, the unpredictable mechanical strength properties of LCC and limited standardized design practices, which further deters LCC usage given the lack of LCC-specific mixture design methods and mixture predictability. However, overall, the findings presented within Figure 14 indicate that the coarse aggregate-centric nature of existing LCC studies has inadvertently resulted in the limited experimental assessment of LCC mixtures developed with FRCA, coarse and fine RCA and the use of RCA and SCM's. Therefore, to provide an in-depth assessment regarding the properties of the various mixture, Chapter 4.3.1 provides a detailed assessment regarding the use of RCA (CRCA, FRCA and combined use of CRCA and FRCA). Chapter 4.3.2 provides a detailed assessment regarding the use of SCM's with RCA in LCC mixtures given the limited experimental assessment and summarization within the existing literature.

4.3.1. Influence of Recycled Concrete Aggregates (RCA)

As mentioned in Chapter 2.2, the properties of RCA have been studied extensively in a variety of research studies [39,43,63,104,107,126]. Compared with NA sources, RCA (CRCA and FRCA) have often presented significantly higher water absorption and porosity values and lower BSG and density values with significant variability in aggregate properties reported amongst various sources, as noted in Appendix B: Aggregate Properties from Literature [12,23,32,38,39,77,94]. As noted within the literature review, increasing CRCA replacements as well as the combined use of CRCA and FRCA sources have often led to reduced mechanical properties of the resulting concrete mixtures, often attributed to the increased micro-structure complexity (i.e. multiple ITZ interfaces) and impact of the residual mortar [30,36,52,78,95,101,111,152,153]. Other studies have found that the mechanical properties of LCC containing RCA were significantly affected due to differences in mix proportioning due to variations within the water absorption characteristics and density properties of RCA sources [69,109,136]. Various studies have found that LCC mixes containing RCA when proportioned with equivalent weight or volume proportioning methods, often had significantly higher total water content (kg/m^3) values due to additional water proportioned to compensate for the higher water absorption properties of RCA sources. Various studies have noted that while the use of increased water contents ensured similar/consistent mixture workability, higher total water content values inadvertently resulted in significant variations and often decreased mechanical properties [115,133,137]. Therefore, for the purpose of the database analysis, three (3) major assessment categories were utilized to analyze and interpret the effect of the various RCA contents on the mechanical properties of LCC mixtures as noted below:

- Replacement Ratio (%): 0%, 1-20%, 21-40%, 41-60%, 61-80%, 81-100%
- Mixture Proportions (kg/m^3): Water content, cement content, RCA content
- Aggregate Properties: Absorption Capacity

These assessment criteria classes were implemented to allow for a detailed analysis and identification of trends, fluctuations, or outliers within each boundary class for an in-depth analysis of the dataset. As well, for the evaluation of the mechanical properties, the smaller boundary classes further improved the applicability and accuracy of and trends/observations for each of the datasets due to the smaller size of the individual boundary classes. It should be re-iterated that while compressive strength (f'_c) assessment was the focus of the database investigation, further mechanical properties such as splitting tensile strength (f'_{ct}) and elastic modulus (E_c) were also discussed.

4.3.1.1. Effect of CRCA

Starting with the first assessment criteria, the evaluating the effect of CRCA base on the replacement ratios of the mixture, ranging from 0% (i.e., conventional concrete mixtures) to 100% replacement (i.e., complete replacement of NCA with CRCA). To further identify the effect of the CRCA, the evaluation was also broken down based on equal 20% replacement intervals to investigate the effect of increasing CRCA replacements up to 100% on the compressive strength properties of LCC mixtures. To visualize the relation between compressive strength and CRCA content, Figure 15 presents a visualization of the various findings presented within existing literature. It should be noted that although included within the table, no entries within existing literature utilized CRCA replacements ranging from 0-19%; therefore, no entries are shown for that specific range of entries.

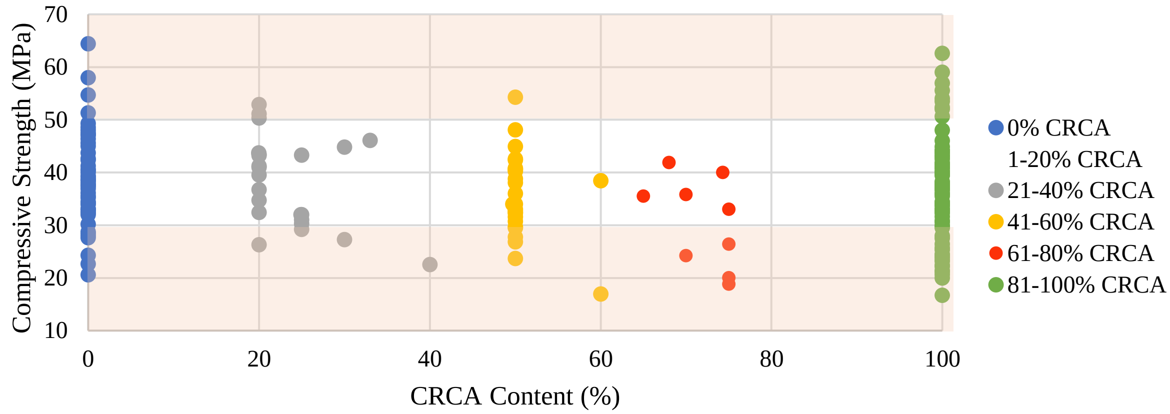


Figure 15-Effect of CRCA Content of compressive strength

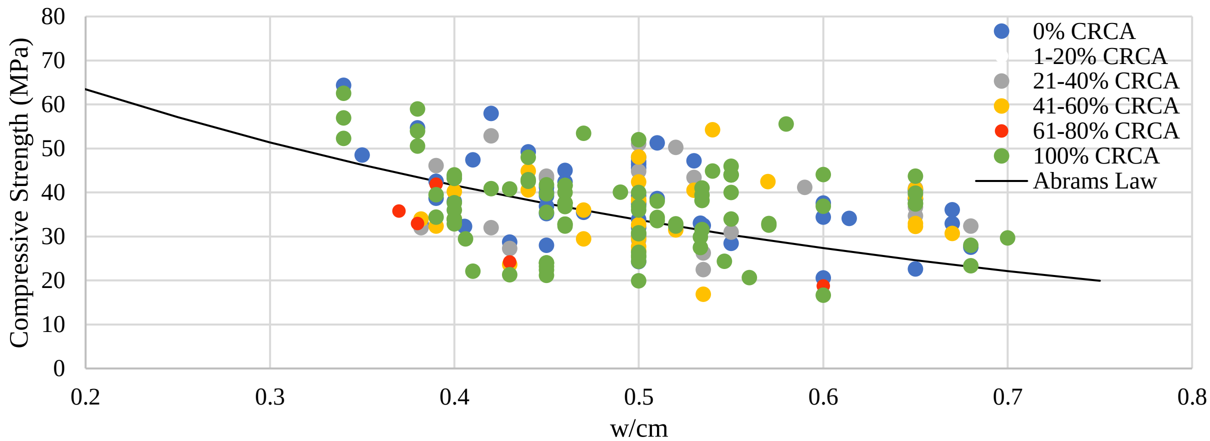
Note: Compressive strength ranges highlighted for clarity

(Ranges shown: 10-30 MPa, 30-50 MPa, 50-70 MPa)

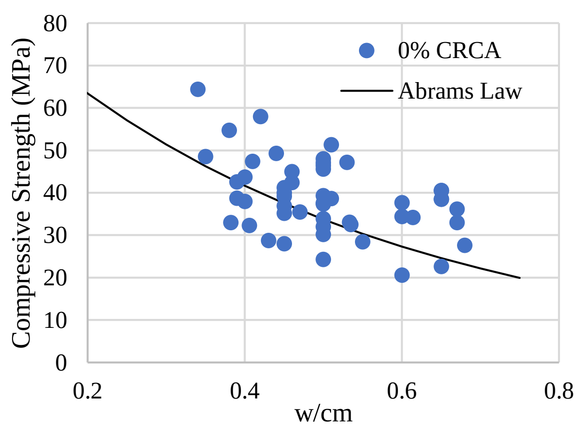
Based on Figure 15, it can be observed that regardless of the CRCA content, compressive strengths ranging from 20 MPa to >50 MPa can be achieved. Even at 100% CRCA replacements, compressive strengths exceeding 50 MPa and 60 MPa were observed within several studies, indicating that contrary to perceptions, CRCA content does not necessarily result in reduced compressive strength. It should be noted that the results shown in Figure 15 do not consider the further effects of mixture proportions, namely the w/cm ratios, water and cement contents which previous studies have determined are statistically significant with regard to the resultant mechanical strength properties of the mixtures [9]. Many international standards have recognized such factors with regard to conventional concrete mixtures and often utilize strength-based design ideologies within the selection for the w/cm ratio as per desired f'_c properties. Standards outlined within CSA A23.1-14 and ACI 211 provide specifications for the selection of the w/cm ratio based on the compressive strength requirements of the mixtures while also providing minimum w/cm ratio requirements based on concrete exposure conditions such as various exposure conditions (i.e. such as those within high sulfate-Exposure class S or chloride rich settings-Exposure class C) [3]. Additionally, Figure 15 does not consider the target f'_c of the mixtures; as a result, while f'_c values of 20-25 MPa were observed, such values may have been the target strengths of the mixtures.

Therefore, to provide an unbiased assessment of the resultant properties with regard to target f'c properties and the effect of mixture proportions, Figure 16a presents the effect of w/cm on the compressive strength properties of LCC mixtures. To distinguish any differences between conventional concrete and LCC mixtures with the highest incorporation of CRCA (i.e., 81-100%), Figure 16b and Figure 16c present the findings for 0% CRCA and 81-100% CRCA, respectively. Further, Abrams law which is often used to express the effect of w/cm ratio on the compressive strength properties of conventional concrete mixtures is also presented within Figure 16a/b/c and provided within Equation 12 to represeet the relation between the concrete f'_c and w/cm ratio.

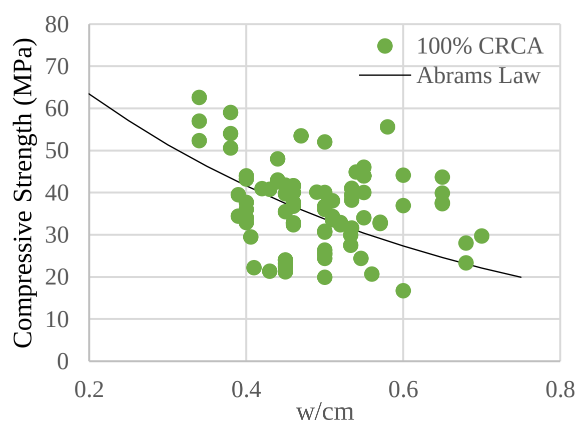
(Abrams law) $f'_c = 96.6 * 8.2^{-w/cm}$ Equation 12



(a)



(b)



(c)

Figure 16-Effect of w/cm ratio on Compressive strength

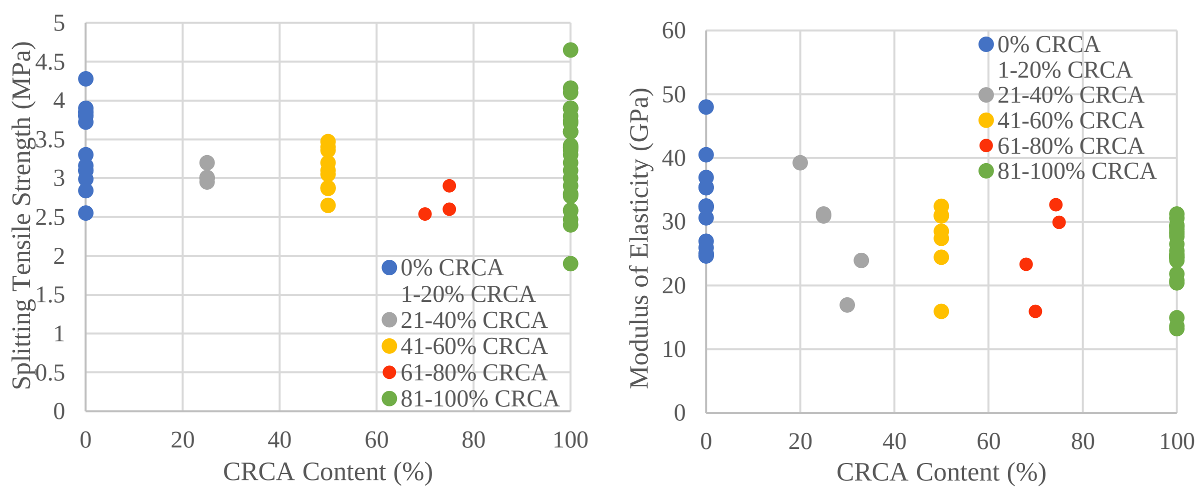
CRCA Content: 0-100%, (b) CRCA Content: 0%, (c) CRCA Content: 100%

Based on Figure 16a, regardless of CRCA content of the mixtures (i.e., 0-100%), the results indicate that with increasing w/cm ratios, the compressive strength properties of the mixtures decrease progressively. Further investigation of the plots presented within Figure 16b and Figure 16c indicate that concrete mixtures containing either 0% CRCA (i.e., conventional concrete mixtures with NCA) or LCC mixtures with 81-

100% CRCA present nearly identical relations in terms of compressive strength and w/cm ratio with only minor variations between each plot. Based on such findings, it can be reasoned to a high degree of certainty that regardless of the w/cm ratio of the mixture, the relations presented within Abrams law for conventional concrete mixtures (i.e., non-linear variations with f'_c and w/cm ratios) may be applicable for LCC mixtures with 100% CRCA contents.

However, as observed in Figure 16, despite the non-linear trends observed with regard to w/cm and f'_c, significant variability exists for both conventional concrete and LCC mixtures with 100% CRCA. Such variation can be attributed to the varying mixture proportions (i.e., aggregate, cement and water contents), differences within the aggregate/material properties, and the general variability of concrete. However, despite the observed variability within the findings of the LCC mixtures, the comparable f'_c and overall variability observed relative to the conventional concrete mixtures indicate that both LCC and conventional concrete mixtures can be treated within a similar manner with regard to mixture design aspects (i.e., strength-based mixture proportioning based on the w/cm properties of the mixtures.

With regard to further experimental properties, previous studies have reported that the use of increasing CRCA contents often leads to reduced splitting tensile strength and modulus of elasticity values compared with conventional concrete mixtures [7,26,33,39,107]. To illustrate such findings, Figure 17 presents the effect of various CRCA contents on the resultant splitting tensile strength and elastic modulus properties of LCC mixtures.

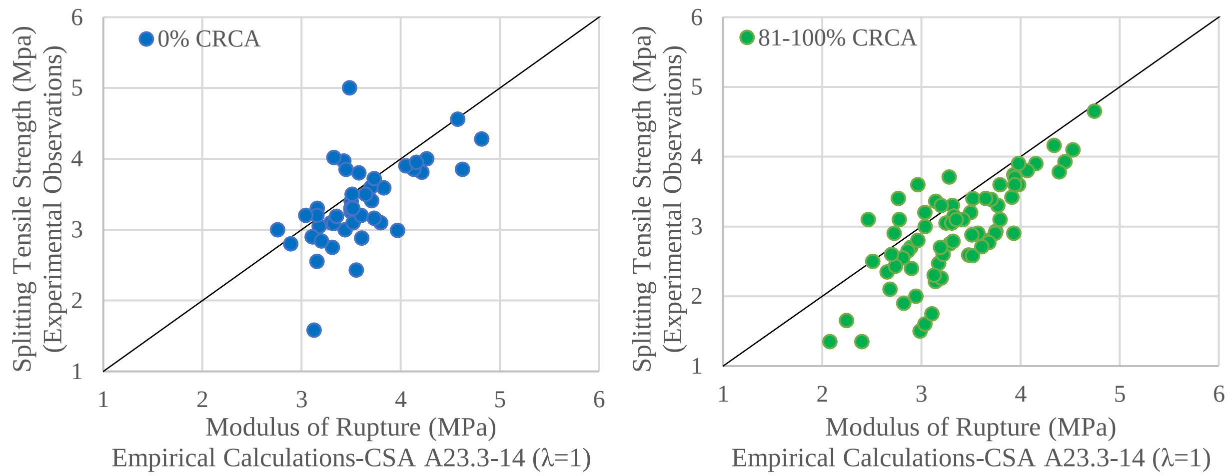


(a) *(b)*

Figure 17-Effect of CRCA content on
(a)-28-day Splitting Tensile Strength, (b)-28-day Concrete Elastic Modulus

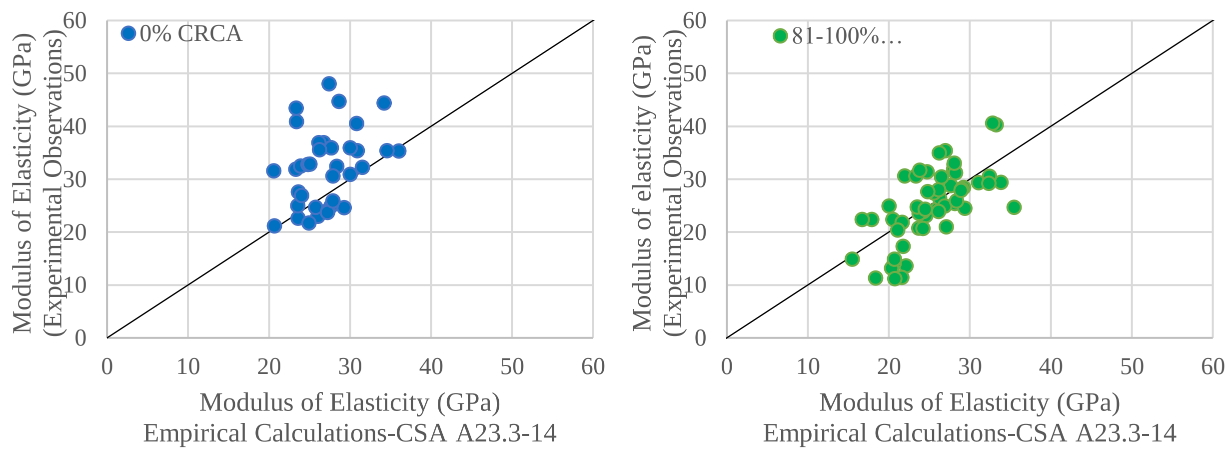
The results shown in Figure 17 indicate that increasing CRCA contents often leads to reduced splitting tensile strength, however for 81-100% replacements, comparable splitting tensile strength values can be achieved even at 100% CRCA replacements, although significant variability is reported. Previous studies have found that the splitting tensile strength reductions for LCC produced with RCA can be attributed to the more porous structure and reduced strength of the RCA [26,33]. While the MOE reductions with increasing CRCA contents can be attributed to the increased deformability of the CRCA given the reduced elastic modulus of the CRCA [26,126]. As listed within the CSA A23.3-14 [68] standards as well by previous researchers, the MOE properties of concrete depend highly on the modulus of elasticity of the aggregate fractions [26,126]; as a result effect of CRCA content on the resultant concrete MOE properties become increasingly apparent with higher replacement ratios. As a result, it can be reasoned that while further factors such as w/cm ratio and mixture proportions influence the MOE and f'_{ct} properties, the reduced stiffness (i.e., MOE) of the CRCA increases mixture deformability (i.e., reduces MOE) and limits the resultant tensile strength development (i.e., limits f'_{ct}) with increasing CRCA contents.

Given the observed experimental findings and effect of CRCA, further testing and analysis are required to gauge the applicability of empirically derived modulus of rupture (f_r) and MOE properties (based on the current CSA A23.3-14 standards-refer to Chapter 2.2.1.2.1) with regards to experimental observations within the database. As a result, Figure 18 presents the relation between experimental f'_{ct} values and empirically predicted f_r values, while Figure 19 compares experimental MOE values with CSA A23.3-14 empirical predictions-refer to Chapter 2.2.1.2.1 for LCC mixtures with >80% CRCA contents. It should be noted that while Equation 5 accounts for the density of the resultant mixture, hardened concrete density values were largely not reported within existing literature and thus could not be used within the MOE calculations. Additionally, the findings for conventional concrete mixtures (i.e., 0% CRCA) are also presented for further analysis and comparison. Concerning f'_{ct} and f_r, although a direct comparison of experimental f'_{ct} values and empirical f_r values is not appropriate, previous studies have noted that similarity in the values indicate the actual modulus of rupture for these cylinders are close to the code prescribed values, and thus similar to experimental splitting tensile strength values [107].



(a) *(b)*

Figure 18-Comparison of the experimental f'_{ct} and empirically f_r modulus
Note: Mixtures with FRCA or SCM's omitted
Conventional Concrete: 0% CRCA, (b) LCC: >80% CRCA



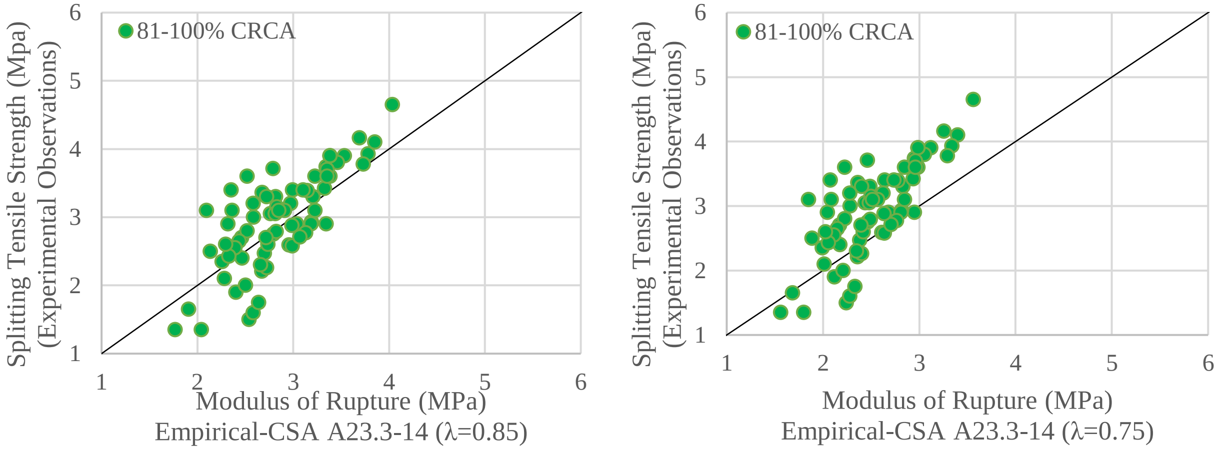
(a) *(b)*

Figure 19-Comparison of observed and empirical calculations for the MOE of LCC mixtures

Conventional Concrete: 0% CRCA, (b) LCC: >80% CRCA
(a) Conventional Concrete: 0% CRCA, (b) LCC: >80% CRCA

Based on the results presented, a comparison of the experimental f'_{ct} observations with the empirically calculated f_r values indicates that the empirically calculated f_r values often exceed f'_{ct} findings. However, it should be noted that, as stated within CSA A23.3-14 Cl 8.6.5, such empirically calculated values pertain to normal density concrete (i.e., λ=1). As reported within numerous studies, the use of increasing CRCA (as well as FRCA) has often led to lower the hardened density properties as indicated by various studies [36,46,51], as a result, the assumption of normal density concrete (λ=1) does not accurately resemble the properties of

LCC mixtures with CRCA and leads to an over-estimation in the empirical modulus of rupture values. Although further clauses are outlined to use modification factors of λ=0.85 or 0.75, the current CSA A23.3-14 equations lack acknowledgement of LCC mixtures and the specific acknowledgement of RCA (CRCA and FRCA). For completeness, Figure 20 compares the experimental splitting tensile strength properties of LCC mixtures with CRCA with empirical modulus of rupture calculations using the modification factors of λ=0.85 (Figure 20a) and λ=0.75 (Figure 20b).



(a) *(b)*

Figure 20-Comparison of the experimental f'_{ct} and empirical f_r for LCC mixtures

Mixtures produced with CRCA. (a) λ =0.85, (b) λ =0.75
Note: LCC mixtures with FRCA or SCM's omitted

Based on the findings presented within Figure 20, it can be observed that in some cases, the use of the density modification factors (λ) (refer to Cl 8.6.5-CSA A23.3-14 [68]) can significantly improve the relation between experimental splitting tensile strength values and predicted modulus of rupture values. As shown within Figure 20a, the use of a density modification factor of 0.85 can improve the relation between modulus of rupture predictions for LCC mixtures. In contrast, a 0.75 modification factor generally underestimates the modulus of rupture properties for LCC mixtures (most conservative). However, despite the improved relations presented through modification factors, the present equations and code provisions regarding the use of modification factors presented within the CSA A23.3-14 standards were not developed for use with LCC mixtures incorporating CRCA. Clause 8.6.5 of CSA A23.3-14 specifics that a modification factor of 0.85 shall be used for structural semi-low-density concrete in which all the fine aggregate is natural sand, while a 0.75 modification factor may be used for low-density concrete in which none of the fine aggregates are natural sand. However, no direct mention is made for RCA usage (CRCA or FRCA)[68]. Therefore, while promising findings can be found through the use of existing modification factors, further extensive experimental studies are required to evaluate the applicability or justify the use of existing standards with regards to LCC mixtures with RCA (i.e., CRCA only, as well as FRCA only or the combined use of CRCA and FRCA).

Regarding modulus of elasticity (MOE), compared with conventional concrete mixtures, LCC presented an average reduction of 14.5%, and maximum reductions of over 40% were observed relative to the conventional concrete within select studies [7,39,107]. Various researchers have found that the typical design expressions used to express the relationships between concrete compressive strength and modulus of elasticity values such as those denoted with CSA A23.1-14 [3] (i.e., Equation 2) as well as those within other organizations (i.e. ACI 318 [5]), may not be applicable for use with LCC mixtures as they tend to over-estimate the properties for LCC mixtures produced with RCA [112,123,129]. However, upon comparison of empirical predictions with experimental values in Figure 19b, it can be observed that the existing CSA A23.3-14 equations can provide relatively accurate MOE predictions relative to experimental values. Although relatively accurate MOE predictions can be made, it should be noted that the empirical values still tended to over-estimate the MOE properties for a significant number of mixtures (i.e., 31.4% of all values). Therefore, from a design perspective, while the serviceability (i.e., SLS) rarely governs the resultant design of the over-estimation of the MOE may provide an in-accurate assessment regarding predicted deflection values for various LCC elements. From a design aspect, the over-estimation of the MOE values may cause excessive cracking, render elements unsafe or result within occupant concerns, especially in deflection sensitive elements regardless of adequate member strength.

It should also be noted that the current design expressions were developed for conventional concrete mixtures and do not consider differences within the composition of various RCA sources (i.e., RMC, AC, etc. Given that the MOE is a function of the total mortar volume fraction of the concrete mixture [92] [108], varying RMC values from various RCA sources may significantly affect the MOE values of LCC concrete despite similar mixture and aggregate proportions [108]. Therefore prior to structural usage or industry application, further testing and evaluation are required to improve the empirical relations and design equations for the MOE and f_r for LCC produced with CRCA as the existing CSA A23.3-14 relations have limited applicability for LCC mixtures.

4.3.1.2. Effect of FRCA

In terms of FRCA, as noted within Figure 14, FRCA has been utilized in far fewer experimental studies relative to CRCA. Despite fewer studies, extensive FRCA data has been presented within literature and although non-extensive from a database perspective, sufficient data is available to allow for a preliminary analysis. In terms of analysis, evaluating the effect of FRCA replacement ratios of the mixture, it can be seen from Figure 21 that FRCA replacement does not have any evident effect on the compressive strength properties of the mixture. It should be noted that given the limited number of research findings available, three (3) data series were utilized, broken down as 0% FRCA, 1-20% FRCA and 51-100% FRCA. It should also be noted that the data presented within Figure 21 (as well as subsequent figures within this section) presented mixtures without any CRCA or SCM's to gauge the sole impact of FRCA.

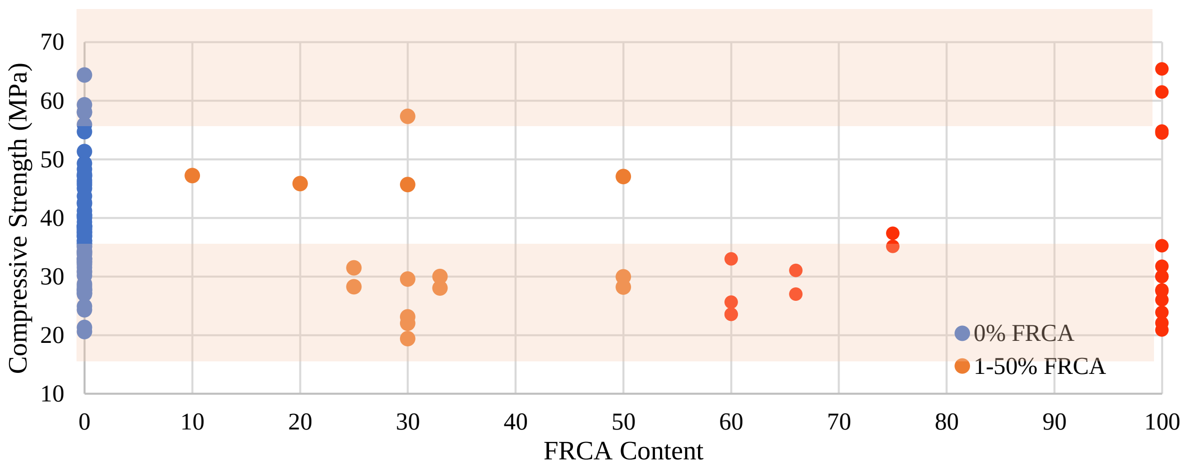


Figure 21-Effect of FRCA Content of compressive strength

Note: Compressive strength ranges highlighted for clarity
(Ranges shown: 10-30 MPa, 30-50 MPa, 50-70 MPa)

Based on the dataset within Figure 21, it can be observed that regardless of the FRCA content of the mixtures (in terms of replacement ratio), compressive strengths ranging from ranges of 20 MPa and upwards of 60 MPa were achieved regardless of FRCA content. One of the notable findings within the dataset presented within Figure 21 is that even at 100% FRCA replacements, compressive strengths exceeding 60 MPa were observed within several studies, indicating that similar to that of CRCA, increasing FRCA content does not necessarily result in reduced compressive strength values or non-structural grade studies. It should be noted, however, that the results shown in Figure 21 do not indicate that FRCA usage does not reduce compressive strength properties relative to conventional concrete mixtures; rather, FRCA contents up to 100% can still be used to develop structural grade concrete mixtures (i.e., compressive strengths ranging from 20-60+ MPa).

While the use of up to 100% FRCA may not present any observed effect on the mechanical properties in terms of replacement ratio, the effect of the aggerate properties of the FRCA should be considered within such assessment. As noted for the CRCA, the aggregate properties of FRCA differ significantly from those of NFA, specifically the absorption capacity of the respective aggregate sources. Therefore, to assess the impact of the absorption characteristics of FRCA, Figure 22 presents the effect of the absorption capacity of the FRCA sources as well as the total absorbed water by the FRCA sources (refer to modified for FRCA).

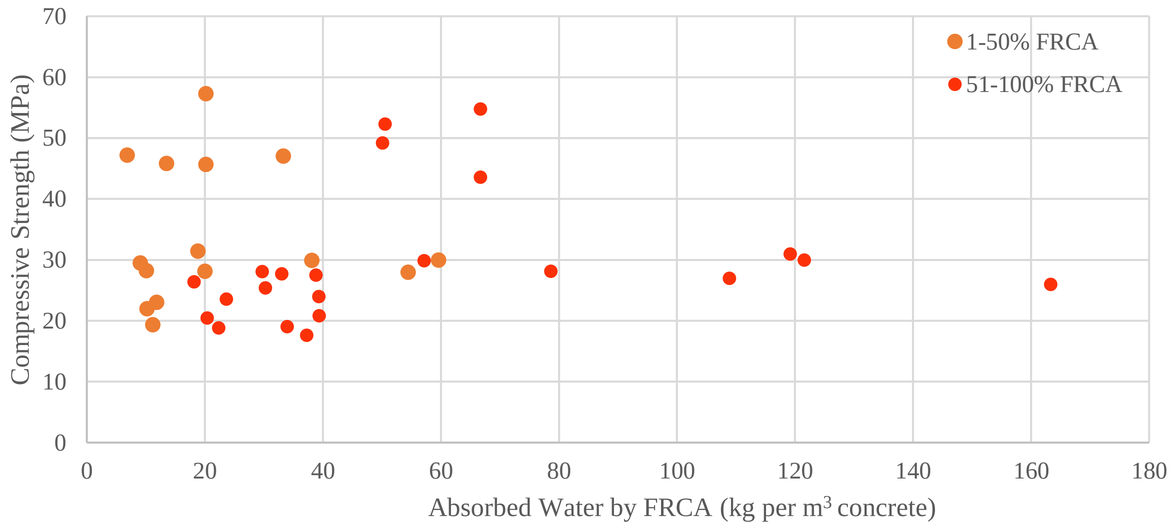


Figure 22-Effect of FRCA Absorption Characteristics on the compressive strength properties

Based on the results presented within Figure 22, it can be observed that the total absorbed water by the FRCA illustrates that regardless of the absorption capacity of the FRCA sources, for total absorbed water values exceeding 60 kg/m^3, progressive reductions within the resultant compressive strength properties of the LCC mixtures were observed. It can be reasoned that for mixtures with highly absorbent aggregates, additional water to compensate for water absorption by the aggregates to ensure adequate workability may significantly impact the result compressive strength properties should discrepancies exist between predicted water absorption and actual water absorption quantities (in terms of kg/m^3 of water) within the proportioned LCC mixtures. As noted with Figure 22 for LCC mixtures developed with FRCA requiring large additional water requirements (i.e., over 60 kg/m^3), minor differences between actual water absorption by the aggregates and predicted water absorption values may result within undesirable and unaccounted increases within free-water contents, resulting in increased w/cm ratios, higher slump values and decreased mechanical strength properties. In terms of remediation options, numerous studies have utilized super-plasticizing agents or implemented aggregate pre-soaking methods prior to concrete mixing to avoid the use of increased mixing water quantities to minimize mechanical strength redactions [22,38,64,111,114,176]. Previous studies by Butler et al. [22] have denoted that aggregate pre-soaking may be utilized to eliminate the water absorption of the aggregates during mixing with minimal effects on hardened concrete properties of the concrete; however, such findings have been made specific to LCC mixtures coarse RCA. As a result, further research investigations are required to asses suitable mixture proportioning/design methods to effectively account for the water absorption characteristics of FRCA (as well as CRCA) to ensure adequate mixture workability without negative repercussions on the compressive strength and further mechanical properties of LCC mixtures

In terms of further analysis and comparison of conventional concrete mixture to mixtures with FRCA, Figure 23 presents the effect of the w/cm ratio on the compressive strength properties of mixtures with various FRCA contents.

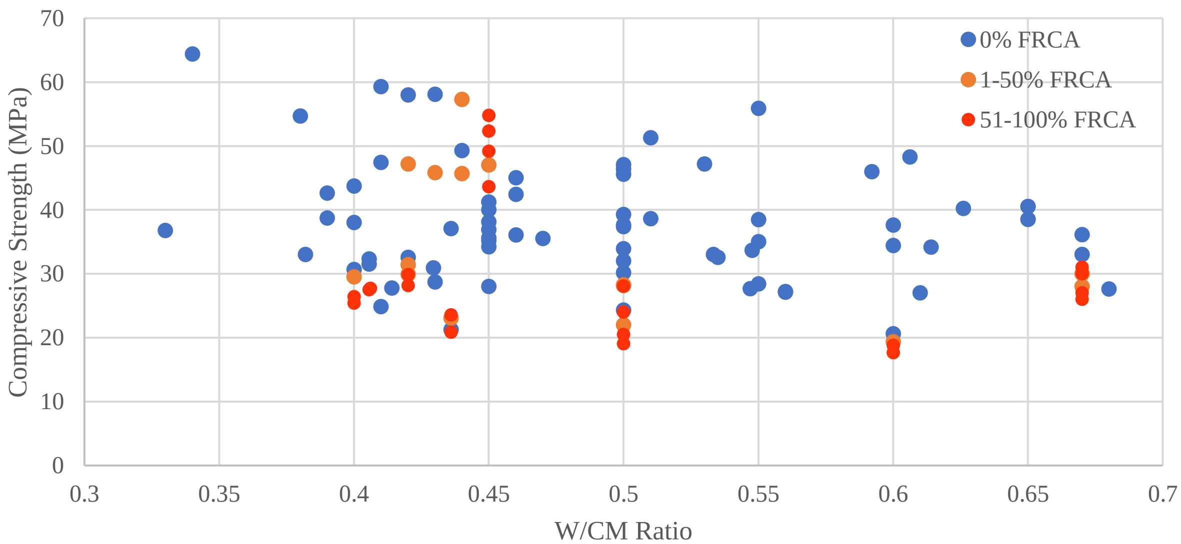


Figure 23-Effect of w/cm ratio on compressive strength properties-mixtures with FRCA

Based on results from Figure 23, regardless of the FRCA content of the mixtures (i.e., 0-100%), the results indicate that with increasing w/cm ratios, the compressive strength properties of the mixtures decrease linearly. However, it can be observed that the comparison of mixtures with similar w/cm ratios indicates that mixtures with increasing FRCA contents often presented lower compressive strength values than mixtures sole comprised of NFA. For mixtures with the same w/cm ratio, at w/cm ratios of 0.5 and greater (refer to Figure 23), the use of FRCA presented reduced compressive strength values relative to mixtures comprised of NFA, while for w/cm ratios below 0.5, such trends were not observed. Based on such findings, it can be reasoned that at high w/cm ratios, the use of FRCA may limit the compressive strength properties of the mixtures and govern the resulting properties. Several preliminary studies, such as those by Fathifazl et al. [51] and Neville [92], have found that compressive strength properties were dependent on the strength of mortar and ITZ, reasoning that the effect of RCA was highly dependent on the w.cm ratio of the mixture. Similar studies have also found similar observations [31,54,77,78,92], although such studies have focused primarily on CRCA with minimal regard for FRCA and the resultant impact on the governing failure mechanisms of the mixture. As a result, further research investigations are required to assess the impact of FRCA on the mechanical strength properties and governing failure mechanisms of LCC mixtures, given the limited research attention and investment.

In terms of further mechanical properties such as splitting tensile strength and elastic modulus, given the limited number of research findings, a detailed assessment cannot be conducted regarding the effect of FRCA content. As noted previously, further research testing is required to thoroughly investigate the effect of FRCA incorporations on splitting tensile strength and elastic modulus properties.

4.3.1.3. Effect of Combined Use CRCA and FRCA

As noted previously, studies involving LCC mixtures incorporating both CRCA and FRCA have been relatively limited. Despite the comparatively limited availability of studies, extensive research has still been presented within available literature for LCC mixtures incorporating CRCA and FRCA. To highlight the extensive volume of available research findings and highlight the effect of various CRCA and FRCA contents, Figure 24 presents the effect of the combined usage of various CRCA and FRCA contents on the compressive strength properties of LCC mixtures. It should be noted that within Figure 24, three (3) data series were utilized to highlight the influence of CRCA and FRCA, consisting of the sole effect of FRCA with no CRCA, effect of FRCA with 1-50% CRCA content (by volume) and the effect of various FRCA content with 51-100% CRCA contents.

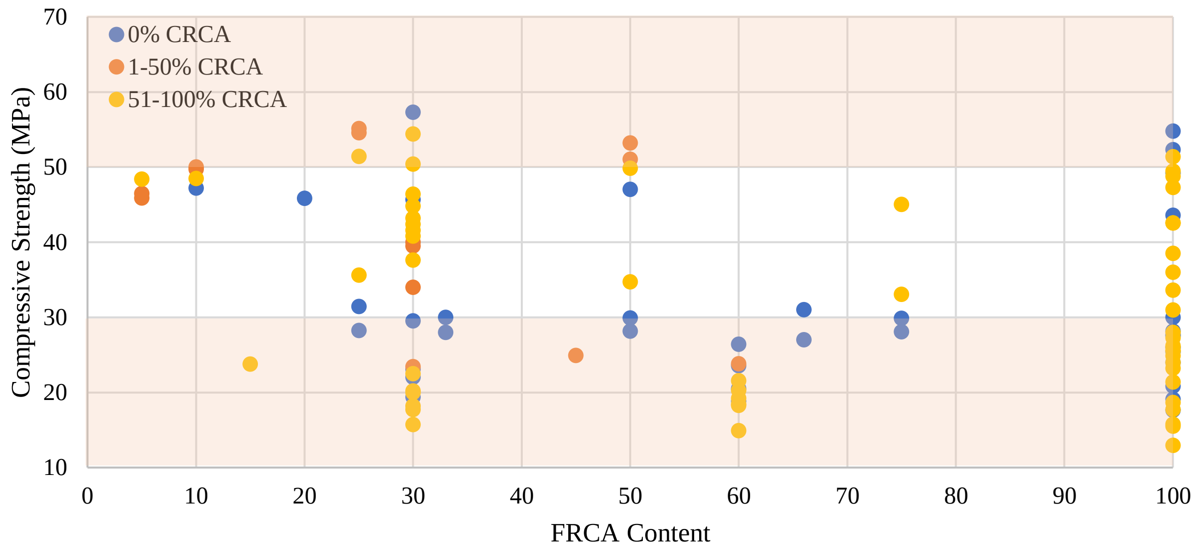


Figure 24-Effect of CRCA and FRCA content of compressive strength

Note: Compressive strength ranges highlighted for clarity

(Ranges shown: 10-30 MPa, 30-50 MPa, 50-70 MPa)

Based on the dataset within Figure 24, it can be observed that regardless of the FRCA and CRCA content of the mixtures (in terms of replacement ratio), compressive strengths ranging from 15 MPa to just under 60 MPa were achieved. As a result, it can be concluded that based on previous experimental studies, CRCA and FRCA can suitably be used with LCC mixtures to produce viable structural grade concrete with compressive strengths ranging from 15-50+ MPa even with 100% CRCA and 100% FRCA replacements. It can be noted that in some cases, significant compressive strength reductions were observed within mixtures utilizing 51-100% CRCA at various FRCA replacements indicating that further considerations apart from replacement ratios must be considered within the mix design process for LCC mixtures with CRCA and FRCA such as possible contributions from aggregate properties (CRCA and FRCA), w/cm ratio of the mixture and aggregate absorption and influence on the water absorption characteristics of the mixture.

To further investigate the effect of additional mixture design attributes on the compressive strength properties of the mixtures, Figure 25 and Figure 26 present the effect of the w/cm ratio and the total absorbed water on the compressive strength properties of LCC mixtures proportioned with various CRCA and FRCA contents. It should be noted that the total absorbed water values (kg/m^3) presented within Figure 26 were calculated using based on the absorption capacity of the aggregate sources multiplied by the content (kg/m^3), of which both the absorption capacity of the CRCA and FRCA fraction were considered.

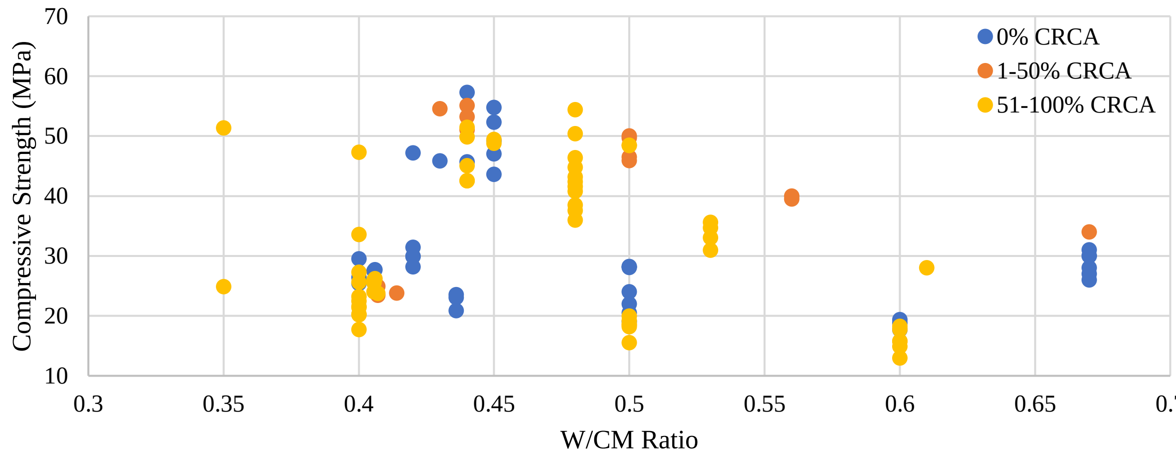


Figure 25-Effect of w/cm ratio on compressive strength properties-mixtures with FRCA and CRCA

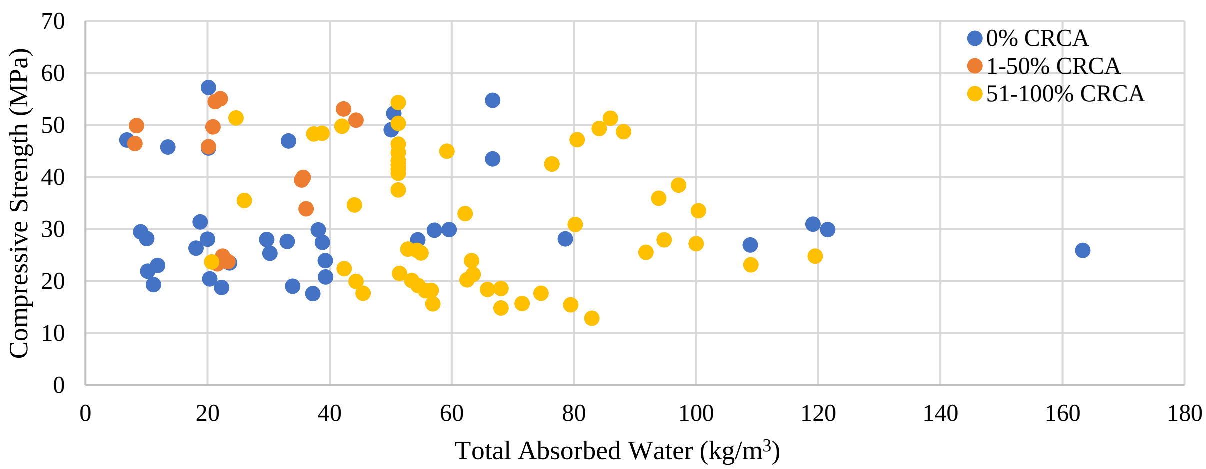


Figure 26-Effect of CRCA and FRCA Absorption Characteristics on the f'_c properties

Based on the results presented within Figure 25 and Figure 26, it can be found that the w/cm ratio and total absorbed water of the mixture both significantly impact the result compressive strength of the mixture. As expected, increasing w/cm ratios led to progressive compressive strength reductions within the LCC mixtures. However, it was found that in several cases as presented within Figure 25, mixtures with higher CRCA contents often presented reduced compressive strength values despite equivalent w/cm ratios as mixtures with 0% CRCA. Similarity, the same conclusions can also be observed within Figure 26, as mixtures with increasing CRCA replacements often presented lower compressive strengths with increasing total absorbed water values. It should be noted that within Figure 26, beyond a total absorbed water threshold (i.e., in the case of CRCA and FRCA mixtures as shown within Figure 26 of 80 kg/m^3), compressive strengths for all mixtures regardless of CRCA and FRCA content were found to be significantly reduced, converging to approximately 25-30 MPa. Based on the findings, it can also be reasoned that in the case of mixtures with highly absorbent aggregates, increasing water contents to compensate for the water absorption of the aggregates led to reduced compressive strength values. As noted previously, the reduced compressive strength findings can be attributed to the inaccuracies within the predicted water absorption characteristics and actual water absorption properties of the mixtures resulting in differences within the free-water contents, w/cm of the mixture and thus compressive strengths of the mixtures (note: similar reductions for other mechanical properties can also be inferred).

Given the limited number of research findings, a detailed assessment cannot be conducted regarding the combined effect of CRCA and FRCA content in terms of further mechanical properties such as splitting tensile strength and elastic modulus. As noted previously, further research testing is required to thoroughly investigate the effect of CRCA and FRCA incorporations on splitting tensile strength and elastic modulus properties.

4.3.2. Influence of Supplementary Cementitious Materials (SCM's)

Supplementary cementitious materials have a long history of use within conventional concrete construction. Despite the widespread global usage and increasing LCC investigation and experimentation, research involving the use of SCM's within LCC production has been limited.

Out of the 612 total mixtures in the database, only 74 (12.1% of all entries) have included the combined use of CRCA and SCM's. In addition, limited studies have utilized large replacements of both CRCA and SCM's, with many studies limiting CRCA replacements (i.e., under 50%) or limiting SCM's to minor replacements (i.e., <30%). To emphasize the limited number of studies as well as the effect of combined CRCA and SCM usage on the compressive strength properties of LCC mixtures, Figure 27 presents the compressive strength findings based on SCM content (i.e., % replacement-by total weight of binder content) and grouped by SCM type (i.e., silica-fume, fly-ash or GGBFS). It should be noted that SCM's were limited to silica-fume, fly-ash and GGBFS given the rather limited number of research studies using other SCM's or filler materials.

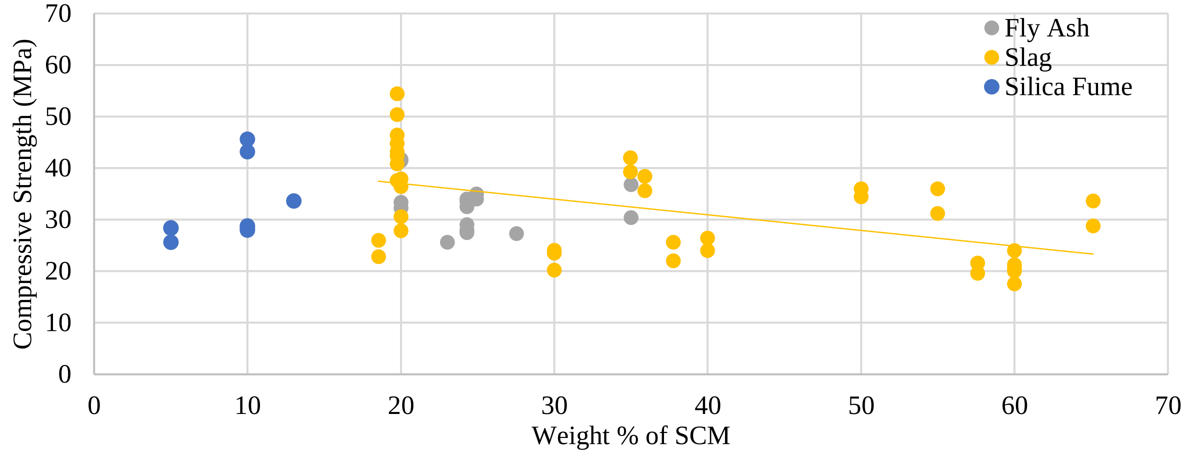
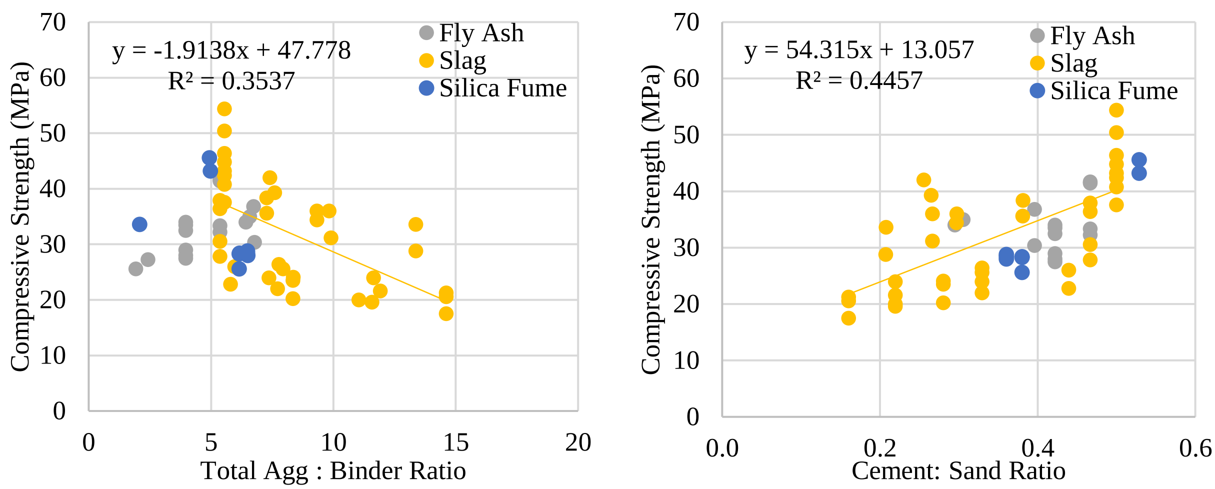


Figure 27-Effect of SCM replacement on f'c

LCC mixtures made with ≥50% CRCA replacement

In terms of the results, the data presented within Figure 27 indicates that SCM content tends to have various effects on the compressive strength of the mixtures; however, such effects are determined based on the replacement contents within the LCC mixtures. In the case of silica fume, increasing replacements (up to 15%-by volume max) resulted in progressive increases within compressive strength properties, attributed to improved strength development properties relative to cement [111]. It should be noted that such findings are only representative for silica fume replacements up to 15%, given the lack of high-volume silica fume usage within mixtures, additional conclusions cannot be made for increasing replacements given the lack of findings. In terms of increased SCM replacements such as in the case of fly-ash and silica fume, the results presented within Figure 27 indicate that the increasing usage of fly-ash or GGBFS led to progressive compressive strength reductions for LCC mixtures with CRCA. Although the incorporation of CRCA may have led to reductions within mechanical properties, many of the mixtures presented within Figure 27, the progressive reductions within compressive strength with increasing SCM content indicates that regardless of the CRCA content, GGBFS or fly-ash content significantly impact the compressive strength properties of the mixture. Numerous experimental studies have also found similar findings attributing reductions in compressive strength reductions and further mechanical properties with increasing SCM replacements towards variations within the pozzolanic behaviour and rate of strength development relative to OPC [36,48,111].

In terms of further relations, previous database assessments by Adams et al. (year) [9] also reported that upon analysis of numerous LCC studies, the influence of SCM's within LCC mixtures can often be expressed using relations based on the material proportions of the various LCC mixtures. To illustrate such relations, Figure 28 presents the effect of the total aggregate-binder ratio (i.e. ratio of combined weight or coarse and fine aggregates to weight of binder) (Figure 28a) and the effect of binder-sand ratio (Figure 28b) for LCC mixtures made with partial SCM replacements (fly-ash, silica fume or GGBFS) and with at least 50% CRCA.



(a) *(b)*

Figure 28-Effect of SCM's replacement on compressive strength

(a)-Effect of SCM % replacements by weight, (b)-Effect of cement: sand ratio
Note: Results shown for studies with CRCA content ≥ 50%

Based on the results presented in Figure 28, linear relations can be observed regarding the compressive strength properties of LCC mixtures and the total aggregate: binder ratio, as well as the cement : sand ratio. The results presented indicate that as the aggregate/binder ratio increases and the binder/sand ratio decreases (i.e., higher aggregate contents), the resultant compressive strength of resultant LCC mixtures are negatively affected. However, it should be noted that for low total aggregate/binder ratio values (~5), a localized compressive strength maxima with the graph can be observed while reduced compressive strengths are observed at lower and higher total aggregate/binder ratio values. Based on the results presented within Figure 28 and Figure 27, it can be concluded that for LCC mixtures incorporating various SCM's, the replacement of minor amounts of cement (i.e., 20% of total binder mass or with reduced total aggregate to binder ratios) their use may improve the compressive strength properties.

However, despite the reduced mechanical strength properties with increasing SCM's replacements in terms of the 28-day mechanical strength properties (i.e. compressive strength), existing studies have noted that long-term compressive strength properties (>90 days) may be improved for mixtures incorporating SCM's [137]. Although such improvements have been observed, from a structural design perspective, the long-term compressive strength properties are rarely considered within concrete design, with attention mainly placed on the early age (i.e., f'_{c7}) as in the case of pre-cast concrete construction or often the 28-day compressive strength properties of the mixtures. Therefore, to ensure effective designs of LCC, the trade-off in terms of increasing SCM contents (i.e., reduced mechanical strength properties, however, improved sustainability-lower carbon emissions) just be adequately considered to ensure the effective design of LCC mixtures with minimized embodied carbon emissions while still achieving adequate structural properties.

In terms of further studies, the number of studies that have investigated the mechanical properties of LCC mixtures developed with SCM's or the use of SCM's with both FRCA or CRCA has been relatively limited existing literature, with only few studies such as those by Kou et al. [35], Corinaldesi et al. [70] and Zhang et al. [28] presenting preliminary findings. While such studies have provided a basis regarding the preliminary effects of SCM's with further RCA combinations, the relatively limited number of studies prohibits any further detailed statistical database analysis or analysis. As a result, the interaction between high-volume replacements SCM's with FRCA or with the combined use of both CRCA and FRCA is not fully understood, limiting the understanding of the mechanical properties and structural capabilities of such ultra-sustainable LCC mixes.

4.4. Database Analysis Part 2: Mixture Design Optimization

4.4.1. Influence of Mixture Proportioning Methods and Optimization

A variety of novel mixture proportioning and mixing methods have been developed to improve the mechanical properties of LCC. In terms of mixture proportioning, the EMV and M-EMV methods have both undergone extensive study and experimentation [1,44,45,49,50,52,69,80,107,119]. While both methods have indicated underlying slump and compaction issues dependant on super-plasticizer usage [45,50,52], both the EMV and modified EMV (M-EMV) methods have demonstrated promising results in improved mechanical performance strength properties compared with similar mixtures proportioned with conventional mix design methods.

To analyze the differences between LCC mixtures proportioned with the EMV and M-EMV method and those with conventional mix design methods (i.e., equivalent volume and weight replacement methods), Figure 29 illustrates the differences between various mixture proportioning methods based on the w/cm ratio, cement content and total aggregate: cement ratio. Additionally, to highlight trends within the EMV/M-EMV mixtures, Figure 29b/d/f presents the linear trends observed within the EMV/M-EMV mixtures.

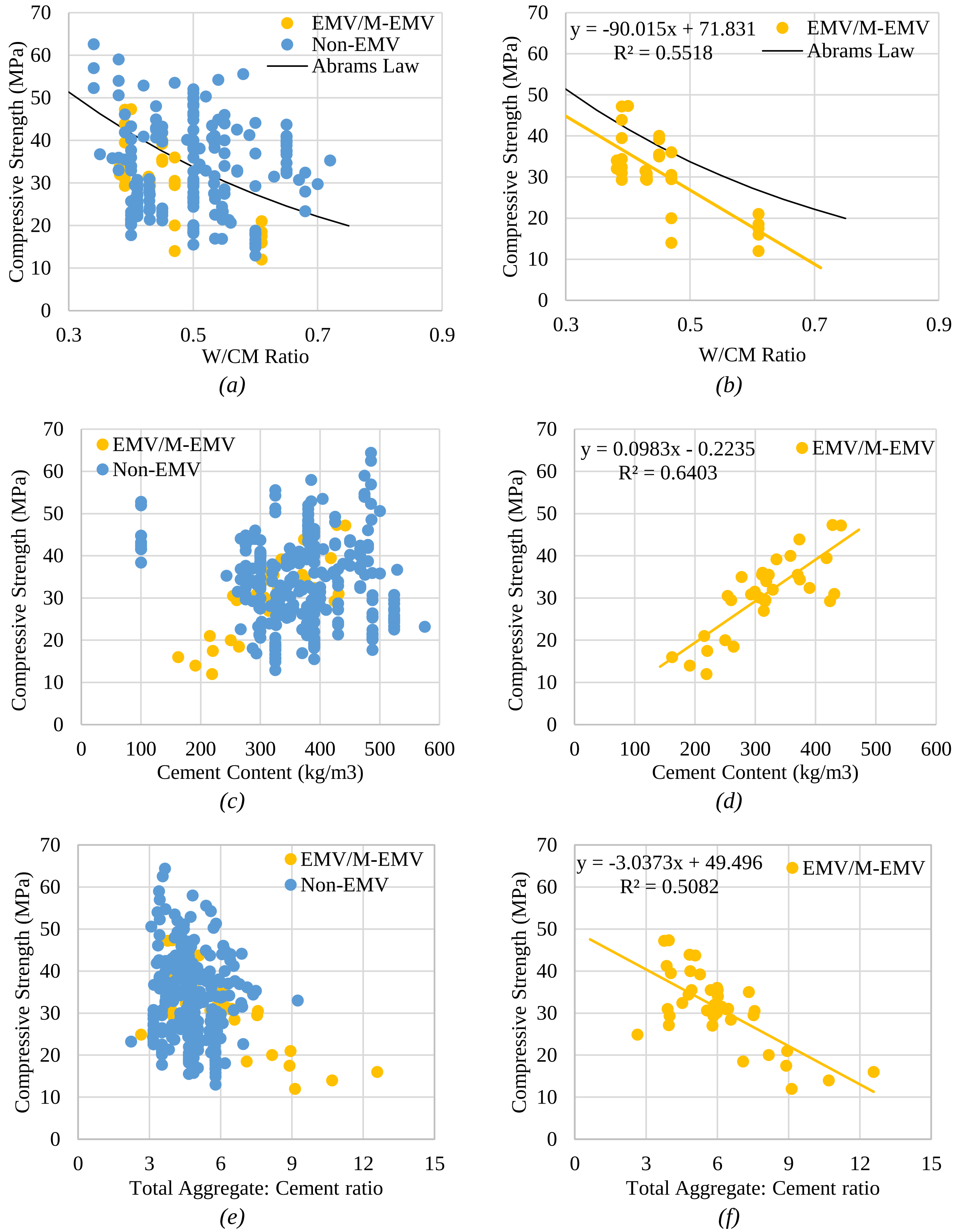


Figure 29-Effect of various mix proportion methods on compressive strength of LCC mixtures

(a/b) Effect of w/cm ratio, (c/d) Effect of cement content, (e/f) Effect of total aggregate: cement ratio Note: Non-EMV mixtures refers to equivalent weight or volume replacement, mixtures with SCM's omitted

Based on the results presented within Figure 29, compressive strength data compiled from various experimental studies indicate that the use of conventional mix design practices (non-EMV) did not present any relatively linear or non-linear trends in terms of w/cm ratio, cement content or total aggregate/binder ratio with extensive variability observed within the results. As indicated within Figure 29 (a/c/e), high variability within the conventional concrete mixtures for each category further indicates a lack of design accuracy regarding the prediction of the compressive strength of mixes containing RCA based on the presented mixture proportion metrics required for effective design of concrete mixtures (i.e., structural relatability and design perspective).

In terms of LCC mixtures developed with either the EMV or M-EMV mix proportioning methods, the results presented in Figure 29 indicate that relative to conventional mixtures, considerable improvements in terms of compressive predictability as well as overall compressive strength values. The results showcased within Figure 29b/d/f highlight that the compressive strength properties of LCC mixes proportioned with the EMV/M-EMV methods can be modelled with a high degree of accuracy based on w/cm ratio, cement content and total aggregate/cement ratio values with R^2 values ranging from 0.5082-0.6403 observed.

It should be noted that while the results presented indicate that the EMV/M-EMV methods improved the compressive strength predictability, a large degree of variability remains within the compressive strength values, as shown within Figure 29 b/d/f with outliers presented regardless of the assessment criteria (i.e., w/cm ratio, etc.…). The noted variability within LCC mixtures regardless of mix proportioning method may be attributed to the heterogeneous characteristics of various RCA sources and resulting differences in aggregate properties/characteristics such as RMC, AC_{24}, density of adhered mortar, source concrete strength, age of crushing from the use of various RCA sources [56,82,96]. Although it should be noted that further factors such as the w/cm ratios of the mixtures (i.e., in the case of low or high w/cm ratios and effect on governing failure mechanisms) and the effects of additional water proportioned to compensate for aggregate absorption (refer to above sections) may have also impacted the resultant compressive strength properties and should also be considered. However, despite the minor variability within the presented findings, given the extensive collection of compressive strength data from various EMV/M-EMV studies, it can be concluded that EMV/M-EMV mixture proportioning provides considerable compressive strength improvements and improved compressive strength predictability compared with conventional weight/ volume proportioning methods.

Further analysis also indicates that with regards to carbon emissions and sustainability, both the EMV and M-EMV mixture proportioning methods present themselves (as noted within literature [45,51]) as sustainable alternatives relative to conventional mix design methods for the production of LCC mixtures. As presented within Table 3, comparison of LCC proportioned with equivalent weight or volume mixture proportioning with the EMV/M-EMV proportioning mixtures indicates that the use of the EMV/M-EMV proportioning results in far lower quantities of cement than equivalent volume/weight proportioning methods for RCA concrete [20]. As noted, many studies have found that cement is by far the most influential material in concrete in terms of its released emissions; as such, the lower cement requirements of the EMV and M-EMV methods provide insight into improved sustainability and lower carbon footprint of such mix proportioning methods [20]. As shown in Table 3), S-factors within the M-EMV method have a significant effect on the cement proportioning requirements of the EMV and M-EMV mixtures (i.e., modifies portion of RM considered as part of cement fraction). However, even with higher S-factor values (i.e. > 5), compared with conventional mix proportioning methods, both the M-EMV and EMV method require far lower cement quantities, amounting to considerable environmental savings compared with conventional mix design methods [20]. Further emissions savings have also been noted through the partial replacement of cement with SCM's such as fly ash, silica fume or GGBFS within LCC mixture, although as noted prior, increasing SCM contents have often presented reduced compressive strength and further mechanical properties for LCC mixtures when proportioned with RCA [20].

Additionally, further metrics such as cement efficiency or "unit cement requirement" may also be used to assess the efficiency and environmental impact of LCC mixes [107]. Using a modified equation to that as presented by Hayles et al. [107], the unit cement requirement (i.e. kg of cement required per compressive strength (MPa)) can be used to expresses the quantity of cement required (by mass), as presented below in Equation 13.

$$Unit\ Cement\ Requirement = \frac{Cement\ (kg/m^3)}{Compressive\ Strength\ (MPa)}$$ Equation 13 [107]

Using Equation 13, the unit cement requirements of the various LCC mixtures compiled as part of the literature database were analyzed for LCC mixtures propertied with conventional weight/volume proportioning and those the EMV/M-EMV methods as shown within Figure 30.

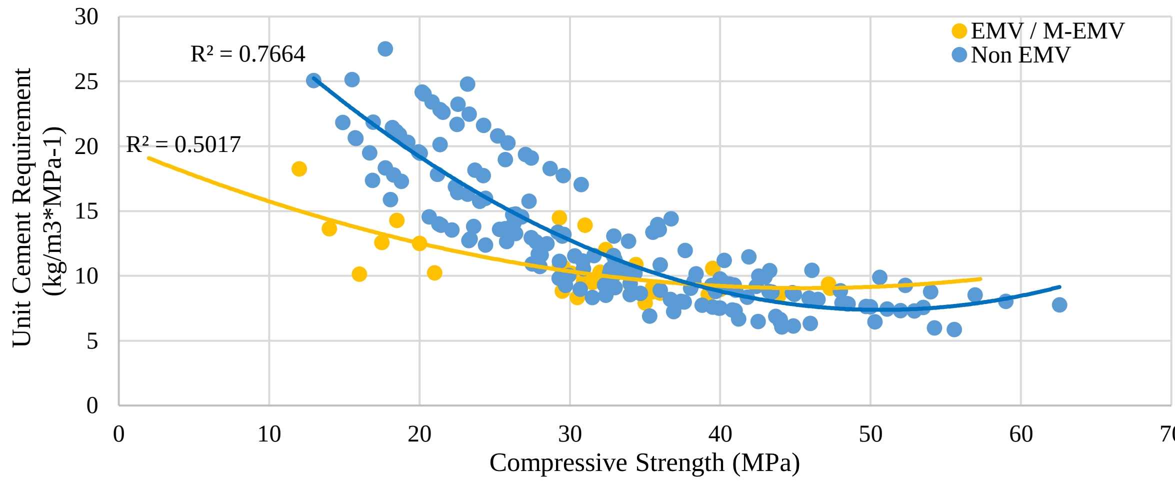


Figure 30-Comparison of unit cement requirements-based on mixture design method Unit cement requirements shown in Equation 13 [107]

It can be seen that in Figure 30 that compared with LCC proportioned with conventional methods, LCC proportioned with either the EMV or M-EMV method presented lower unit cement requirements for compressive strengths below 40 MPa. Therefore, for compressive strengths below 40 MPa, the use of the EMV/M-EMV method requires lower cement quantities compared with conventional weight/volume proportioning to achieve such compressive strength values. Such findings indicate the improved efficiency of the EMV/M-EMV method compared with conventional mixture design methods for the proportioning of LCC given the lower cement requirements to achieve similar compressive strength.

For compressive strength greater than 40 MPa, the EMV/M-EMV methods have similar unit cement requirements as conventional mixture portioning methods. However, given the relatively limited number of experimental studies, further testing is required to assess the unit cement efficiency for LCC mixtures with compressive strengths greater than 40 MPa. Based on the database analysis, it is suggested that the EMV/M-EMV be used to develop LCC with compressive strengths < 40 MPa to maximize the sustainability benefits and lower unit cement requirements.

4.4.2. Influence of Mixing Methods and Optimization

Mixing methods such as the two-stage mixing approach (TSMA), double mixing (DM), triple mixing method (TMM) and variations of such methods have become increasingly popular within recent LCC experimental studies as alternatives to the normal mixing approach (NMA) presented in existing design standards (i.e., CSA A23.3-14 [68]). Despite promising findings, these methods have not been thoroughly analyzed within existing researcher LCC database assessments, with limited assessments conducted regarding the mechanical strength benefits of such methods from a literature review perspective. Therefore, to analyze the differences between LCC mixtures prepared using alternative mixing methods such as the TSMA, DM or TMM to those prepared with standard mixing methods as outlined in CSA A23.1-14 and ACI 211), Figure 31 was produced. It should be noted that Figure 31(b) highlights the compressive strength values for the mixtures prepared with the alternative mixing methods only.

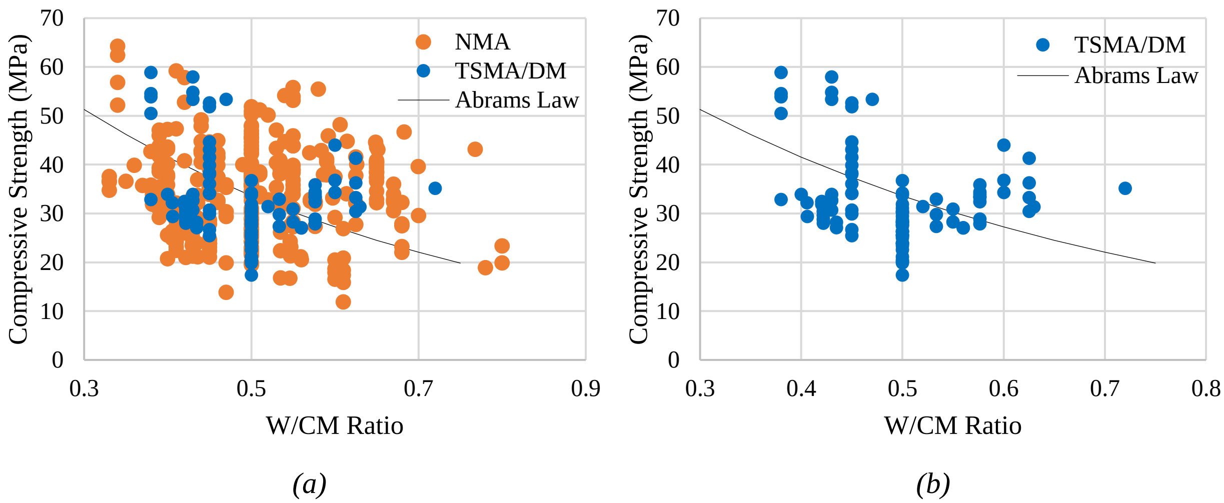


Figure 31-Effect of various mixing methods on compressive strength of LCC mixtures (a) All Data (b) Alternative mixing methods, note: mixtures with FRCA omitted

It can be observed that the use of alternative mixing methods (i.e., TSMA, DM or TMM) tended to lead to an increase in compressive strength based on the w/cm ratio of the mixture as well as decreased with overall variability relative to the mixture proportioned with the NMA. Further analysis also indicates that the use of the NMA tended to result in significant variability within the resultant compressive strength properties. As observed within Figure 31, the TSMA tended to reduce the overall mixture variability, especially at high w/cm ratios where the higher free-water content and w/cm ratios may have more of an effect on the resultant strength properties.

It should be noted that the use of alternative mixing methods such as the TSMA, DM or TMM does not modify the mixture proportions of the prepared LCC mixtures (i.e., water, cement or aggregate contents); rather, they provide an alternative procedure for the order and duration of mixing of the various concrete constituents. As a result, while numerous experimental studies have utilized alternative mixing methods, the mixtures developed are still negatively impacted by inaccuracies within water absorption characteristics (i.e., differences within actual and predicted absorption aggregate absorption properties), RCA aggregate properties (i.e., weaker microstructure, RM fraction) and further mixtures characteristics such as the w/cm ratio of the mixtures.

It should be noted that similar conclusions can also be drawn upon assessment based on CRCA content, total absorbed water, and cement content as no definitive improvements can be identified regarding the compressive strength properties of LCC mixtures prepared using the TSMA, DM or TMM methods relative to LCC mixtures prepared with conventional mixing methods. It should also be re-iterated that while a lack of statistical improvements was observed for LCC mixtures prepared using alternative mixing methods, the scope of the analysis was limited to the compressive strength properties of LCC mixtures. As a result, plausible benefits provided by the use of such mixing methods such as densification of the hardened microstructure, improved ITZ strength characteristics and durability improvements as observed within literature [43,53,54] have not been observed. As a result, while the statistical findings indicate a lack of improvements within an overall assessment of existing literature, it is recommended that the effect of alternative mixing methods (i.e., TSMA, DM or TMM) be further evaluated within experimental studies as well as with evaluated with regards to the implications on the aggregate absorption properties given the lack of existing experimental data and available literature. Additionally, given the lack of available literature regarding the use of TSMA, DM and TMM with LCC mixtures prepared with materials such as FRCA, or SCM's with RCA it is advised that further experimental research be undertaken to investigate the effect of such methods with increasing LCC materials not discussed or presented within available literature.

4.5. Summary and Conclusions

Based on the statistical findings and analysis conducted, the following points summarize the results obtained from the LCC database assessment.

Database Analysis Part 1: Mixture Materials

- Assessment of existing literature and mixture data indicates that limited assessment has been conducted for LCC mixtures incorporating FRCA, combined CRCA and FRCA, mixtures with RCA and SCM's, or the influence of various optimization methods on the properties of LCC.
- It was observed that the use of CRCA, FRCA or combined usage (even at 100% replacements) did not impact compressive strength properties; rather, the w/cm ratio largely governs the resultant strength properties. Comparison with conventional concrete mixtures indicates that LCC presents similar relations with regard to f'c and w/cm ratios with similar variability observed.

- In terms of splitting tensile strength (f'_{ct}) and modulus of elasticity (MOE), increasing CRCA contents led to reduced values. The observed f'_{ct} reductions can be attributed to the more porous structure and reduced strength of the RCA [26,33]. While the reduced MOE values can be due to the fact that the concrete MOE depends highly on both the aggregate and mortar fraction, therefore the reduced stiffness of the mixture can be attributed to the increased deformability of the CRCA fraction given the reduced elastic modulus of the CRCA [26,126].
- Comparison of the experimental f'_{ct} observations with the empirically calculated fr values indicates that the empirically calculated f_r values often exceed f'_{ct} findings given the effect of the CRCA on the stiffness and deformability characteristics of the resultant mixture. In terms of MOE, existing CSA A23.3-14 equations can provide an accurate assessment regarding experimental MOE values; however, empirical predictions over-estimate approximately 31.4% of all findings, which may result in unconservative stiffness and deflection predictions.

Database Analysis Part 2: Mixture Design Optimization

- Comparison of LCC mixtures found that, relative to conventional LCC mixture proportioning (i.e., equivalent weight or volume proportioning), EMV/M-EMV proportioning reduces the variability of compressive strength and improves overall compressive strength values based on w/cm ratios, cement content and total aggregate-to-binder-ratios. It was reasoned that such improvements were attributed to the effective consideration of residual mortar content of the CRCA sources while also reducing the cement requirements of the mixtures.
- Mixtures proportioned using the EMV/M-EMV required reduced cement contents (relative to mixtures proportioned with conventional mixtures proportioning methods) to achieve specified compressive strength values. It was noted that due to the limited number of studies, such conclusions were only valid for LCC mixtures up to 45 MPa.
- Assessment of alternative mixing methods found that such methods did not provide any observable benefits in terms of compressive strength improvement. However, given the lack of studies that have utilized such methods with LCC, further experimental testing is required.

5. MATERIAL PROPERTIES TESTING

The following chapter outlines the various materials as well as provides an overview of the properties of the materials utilized throughout the experimental program. An overview of the various cementitious materials and water sources are provided, while an extensive presentation, analysis and comparison of the aggregate properties for RCA as well as natural aggregates sources is provided.

5.1. Cementitious Materials

The cementitious materials utilized throughout the experimental program were limited to standard general-use ordinary Portland cement (OPC) (henceforth referred to as cement) and ground granulated blast furnace slag (GGBFS). The cement and GGBFS sources were both sourced from local material suppliers within the Southern Ontario, Canada region and were limited to the same sources through the entirety of the experimental program. The cement and GGBFS sources were both stored in dry environments throughout the duration of experimental testing, while opened packages were transferred into dry buckets and sealed to eliminate moisture ingress.

As per supplier material datasheets, the OPC had a BSG value of 3.15 and a fineness ranging between 334 and 431 m^2/kg; GGBFS had a BSG value of 2.95 and a fineness between 400 and 600 m^2/kg. A summary of the material properties of the cement and GGBFS are summarized within Table 8.

Table 8-Cementitious Material Properties

Material	Material Provider	BSG*	Fineness* (kg/m^3)
Cement	Votorantim Cimentos (St. Mary's)	3.15	334-431
GGBFS	CRH	3.00	400-600

* *Values provided by supplier datasheets*

5.2. Mixing Water

Within the experimental program, a single potable water source was used in all concrete mixture development as well as any further water-related requirements (i.e., curing, casting, mixing, etc.). The water source was tested at the start of the experimental program, where the BSG was measured to be 1.001, and the density was found to be 998.9 kg/m^3. The properties of the potable water source are summarized in Table 9.

Table 9-Water source information and properties utilized throughout the experimental program

Material	Material Provider	BSG*	Density (kg/m^3)	Average Temperature (ºC)
Potable Water	Municipal Tap Water (City of Toronto)	1.0	998.9 (*1000)	2-4

**Actual BSG: 0.998 based on temperature, for simplicity modified values used in the experimental program*

5.3. Coarse and Fine Aggregates

To assess the quality of current RCA production within the Southern Ontario, Canada region, four (4) RCA sources (i.e., RCA-1, RCA-2, RCA-3, RCA-4) consisting of both coarse and fine RCA (CRCA and FRCA) were collected and tested. Multiple RCA sources were tested to ensure the applicability of the collected findings, as well as help provide an understanding of the current RCA production methods currently utilized by major RCA producers. In terms of natural aggregates, a singular NA sources (NA) for both the coarse and fine fraction were utilized given the standardized nature of NA production methods as well as the strict enforcement of existing design standards within NA production. Table 10 provides the sourcing information for each of the various RCA and NA sources. It should be noted that although RCA-1 and RCA-3 were sourced from the same supplier, the RCA sources differed (i.e., different source concrete used within RCA production)

Table 10-Aggregate source information

Aggregate Source	Identifier*	Material Provider	Material Provider Location	Deleterious Materials
NA Source	NA	Brock Aggregates	Southern Ontario, Canada	No
RCA-Source 1	RCA-1	Franceschini Bros. Aggregates	Mississauga, Ontario, Canada	Yes
RCA-Source 2	RCA-2	Dufferin Aggregates	Vaughan, Ontario, Canada	Yes
RCA-Source 3	RCA-3	Franceschini Bros. Aggregates	Mississauga, Ontario, Canada	Yes
RCA-Source 4 **	RCA-4	Laboratory Crushed Concrete	Produced in lab**	No

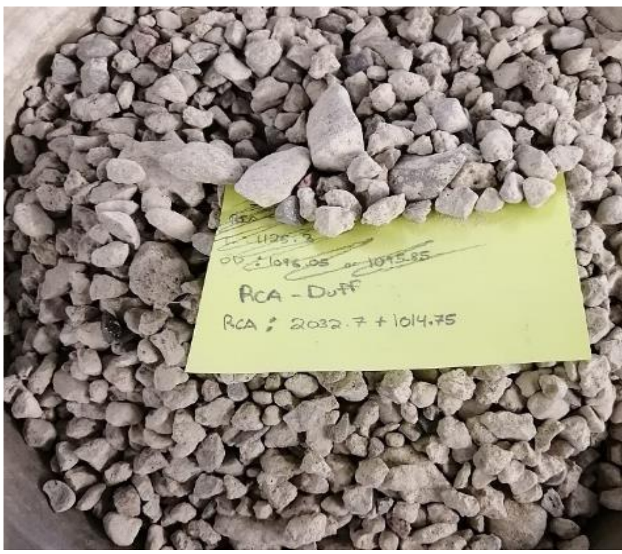
**Identifier of each aggregate source corresponds to both coarse and fine aggregate fraction,*
***Produced from the manual crushing of laboratory specimens*

Regarding the natural aggregate source (NA), the coarse natural aggregate (NCA) fraction consisted of a nominal size of 19 mm (3/4”) crusher stone aggregates, while the natural fine aggregate (NFA) fraction consisted of standard concrete sand with a nominal size of 4.75 mm. Coarse and fine fractions were delivered separately (separate storage bags) and did not contain any deleterious materials or substances.

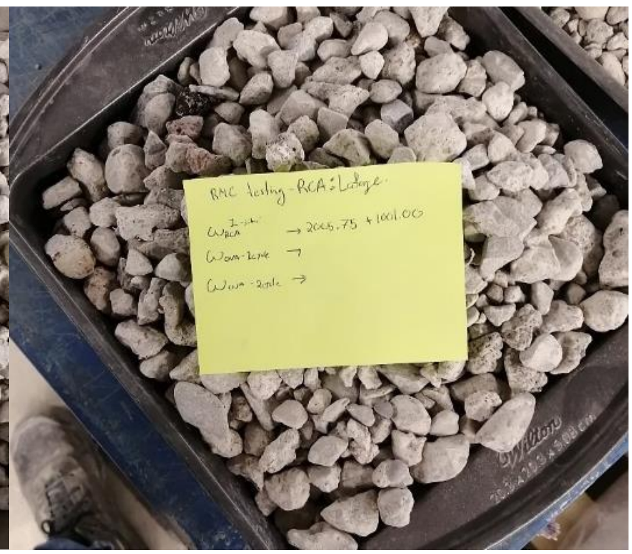
Regarding the RCA sources, the RCA was not available with the same gradations as the NA sources, rather available in continuous gradations containing aggregates ranging in size from 0-19 mm (Granular A) or 0-25 mm (Granular B). As a result, prior to further testing/examination, each of the RCA sources was regarded by sieving over a 4.75 mm sieve to allow for separation and collection of the coarse and fine aggregate fraction. Figure 32 and Figure 33 present representative samples of the coarse and fine fractions for the NA and RCA sources, respectively.

(a)

(b)



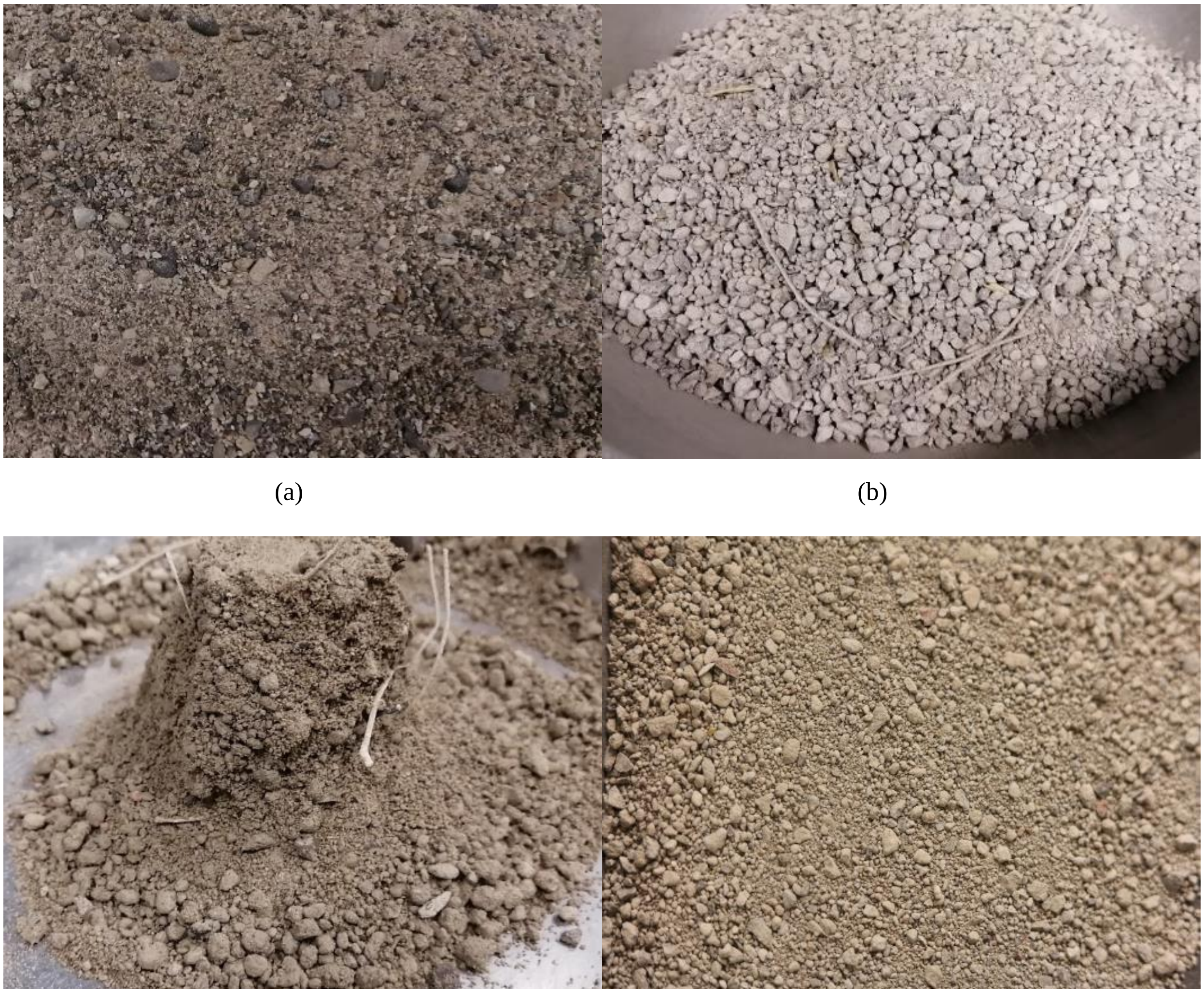
(c)



(d)

Figure 32-Coarse Aggregates

(a)Natural coarse aggregates (NCA), (b)Coarse RCA (CRCA)-RCA-1, (c) CRCA-RCA-2, (d) CRCA-RCA-3



(a) (b) (c) (d)

Figure 33-Fine Aggregates,

(a) Natural fine aggregates (NFA), (b)Fine RCA (FRCA)-RCA-1, (c) FRCA-RCA-3, (d) FRCA-RCA-4

Upon visual inspection (refer to Figure 32 b/c/d and Figure 33 b), both the coarse and fine RCA samples (with the exception of RCA-4) were found to contain small quantities of deleterious materials (e.g., wood chips, various fibres, trace amounts of brick, ceramics, asphalt, etc...). To ensure wider applicability of the research results and to better capture the influence of current RCA production methods, deleterious materials were not removed from any of the RCA sources (coarse or fine fraction). RCA-4 was produced from the manual crushing of various laboratory-produced concrete specimens with compressive strengths ranging from 30 to 50 MPa (see Table 10). As a result, RCA-4 did not contain any deleterious substances with the coarse or fine fractions. It should be noted that although unrepresentative of current industry RCA production methods, RCA-4 was included within the experimental program to provide an indication of the effect of deleterious substances, as well as evaluate the effect of differences within RCA production methods based on differences within the aggregate properties of various RCA sources. It should be noted that RCA-1 ad RCA-3 were sourced from the same supplier, however, consisted of RCA produced from different source concretes as indicated by the supplier given the time-interval between the production of the two RCA sources.

While the aggregate properties for each RCA source were tested, for the further stages of the experimental program, only NA-1 and RCA-1 were used as the primary NA and RCA sources. The remaining RCA sources (i.e., RCA-2, RCA-3 and RCA-4) were not used for concrete mixtures and were used exclusively for aggregate properties testing and comparison between the various RCA sources. RCA-1 source was chosen over the other RCA sources based on preliminary aggregate testing findings highlighted within Chapter 5.3.1 as well as logistical restrictions.

5.3.1. Coarse Aggregate Properties

The properties of the coarse aggregates within the experimental program were assessed using the corresponding CSA A23.2-14 [3], ASTM [169] and provincial OPSS [170] testing standards and are provided within *Table 11,* while the particle size distribution (i.e., gradation) for each of the various coarse aggregate sources is provided within Figure 34. It should be noted that further testing was also conducted to evaluate the residual mortar content (RMC) percentage of the CRCA sources (by weight) using both a thermal and chemical treatment method as provided within *Table 11*; an overview of the RMC testing procedures is provided within Chapter 5.3.1.1. An list of the CSA A23.2-14 [3], ASTM [169] and provincial OPSS [170] testing standards used within the experimental program is provided within

APPENDICES

Appendix A: Testing Standards.

Table 11-*Coarse Aggregate Properties*

Coarse Aggregate Property	Coarse Aggregate Source				
	NA-1	RCA-1	RCA-2	RCA-3	RCA-4
Bulk Density $_{OD}$ (kg/m^3)	1607	1373	1489	1555	1442
Bulk Density $_{SSD}$ (kg/m^3)	1640	1458	1595	1667	1520
Void Content (%)	38.23	39.87	33.93	30.06	38.77
BSG $_{OD}$	2.61	2.29	2.26	2.23	2.36
BSG $_{SSD}$	2.66	2.43	2.42	2.39	2.49
Absorption Capacity-AC_{24} (%) *	2.09	6.21	7.11	7.24	5.44
Micro-Deval Abrasion Resistance (%)	12.14	21.17	21.88	21.37	-
RMC $_{Thermal}$ (% by weight) **	-	27.50	20.91	31.09	-
RMC $_{Chemical}$ (% by weight) **	-	-	31.82	27.87	16.67

Note: Aggregate properties denoted with "-" were either not tested or are non-applicable,
**AC_{24}: 24-hour absorption capacity values,*
*** Various RMC testing methods specified*

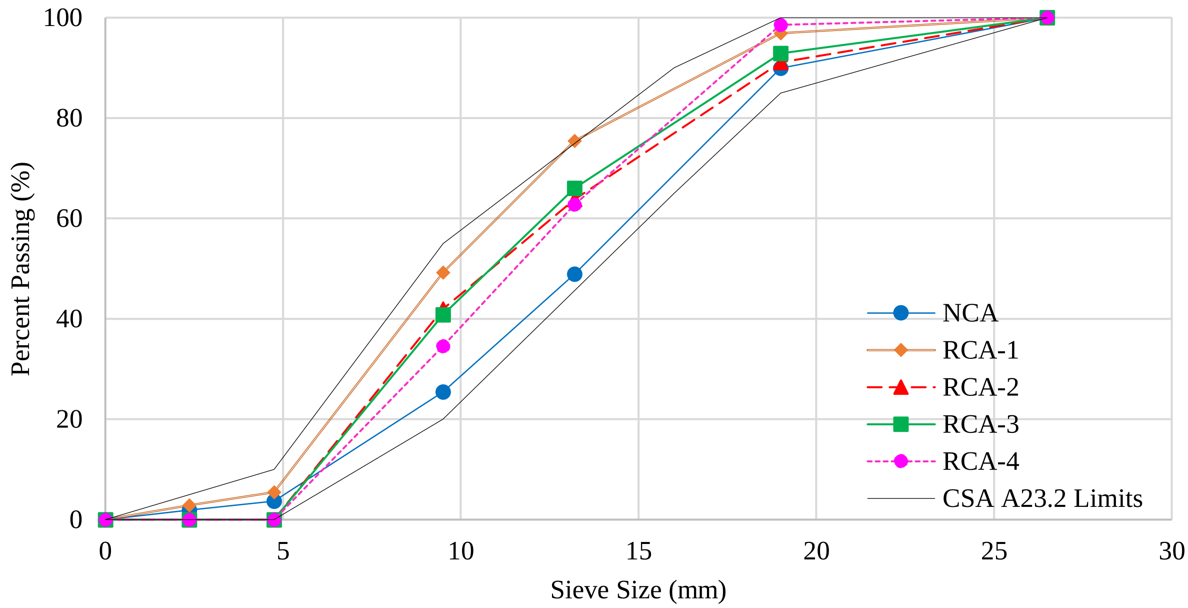


Figure 34-Coarse Aggregate Gradations

Analysis of the coarse aggregate properties indicates that compared with the NCA, each of the CRCA sources presented significantly different 24-hour absorption capacity (AC24), bulk specific gravity (BSG), abrasion resistance and bulk density values. It was found that that CRCA sources presented 160-246.5% higher AC24 values, up to 14.5 % lower BSG values, 74-80.2% lower abrasion resistance values and up to 14.6% lower bulk density relative to the NCA source. Further testing also found that the RM of the various CRCA sources was highly variable, ranging between 16.7-31.8%. Similair RM values were observed regardless of testing method (thermal or chemical) for each source. Despite similar findings within the CRCA sources, the variability within the properties for each of the CRCA sources as well as with respect to the NCA source can be attributed to differences within the residual mortar (RM) fraction due to differences within production methods and parent concrete sources of the CRCA sources [25,139].

As shown within Figure 32, the CRCA consisted of two distinct materials, original aggregates (OA) and residual mortar (RM), with the boundary between referred to as the interfacial transition zone (ITZ). The OA fraction within the CRCA sources consists of the NA fraction (coarse and fine aggregates) from within the original source concrete (i.e., concrete used to produce the RCA), while the RM is a result of the hardened cement mortar from the source concrete. Previous studies have determined that compared with the OA fraction, the hardened cement paste of the RM fraction is significantly more porous, less dense and primarily contributes towards the differences within the properties of the RCA sources (i.e., water absorption, BSG, bulk density/BSG) compared with NA sources [12,44,45,77]. Further studies have also found given the added micro-structural complexity of RCA (specifically CRCA), the abrasion resistance properties of the RCA sources are highly dependent on the bond between the RM-OA fractions at the ITZ, which as a result of RCA production (i.e., crushing stages), may weaken the bond strength at the ITZ due to the formation of micro-cracks during RCA production and led to poor abrasion resistance properties [10,60,139]. Based on the results, it can be observed that while the RM only represents a minor portion of the total CRCA (by % weight, ranging from 16.7-29.5%), the influence on the CRCA properties is very apparent given the significant bulk density, BSG and abrasion resistance reductions and the higher absorption capacity values compared with the NCA source.

Further research investigations, as shown within Figure 35, highlight the relations between the residual mortar content of the CRCA sources with respect to the absorption capacity and BSG properties of the various coarse aggregate sources.

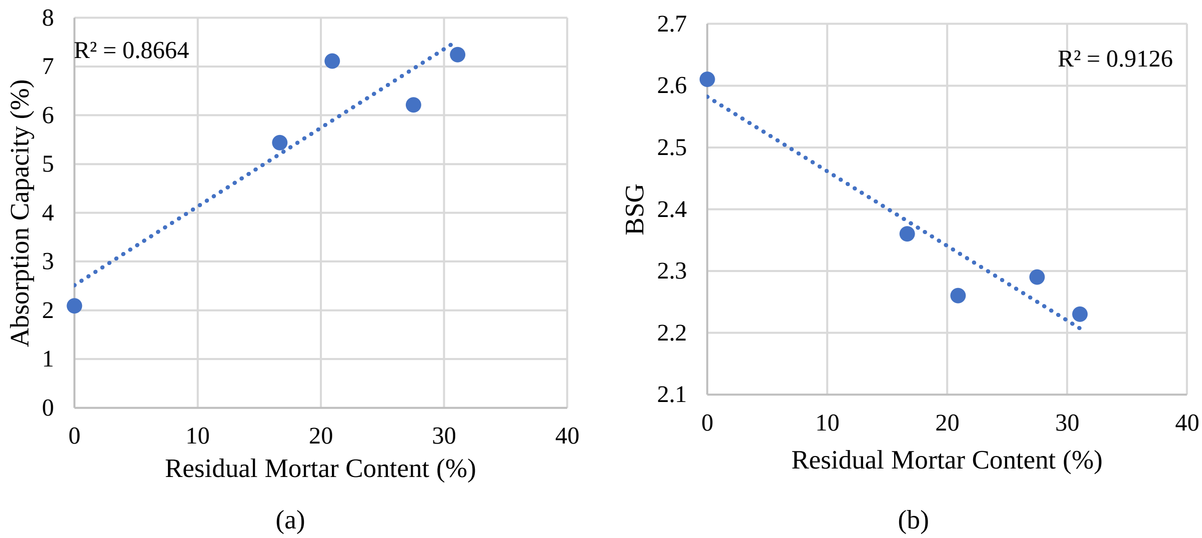


Figure 35-Effect of residual mortar content on coarse aggregate properties

(a) Absorption Capacity (b) BSG

It can be observed that with increasing residual mortar content, the absorption capacity values of the CRCA increased, while the BSG values decreased linearly, as shown in Figure 35a/b. As noted that increased water absorption and lower BSG values of the CRCA with increasing residual mortar content can be attributed to the low density and porous nature of the residual mortar [128], however as presented given the various residual mortar content values of the CRCA sources, a high degree of variability was presented within the observed water absorption and BSG values of the tested CRCA sources. Despite the variability amongst the aggregate properties for the CRCA (RCA-1, 2, 3, 4) sources and with respect to the NCA sources (NA-1), the observed values are similar to those found within existing literature [22,37,44,49,94,107].

5.3.1.1. Residual Mortar Content testing

Given the influence of the RM on the properties of the RCA sources, a proper assessment to quantify the amount of residual mortar (i.e., residual mortar content-RMC) within RCA sources is vital to further understand how the properties of the RCA differ from those of NA. Given the novelty of RCA, no standardized testing process currently exists for the specific determination of the RMC. However, within the existing literature, researchers have developed dedicated freeze-thaw and chemical degradation [15] and thermal-based treatment [7] methods to quantify the RM fraction of CRCA samples. Such methods have been used in a number of existing LCC research studies [7,22,107,23,37,44,45,49,51,52,94] and have proven effective at accurately determining the RMC of CRCA sources. Further studies have also investigated the use of acid-based treatment methods and have found that while such methods remove a significant portion of the residual mortar, acid-based treatment methods were found to dissolve the outer layer or surface of the adhered mortar without weakening and mortar-aggregate bond, resulting in a significant experimental amount of remaining residual mortar within treated CRCA sources [22]. Acid-based treatment methods were also found to potentially react with select RCA sources (i.e., due to RCA composition), which may impact the residual mortar content values obtained from testing [22].

Therefore, based on the previous findings found within the literature, the chemical and thermal treatment methods were utilized given the improved safety considerations, minimization of further hazards (i.e., environmentally harmful acids) and the improved testing accuracy relative to the acid-based treatment methods. An overview of freeze-thaw cycling with chemical degradation [15] and Thermal Treatment (Modified Thermal Shock) RMC [7] testing methods is provided below:

Method 1: Freeze-thaw cycling with chemical degradation

The freeze-thaw cycling with chemical degradation treatment method consisted of submerging CRCA samples (after drying and grading to specifications outlined within Table 12) within a 26% solution of sodium sulphate (Na_2SO_4) solution (by weight), followed by five freeze-thaw cycles (i.e., 8 hours at 80^oC and 16 hours at -17^oC) while in solution [15]. After five (5) completed daily cycles, the treated CRCA samples were then washed over a 4.75 mm sieve to dispose of loose or small residual mortar particles, dried, weighed (W_f) where the RM was then calculated based on the formula provided within Equation 14. It should be noted that while differing chemical concentrations, duration and/or chemical compounds have been used in research studies, Na_2SO_4 was utilized given the much safer nature relative to compounds such as hydrochloric (HCL) or nitric acid. Figure 36 showcases images of the CRCA sources (a) within the Na_2SO_4 solution, (b) after five (5) days of testing and (c) after washing and sieving of the removed residual mortar.

(a) (b) (c)

Figure 36-Residual mortar content testing-freeze-thaw chemical degradation treatment

Note: RCA-1 shown(a)-Within Solution, (b) after removal of solution, (c) after washing

Method 2: Thermal Treatment (Modified Thermal Shock)

The thermal treatment method consisted of rapidly heating the CRCA samples (after drying and grading to specifications outlined within Table 12) for a duration of 2 ± 0.5 hours at temperatures of 500 ^{o}C, followed by immediate submersion of the heated within cold water to induce differential thermal stresses between the adhered mortar and the original coarse aggregates [7]. Similar to the freeze-thaw cycling with chemical degradation method, after treatment, the treated CRCA samples were washed over a 4.75 mm sieve to dispose of loose or small residual mortar particles, dried, weighed (W_f), and the RM was then calculated based on the formula provided within Equation 14.

It was observed that after 1 cycle of thermal treatment (heating at 500 ^{o}C and then submersion with cold water), a significant portion of RM was still attached to the CRCA sources. As a result, two complete cycles of thermal treatment were conducted, while a rubber mallet (2-3 minutes) was also used to ensure adequate separation and removal of the RM from the various CRCA sources. After washing the treated CRCA samples over a 4.75 mm sieve to dispose of loose or small residual mortar particles, the samples were dried, weighed (W_f), and the RMC was then calculated based on the formula provided within Equation 14.

Figure 37 presents images of the RCA-2 source (a)-before treatment, (b) after 1 thermal treatment cycle and (c) after 2 thermal treatment cycles. As presented, with progressive treatment cycles, the residual mortar content within the CRCA source (RCA-2 shown) was found to progressive decrease as per visual inspection. After 2 cycles, it was assumed that any remaining residual mortar adhered to the OVA fractions presented sufficient bond strength. It should be noted that while multiple treatment cycles were required to ensure adequate removal of all of the residual mortar, the thermal treatment method provides considerable savings in terms of duration as well as material simplicity relative to the freeze-thaw chemical degradation treatment.

(a) (b) (c)

Figure 37-CRCA after residual mortar content testing-thermal treatment (RCA-2 shown)

(a)-Before Treatment, (b) after 1 treatment cycle, (c) after 2 treatment cycles

5.3.1.1.1. Testing Preparation

Prior to RMC testing (regardless of method), CRCA samples from the various RCA sources were brought to oven-dried (OD) moisture conditions by drying at 110 ± 5 °C for at least 24 hours to remove any moisture. After drying, the OD aggregates were graded to the gradation distribution requirements outlined within Table 12 and then weighed (W_i).

Table 12-Gradation distribution for RMC testing

Size Fraction (mm)	*Minimum Amount required (g)
4.75-9.5	1000
> 9.5	2000

**Minimum amounts shown, the exact weights of the OD aggregates were measured prior to RMC testing*

After testing, each of the treated CRCA samples from both testing methods were washed over a 4.75 mm sieve to allow for the disposal of any loose or small residual mortar particles. After thoroughly washing the treated samples, the samples were dried at 110 ± 5 °C for at least 24 hours to remove any moisture and then weighted (W_f). The RMC for each of the RCA sources was then calculated based on the differences between its initial weight (W_i) and the weight after treatment (W_f), as shown in Equation 14 [15].

$$\frac{W_i - W_f}{W_i} \times (100\ \%) \qquad \text{Equation 14}$$

Where:

W_i *: Initial oven-dry (OD) weight prior to testing (g)*
W_f *: Oven-dry weight after testing (g)*

Overall, it was found that regardless of the testing method and RCA source, both testing methods were effective at separating the RM fraction from the CRCA sources. It should be noted that while differences were observed with the same RCA source based on the testing method utilized, the observed differences could be attributed to the variable nature of RM within the CRCA sample tested. The accuracy of the findings could be improved through the use of additional testing cycles for each of the methods; however, it was visually concluded that the specified RM testing methods were able to remove nearly 100% of the RM within the CRCA sources. It should be noted that each of the RM testing methods was only applicable for the CRCA fractions [7,15]. As such, the RM for the FRCA fractions was unable to be directly assessed. Therefore, the RM values reported within *Table 11* only consider the RMC within the tested CRCA fraction of the tested RCA sources.

5.3.1.2. Micro Deval Abrasion Resistance

In terms of micro-deval abrasion resistance, as presented within *Table 11*, the CRCA sources presented significantly lower abrasion resistance properties relative to the NCA-1 source, with similar findings observed for all CRCA sources. It was found that weak bond between the OVA and RM fraction led to the reduced abrasion resistance properties, given the propensity for separation of the residual mortar under abrasive action. Similar micro-deval abrasion resistance findings were also within existing studies, which also found that the abrasion resistance properties were highly dependent on the quality of the CRCA sources and proportional to the residual mortar content of the CRCA sources [139]. In terms of a visual inspection, a qualitative inspection of the CRCA sources indicated that the use of micro-deval testing significantly reduced the residual mortar content of the various CRCA sources and reduced the roughened surface texture of the aggregates [139]. Images of the various CRCA sources after micro-deval testing are provided within Figure 38, while images of the NCA before and after micro-deval testing are provided within Figure 39.

(a) (b) (c)

Figure 38-Abrasion testing of CRCA

(a)- Before testing-RCA-2 (b)- after testing-RCA-2, (c)- after testing-RCA-1

(a) (b)

Figure 39-Abrasion testing of NCA (NCA-1)

(a) Before testing (b) After testing

5.3.2. Fine Aggregate Properties

Similar to the coarse aggregates, the properties of the fine aggregates within the experimental program were assessed using the corresponding CSA A23.2-14 [3], ASTM and provincial OPSS testing standards and are summarized in Table 13. The particle size distribution (i.e., gradation) for each of the various fine aggregate sources is shown in Figure 40. It should be noted given the inability to assess directly evaluate the RMC within the FRCA sources based on the testing methods outlined within 5.3.1.1, an in-direct quantitative assessment was conducted to assess the influence of the RM on the FRCA, based on the absorption rate and absorbed moisture (AM) properties of the FRCA sources relative to the NFA source. An overview of the absorption rate and absorbed moisture testing procedures is provided within Chapter 5.3.2.1.

Table 13-Fine Aggregate Properties

Fine Aggregate Property	Fine Aggregate Source				
	NA-1	RCA-1	RCA-2	RCA-3	RCA-4
BSG_{OD}	2.61	1.93	2.00	2.04	2.17
ASG_{OD}	2.72	2.67	2.62	2.57	2.64
Absorption -AC_{24} (%)	1.51	14.40	11.77	10.23	8.17
Fineness Modulus (FM)	2.73	2.97	3.04	2.70	3.15

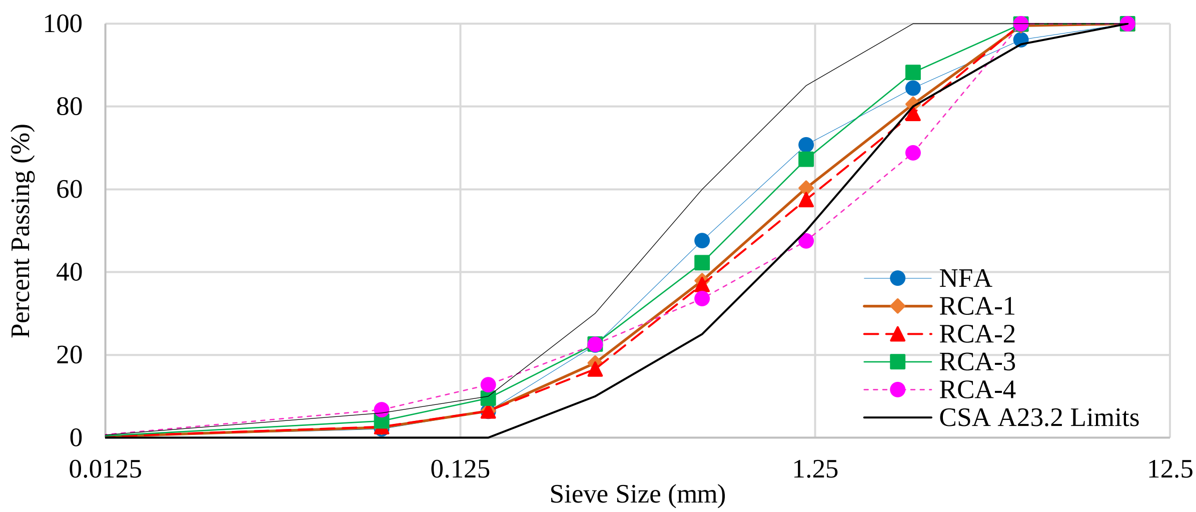


Figure 40-Fine Aggregate Gradations

Analysis of the fine aggregate properties indicates that compared with the NFA, each of the FRCA sources present significantly higher 24-hour absorption (AC_{24}) and lower BSG and apparent specific gravity (ASG) values despite the coarse gradations relative to the NFA source (indicated by 0-15.5% higher fineness modulus (FM) values). Compared with the NFA source, the FRCA sources presented 442-856% higher AC_{24} values and 16.7-26.2% lower BSG values.

Compared with the findings of the respective coarse aggregate fraction, the FRCA sources present much higher AC_{24} values than what was found within the respective CRCA fractions, which can be attributed to the smaller particles size of the FRCA. However, it is interesting to note that even with the coarser gradation of the FRCA sources relative to the NFA source, AC_{24} ranging from 442-856% higher were found within the FRCA sources. Based on the findings presented, the differences within the properties of the FRCA and NFA sources can be attributed to the presence of fine, porous, highly absorbent residual mortar particles (i.e., < 4.75 mm) within the FRCA sources, which contribute towards the drastically higher the water absorption and BSG properties of the FRCA sources [25,139].

In terms of variability amongst the FRCA sources that while the absorption capacities of the FRCA sources were much higher than the NFA sources, it was observed that RCA-4 displayed significantly lower absorption capacity and the highest BSG values relative to the other FRCA sources FRCA sources. Previous studies have reasoned the variability amongst the various FRCA sources, the differences within the observed fine aggregates properties can be attributed to differences within the FRCA composition, stemming from variability within the fine residual mortar particles, source concrete composition and production methods of the various sources [56]. It can be reasoned that the variability within the RM of the FRCA sources (although not able to be directly assessed) led to the observed differences within the fine aggregate's properties. Although the residual mortar content of the FRCA sources was not evaluated directly, the differences within the residual mortar content of the coarse aggregate counterparts of the various RCA sources can be used to provide a preliminary indication of the variable residual mortar content values of FRCA sources. It can be reasoned that in a similar fashion to the CRCA sources, the differences within the residual mortar content properties of the various RCA sources (CRCA and FRCA), attributed to differences within the sources concretes (f'_c, mixture composition/proportions, w/cm ratios, age at crushing or the combination of various source concretes) [25,56,139]. Given the lack of information regarding the sourcing of the RCA sources (i.e., RCA-1, RCA-2 and RCA-3), no clear conclusions can be made to explain the differences within the observed aggregate properties amongst the various RCA sources. Compared with literature, similar aggregate properties for both the NFA and FRCA sources have been to those with literature [22,37,44,49,94,107].

5.3.2.1. Water Absorption with Time

Given the difference within the water absorption properties between the FRCA and NFA sources relative to the NFA source, an in-direct quantitative assessment was conducted to assess the influence of the RM on the absorption rate and absorbed moisture properties (AM) of the FRCA sources. The absorption rate and absorbed moisture testing were conducted given the inability to directly assess the residual mortar content of the FRCA sources, as well as investigate the various components of the absorption properties of the FRCA in terms of the absorbed (internal) and surface moisture components. Prior to testing, fine aggregate samples sources were brought to oven-dried (OD) moisture conditions by drying at 110 ± 5 ºC for at least 24 hours.

The testing procedure developed as part of this research consisted of submerging 100-gram oven-dried fine aggregate samples in water at pre-assigned time intervals (up until a period of 24 hours). Following submersion, the fine aggregates were removed from the water, drained of any excess free water and then weighed ($W_{IN\text{-}SITU}$). Four (4) separate samples were taken for each of the specified testing time intervals up until a period of 24 hours. After the weight of the wet samples was recorded, the fine aggregates samples were once again brought to oven-dried (OD) moisture conditions. The oven-dried weight of the various fine aggregate samples was recorded (W_{OD}). The absorbed moisture (AM) for each of the various fine aggregate samples (i.e., amount of total water absorbed by the fine aggregate sources for each time internal) was then calculated using the formula presented within Equation 15:

$$Total\ AM = \frac{W_{IN-SITU} - W_{OD}}{W_{IN-SITU}} \times (100\ \%) \quad \text{Equation 15}$$

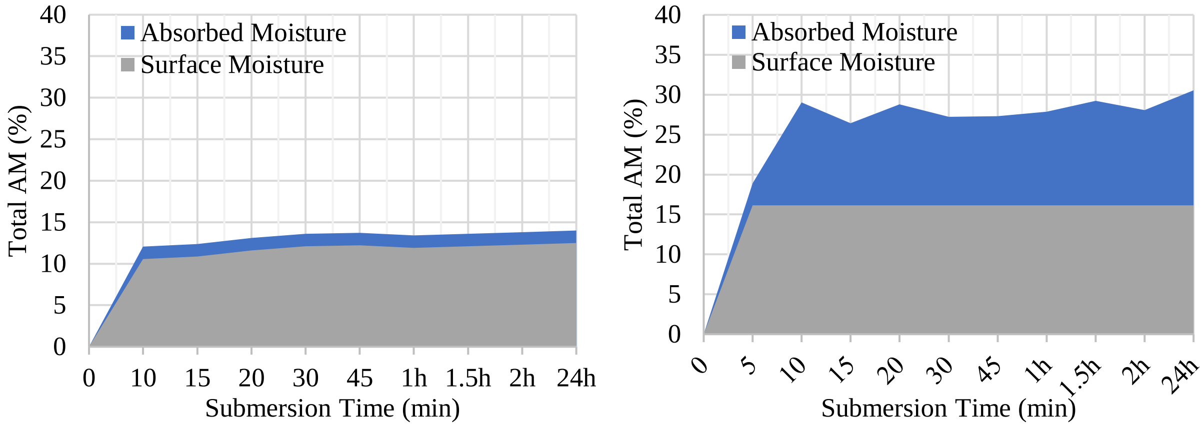
Where:

Total AM : Total Absorbed Moisture Content (%)
$W_{IN\text{-}SITU}$: In-situ weight of fine aggregates after soaking for a specified duration (g)
W_{OD} : Oven-dry (OD) weight of fine aggregates (g)

As noted, the testing process was conducted at several time intervals up to a period of 24-hours. The absorbed and surface moisture components were then determined based on the Total AM values calculated for each of the fine aggregate samples during the testing period. It was assumed that saturated surface moisture conditions were achieved upon initial submersion and remained constant throughout further testing. The surface moisture values were then determined by subtracting the AC_{24} values for each fine aggregate source from their total AM moisture (AM_{24}) using Equation 16.

$$Surface\ Moisture = AM_{24} - AC_{24}\ (\%) \quad \text{Equation 16}$$

The change in total absorbed moisture content values observed during testing was proportional to the change in the internal (absorbed) moisture content, represented as part of the AC24 of the NFA and FRCA sources at various time intervals. The total moisture content (surface and absorbed) results for the NFA and FRCA sources are presented in Figure 41. For the FRCA, RCA-1 was utilized as the RCA-1 source was found to have the highest AC_{24} values amongst the various FRCA sources, allowing for differences between the NFA and FRCA sources to be emphasized.



(a) (b)

Figure 41-Variation of total moisture content with submersion time, (a) NFA, (b) FRCA

Note: Values presented denote total absorbed moisture components: surface moisture + absorbed moisture

The results indicate that the NFA (Figure 41a) was able to achieve and maintain the maximum total absorbed moisture content after initial submersion, as further submersion (i.e., >10 mins) did not result in significant changes in the total moisture content. Compared with the FRCA (Figure 41b), it was observed that with continued water submersion, the FRCA continually absorbed water throughout the entire testing duration (up to 24 hours), with significant absorbed moisture content fluctuations within the first two hours of submersion. Based on these results, the impact of the RM particles within the FRCA is evident given the significantly higher total AM values as well as the AC_{24} values relative to that observed within the NFA sources.

The results further provide insight into the absorption rate properties of the FRCA. Based on these findings, it can be seen that the NFA sources achieve saturated internal moisture conditions within initial water submersions (i.e., internal water absorption is equivalent to the AC_{24} values of the NFA). FRCA, however, upon initial submersion presented, absorbed moisture values were calculated to be between 25-32.2% lower than the AC_{24} values. The findings indicate that the adhered mortar content present within the FRCA does not allow them to reach saturated moisture conditions during initial water submersion (as was observed with NFA samples). Therefore, given the highly variable nature of FRCA (i.e., varying fine RM quantities), even at 2 hours, absorbed moisture values up to 23% lower than the AC_{24} of the FRCA were observed. However, multiple trial batches indicated that after 2 hours, the absorbed moisture values were generally within 8% of the AC_{24} values for the FRCA sources.

5.3.2.1.1. Implications on Concrete Mixture Design

In terms of the effect on concrete mix design the use of FRCA within concrete, the results indicate that while FRCA sources may require significantly higher water contents to account for the increased water absorption values, the total AM testing indicates that the absorption rate of the FRCA cannot be assumed to be same as that of NFA. Given the slower absorption rate of the FRCA relative to the NFA, as per typical mix design methods, additional water may not be effectively absorbed during the concrete mixing and setting process (duration of 1-2 hours). The progressive increase in the total absorbed moisture values of the FRCA source (Figure 41b) beyond two hours indicates FRCA requires 24-hours of water submersion to achieve saturated internal (absorbed) moisture conditions (absorbed moisture values equivalent to the stated AC_{24} values), which cannot be attained during typical concrete batching/casting durations. As a result, the use of typical mix design methods such as those expressed within the current CSA A23.1-14 [3] standards for concrete mixtures with FRCA may result in excessive free water that is not absorbed by the FRCA sources.

The results indicate that FRCA may only absorb a portion of the reported AC values and, as such, mixtures may contain higher than assumed free-water contents and higher w/cm ratios. Such findings indicate that without modification, the use of the current mix design practices may introduce uncertainty in the resulting fresh concrete workability, compressive strengths and other mechanical properties. Similar studies have reported that during concrete mixing periods of 10 to 30 minutes, FRCA absorption stabilizes, reaching around 50% of its maximum absorption capacity [115]. Other studies have found that the introduction of cement and SCM's within the concrete mixture during mixing further limiting the water absorption properties of RCA and NA as the binder materials seal the aggregate pores, limiting the quantity of absorbed water [92]. However, while the extent of RCA (CRCA and FRCA) absorption-rate values reported within the literature have been inconsistent, similar conclusions stating that RCA may not reach SSD conditions given the lack of absorption during concrete mixing have been found [9,33]. Based on the findings, it is recommended for mixtures incorporating FRCA, the 2-hour absorption capacity values (AC_2) be used in lieu of the AC values for mixture design calculations to improve consistency in workability while minimizing the potential for undesired w/cm values and reductions in hardened properties.

Further visual studies were also conducted to further validate the total absorbed moisture testing results for the FRCA and NFA sources. Equal mass samples of FRCA and FNCA were placed in testing flasks filled with water. The testing flasks for all samples were then filled to the "0 ml" mark and sealed to prevent moisture loss and evaporation. The set-up of the visual study for both the FRCA and FNCA is shown in Figure 42. Upon leaving the testing samples and checked then at 2-week intervals, upon visual inspection, the results from the testing samples indicate that the water absorption of the FRCA continued throughout the testing phase (up to 2 weeks), while the absorption of the NFA specimens did not display any noticeable change after initial absorption

Figure 42-Total absorbed moisture with time after 2 weeks [Left]-FRCA [Right]-NFA

5.4. Summary

Based on the experimental findings observed within the testing of the various concrete materials (i.e., coarse and fine aggregate sources, water and cement), the following conclusions were obtained.

- Despite differences within production methods, deleterious materials or increased variability within parent concrete sourcing, all of the RCA sources for both the coarse and fine fractions presented gradations within the CSA A23.3-14 permissible guidelines for structural concrete usage.
- The coarse and fine RCA sources all presented reduced BSG, bulk density and increased absorption values compared with the natural aggregate sources, as well as reduce abrasion resistance properties. It was also found that significant variability was observed among the aggregate properties of the various RCA sources.
- It was found that the differences within the aggregate properties of the RCA relative to the NA sources and amongst the various RCA sources was attributed to differences within the residual mortar (RM) fraction of the RCA sources due to production methods and variability of the parent concrete sources used for RCA production [25,139].
- It was also observed that both freeze-thaw chemical degradation and thermal treatment methods proved effective in the determination of the residual mortar content of the CRCA sources, with similar findings observed for both methods. It was noted that thermal treatment was preferred given the similarity amongst the findings relative to freeze-thaw chemical degradation treatment as well as the significant savings in terms of testing/treatment duration.
- Despite differences amongst the properties of the NA and RCA sources, strong correlations between the residual mortar content values of the CRCA were observed with regards to the absorption (AC_{24}) and BSG properties of the CRCA sources (refer to Figure 35).
- With regards to abrasion resistance, it was found that the CRCA sources present significantly reduced abrasion values compared with the NCA source. It was reasoned that the weak bond between the OVA and RM fraction at the ITZ led to reduced abrasion resistance properties, given the propensity for separation under abrasive action.
- Total absorbed moisture testing of the fine aggregates (refer to Chapter 5.3.2.1) found that while NFA were able to achieve maximum total moisture content after initial submersion (i.e., saturated internal and absorbed moisture conditions), FRCA continually absorbed water throughout the entire testing duration (up to 24 hours).
- With regards to concrete mixture design, the total absorbed moisture testing of the FRCA indicates that FRCA may only absorb a portion of the reported AC values during typical concrete mixing and setting durations, which may result in higher than assumed free-water contents and higher w/cm ratios. It was recommended that for mixtures incorporating FRCA,

the 2-hour absorption values (AC_2) be used in lieu of the AC values for mixture design calculations to improve consistency in workability while minimizing the potential for undesired w/cm values and reductions in hardened properties.

6. MIX DEVELOPMENT AND TESTING OVERVIEW

The second stage of the experimental program consisted of the mechanical properties testing of three series of various concrete mixtures (Series A, B, and C) and select mortar mixtures developed with multiple combinations of natural and LCC materials and mixture design methods. As mentioned within Chapter 3.2.2, the Series A mixtures were developed to systematically assess the effect of LCC materials (i.e., fine and coarse RCA and GGBFS) on the fresh and hardened mechanical properties and the governing failure mechanisms of concrete and mortar specimens. It should be noted that mortar mixtures were only developed for select mixtures within the Series A mixture set and not for any further mixture series (i.e., Series B or C mixtures). The mortar mixtures were developed using the same mix design properties and mixture proportions for each respective mixture; however, the coarse aggregate fraction was omitted to assess the strength properties of the mortar specimens for further analysis and use within the experimental program. Series B concrete mixtures were developed to gauge the effect of novel mixture proportioning and mixing methods on the fresh and hardened properties of LCC and compare the experimental finding with regards to the results observed within the LCC database analysis. Series C mixtures were then developed based on the practical conclusions within the Series A and B mixtures. As a result, the Series C mixtures are presented within Chapter 7.2, although the various mixing and mixture proportioning methods utilized within the Series C mixtures are discussed briefly.

6.1. Mixture Design

6.1.1. Series A Mixtures

The Series A mixtures consisted of six different concrete mixtures per target strength classes, one (1) control mixture (NNC-A) and five (5) LCC mixtures developed with various combinations of LCC materials (CRCA, FRCA, SCM-GGBFS) for a total of 12 mixtures. Four (4) mortar mixtures were also developed per target strength to investigate further the mechanical strength of the mortar fraction within the hardened concrete structure, specifically the effect of LCC materials (i.e., fine RCA and SCM's) on the mortar characteristics. To ensure an accurate assessment of the LCC concrete specimens' mortar strength properties, the mortar specimens were developed with the same mix design (mix proportioning, mixing method and proportions) as the respective concrete mixtures while omitting the coarse aggregate fraction. The following subchapters provide an overview regarding the mixture development/proportioning of the Series A concrete mixtures. A summary of the mixture proportions for the Series A concrete mixtures is provided below within Table 14. In contrast, the mixture proportions for the mortar specimens developed for the select Series A concrete mixtures are presented separately within Table 15 for clarity.

Table 14-Mixture Proportions: Series A Concrete Mixtures

Mix-Series	Target f'c (MPa)	Mix Proportions (kg/m³)									% LCC Materials ***
		w/cm **	Water (Free)	Water (Agg.)	Cement	GGBFS	NCA	NFA	CRCA	FRCA	
NNC-A-30 *M	30	0.58	177	24	305	0	1035	752	0	0	0
RNC-A-30			177	33	305	0	0	750	935	0	47.0
NRC-A-30 M			177	67	305	0	1037	0	0	594	30.7
RRC-A-30			177	81	305	0	0	0	926	578	83.1
NNS-A-30 M			177	28	152	152	1015	832	0	0	7.1
RRS-A-30 M			177	112	152	152	0	0	836	690	91.7
NNC-A-50 *M	50	0.42	213	21	507	0	1035	505	0	0	0
RNC-A-50			213	30	507	0	0	504	935	0	48.0
NRC-A-50 M			213	50	507	0	1037	0	0	398	20.5
RRC-A-50			213	63	507	0	0	0	929	382	72.1
NNS-A-50 M			213	25	253	253	1015	570	0	0	12.1
RRS-A-50 M			213	91	253	253	0	0	836	490	86.2

M Mortar mixture also developed
*Control mixture per strength designation
**Effective water-to-cementitious materials ratio,
***Percentage of LCC materials (CRCA, FRCA and GGBFS) by weight, excludes water
Water (Free): Free-water content, Water (agg.) Additional water added to compensate for aggregate absorption

Table 15-Mixture Proportions of the Series A Mortar Mixtures

Mix-Series	Target f'c (MPa)	Mix Proportions (kg/m³)							
		w/cm**	Water ***	Cement	GGBFS	NCA	NFA	CRCA	FRCA
NNC-A-30 *M	30	0.58	177	305	0	0	752	0	0
NRC-A-30 M			177	305	0	0	0	0	594
NNS-A-30 M			177	152	152	0	832	0	0
RRS-A-30 M			177	152	152	0	0	0	690
NNC-A-50 *M	50	0.42	213	507	0	0	505	0	0
NRC-A-50 M			213	507	0	0	0	0	398
NNS-A-50 M			213	253	253	0	570	0	0
RRS-A-50 M			213	253	253	0	0	0	490

*Control Mixture

**Effective water-to-cementitious materials ratio
***Free-water content

6.1.1.1. Control Mixtures

Series A control mixtures (NNC-A) were developed for target compressive strengths (f'_c) of 30 MPa and 50 MPa based on absolute volume mixture proportioning methods as per CSA A23.1-14 standards [3]. Control mixtures (NNC-A-30 and NNC-A-50) were developed with natural coarse and fine aggregates (NCA and NFA) for interior exposure conditions (Exposure class: N, as per CSA A23.1-14 standards [3]). The development of the control mixtures involved casting several trial batches (refer to Appendix G: Trial Mixture Data), where the w/cm ratios and water content of the mixtures were adjusted incrementally, such that the compressive strength targets of 30 and 50 MPa were achieved for each of the control mixtures. Due to batch variations, aggregate moisture and overall mixture variability, compressive strengths exceeding target compressive strength by max 7.5 MPa (i.e., up to 35 and 55 MPa) for each strength class were deemed acceptable for the control mixtures during initial mixture development. After incremental adjustments, w/cm ratios of 0.58 and 0.42 were chosen for the 30 MPa and 50 MPa control mixtures. Air contents of 2% (by volume) were utilized within the mixture design of the various concrete mixtures, although the actual air content may have differed as this was not verified experimentally. Target slumps of 100 ± 25 mm were selected for the design of the control mixtures. Initial estimates for water contents were provided by the CSA A23.1-14 [3] mix design standards (based on coarse aggregate size, air entrainment and target slump values); however, were modified incrementally to achieve the required target slump values (while maintaining the specified w/cm ratios) of the mixtures. Refer to Table 14 regarding the complete mixture proportions of the control mixtures

Regarding aggregate contents, natural coarse (NCA) and fine aggregates (NFA) were used within the control mixtures and tested as per the properties provided within Chapter 5.3. Bulk volumes of 0.63 were used within the design of the control mixtures based on the gradation values of the NFA sources and nominal size of the NCA (19 mm)-refer to Chapter 5.3.1 for more details. Lastly, as per the CSA mix design specifications, the fine aggregates were proportioned based on each control mixture's remaining volumes (per cubic meter). No further additives, admixtures or mixture materials were added to the control mixtures. A summary of the mix design properties (design values) for each of the control mixtures is provided within Table 16, while a step-by-step procedure regarding the proportioning of the control mixtures is provided within Appendix C: Absolute Volume Proportioning Sample Calculation. It should be noted that while consistent free-water content values were used for the various Series A mixtures (i.e., refer to Table 14), mixture specific adjustments were made to account for the aggregate absorption and in-situ moisture content values of the aggregates prior to concrete batching/mixing for all of the prepared mixtures. Table 16 provides a summary of the mixture characteristics of the control mixtures.

Table 16-Summary of Mix Design Properties for control mixtures

Mixture	Mix Design Method	Target f'c (MPa)	Exposure Class	w/cm *	Air (%) **	Target Slump (mm)	Free Water (kg/m³) *, ***	Bulk Volume
NNC-A-30	CSA-Absolute Volume Method	30	N	0.58	2	100 ± 25	177	0.63
NNC-A-50		50		0.42			213	

* Based on incremental adjustments to achieve target strength and slump values
** Actual air content not tested, design air content values for mixture proportioning shown.
*** Additional water content adjustments conducted to account for in-situ aggregate moisture contents

As indicated in Table 14, mortar mixtures were also developed for each control mixture (NNC-A-30 and NNC-A-50). As noted, the mortar mixtures were developed using the same mix design properties and mixture proportions for each respective mixture with the coarse aggregate fraction (NA or RCA) omitted. It should be emphasized that the mortar mixtures were developed to supplement the Series A concrete mixtures and further assess the hardened mortar strength properties of the mortar specimens without the influence of the coarse aggregate fraction for further analysis and use within the experimental program. Table 15 provides a detailed overview of the mixture proportions of the various mortar mixtures developed within the experimental program.

6.1.1.2. LCC Mixtures

The LCC mixtures were comprised of various proportions of CRCA, FRCA and GGBFS. Similar to the mixture proportioning and development of the control mixtures, the Series A LCC mixtures were developed using the CSA mix design procedure as per the CSA A23.1-14 [3] mix design standards (i.e., adapted from ACI 211).

Regarding the proportioning of the coarse and fine aggregates, regardless of the differences within the aggregate properties of the RCA sources relative to the NA sources, the RCA sources (CRCA and FRCA) were used in the same manner as the NA sources with the control mixtures by substituting the aggregate properties of the NA sources with those of the RCA sources (as applicable). To ensure consistency amongst the various mixtures and to identify the effect of the LCC materials, regardless of the aggregate properties of the RCA sources (which impact aggregate proportioning only), the same free-water content, cement content, exposure class and design air content (%) were used for the proportioning of the Series A LCC mixtures for each strength class as those presented for the control mixtures for the respective target strength class. Modifications to the water or cement contents were not made (relative to the control mixture) to systematically identify the impact of the CSA mix design methods and impact of LCC materials on the fresh and hardened properties of the proportioned LCC mixtures.

Similar to the control mixtures, additional water was added to each of the LCC mixtures to account for differences within the absorption capacity and moisture contents of the in-situ aggregates at the time of mixture proportioning. Minor modifications were made to bulk volume values of the LCC mixtures (modification of 0.63→0.6) to account for differences within the gradation of the RCA sources relative to the NA sources. Regarding the proportioning of the cementitious materials, GGBFS was used to replace 50% of the total cementitious materials. Unlike the RCA, GGBFS proportioning was conducted based on equivalent mass proportioning (i.e., equivalent masses of cement and GGBFS). It should be noted that differences within the BSG of the cement and GGBFS were not considered. Mortar mixtures were also developed for select LCC mixtures (NRC-A-30, NRS-A- NRC-A-50) using the same mix design properties and mixture proportions as the respective concrete with the omittance of the coarse aggregate fraction.

6.1.2. Series B mixtures

The second set of concrete mixtures (Series B) consisted of the development and testing of 8 different LCC mixtures (i.e., 4 per strength class) as summarized below within Table 17.

Table 17-Concrete mixture proportions- Series B Mixtures

Mix-Series	Mixture Proportions (kg/m^3)									% LCC Materials ****
	w/cm *	Water**	Water***	Cement	GGBFS	NCA	NFA	CRCA	FRCA	
RNC-E-B-30	0.58	113	74	194	0	0	530	1416	0	66.2
RNC-M-B-30		154	57	265	0	0	726	1090	0	52.4
RRC-M-B-30		154	110	265	0	0	0	1090	549	86.1
RRS-M-B-30		154	109	133	133	0	0	1086	552	93.0
RNC-E-B-50	0.42	136	75	323	0	0	362	1413	0	67.3
RNC-M-B-50		185	54	441	0	0	497	1090	0	53.7
RRC-M-B-50		185	90	441	0	0	0	1090	376	76.9
RRS-M-B-50		185	91	220	220	0	0	1086	382	88.5

*Effective water-to-cementitious materials ratio,
**Free-water content, ***Additional water added to compensate for aggregate absorption,

****Amount of LCC materials (CRCA, FRCA and GGBFS) by weight, excludes water

The Series B mixtures were proportioned using the EMV and M-EMV proportioning methods as presented within literature [45,51] to maximize LCC material usage (by % weight) and evaluate the effectiveness of EMV/M-EMV proportioning in terms of the effect on the mechanical properties. Despite workability reductions often reported for LCC mixtures prepared with the EMV or M-EMV methods [14,30,51,64,107,138], no admixtures were added or water content modifications made to the Series B mixtures to ensure adequate comparison with the Series A mixtures.

It should be noted regarding fine aggregate proportioning, both the EMV and M-EMV methods were developed strictly for use with CRCA [45,51], given the inability to directly assess the RM content properties of the FRCA sources (as noted within Chapter 2.2.3.1). As noted earlier, within existing literature, the EMV/M-EMV methods have been limited in further application with additional LCC materials (i.e., FRCA and SCM's). Therefore, to further incorporate FRCA and GGBFS, within select Series B mixtures, FRCA was proportioned based on equivalent volume-replacements based on the NFA proportions, while SCM's (i.e., GGBFS) was proportioned based on equivalent weights proportioning to replace 50% of cement (similar to the Series A mixtures).

It should be noted that with the expectation of the specific mixture proportions (coarse/fine aggregates, water and cement), the Series B mixtures were develop using the same mix design properties as the Series A mixtures (i.e., exposure class, design air content, w/cm ratio). Additionally, no mortar mixtures were developed for any of the Series B mixtures. Refer to Chapter 2.2.3.1 for further information regarding the EMV and M-EMV proportioning methods. Additionally, step-by-step sample calculations of the EMV and M-EMV proportioning methods are provided within Appendix D: EMV Proportioning Sample Calculation and Appendix E: M-EMV (S=5) Proportioning Sample Calculation, respectively.

Regarding mixing methods, the Series B mixtures were developed based on the two-stage mixing approach (TSMA) [53] as summarized within Chapter 2.2.3.2. As stated prior, the TSMA consisted of adding half of the total water to the aggregates prior to the cementitious materials, promoting further water absorption by the RCA and reducing the w/cm ratio within the vicinity of the RCA [53]. Previous studies have found that the TSMA can effectively fill imperfections within the RCA structure [43,53,54] while scanning electron microscopic (SEM) analysis further found that TSMA was able to create a denser cementitious matrix and strengthen the microstructure of the CRCA [53]. Therefore to further improve the mechanical properties of the Series B mixture as well as evaluate the effect of the TSMA on the mechanical properties of the LCC mixtures relative to the normal mixing approach (NMA-i.e., CSA A23.2-2C [3] mixing standards), the TSMA was used for mixing all Series B mixtures.

6.1.3. Series C Mixtures

As mentioned at the start of the chapter, the Series C mixtures were developed based on the experimental findings observed within the Series A and B mixtures and were optimized to ensure similar mechanical performance (fresh and hardened properties) as the control mixtures developed within the Series A mixtures for both 30 and 50 MPa strength classes (i.e., NNC-A-30 and NNC-A-50). It should be noted that the design of the Series C mixtures was based on the governing failure mechanisms presented within the Series A and B mixtures (refer to Chapter 7.1.3). The mix design rationale (i.e., selection of mixture proportioning and mixing methods) for the preparation of the Series C mixtures was completed to ensure comparable properties as the control mixtures. Chapter 7.2 provides a detailed discussion regarding the mix design development for the Series C mixtures.

6.2. Concrete and Mortar Mixing, Specimen Preparation and Testing

6.2.1. Concrete Mixing

In terms of mixture preparation, although mixture designs varied among mixture sets (i.e., mixture proportioning and mixing methods), to minimize variability within the various mixtures the Series A, B and C mixtures all of the mixtures were mixed, cured and tested under standardized conditions to ensure consistency amongst the various mixtures. A rotary drum mixer with a capacity of 40 L was used for all concrete mixing, while the mortar mixtures were mixed using a 5L bowl mixer. Both mixers (as required through water spray) were pre-dampened prior to usage and thoroughly washed after mixing.

6.2.2. Workability Assessment

After mixing, the workability properties of the fresh concrete mixtures (i.e., slump) were assessed using the slump-cone testing procedure immediately following concrete mixing as per CSA A23.2-5C standards [3]. Before each slump test, the slump cone and base were pre-dampened with water to minimize concrete sticking to the surface of the base and side of the slump cone. It should be noted that the workability of the mortar mixtures was not tested during the experimental program (i.e., by use of slump flow, J-ring testing, or similar test methods) given limited implications/applicability of the slump values of the mortar specimens within further stages of the experimental program. Images from slump testing are provided in Figure 43.

(a) (b)

Figure 43-Visualization of concrete slump test

(a)-Prior to slump cone removal, (b) After removal of slump cone with measurement

6.2.3. Specimen Preparation and Curing

After slump testing, the fresh concrete mixtures were cast into cylindrical specimens of 100 mm x 200 mm (diameter x height) as shown in Figure 44 based on the specifications outlined within CSA A23.2-3C [3]. Mortar mixtures were cast using similar preparation methods as the concrete cylinders, however, cast into 50 mm cubic specimens and lightly vibrated to remove excess air. It should be noted that care was taken to avoid excessive vibration/disruption of the concrete and mortar specimens during curing to avoid unwanted segregation, bleeding or other mixture imperfections (i.e., specimen deformations and voids).

All concrete and mortar specimens were air-cured for 24 ± 6 hours prior to demolding and were either sealed (select concrete cylinders) or covered with a non-absorbent plastic sheet to prevent evaporation and moisture loss until de-moulded.

(a) (b)

(c) (d)

Figure 44-Overview of Concrete Cylinder Preparation-Casting

Filling, (b) Tamping, (c) Leveling/finishing, and (d) Sealing to prevent moisture loss

After demolding, the concrete and mortar specimens were moist cured (submerged within water) until future compressive (f'_{c7} and f'_{c}) or splitting tensile strength (f'_{ct}) testing dates 7 or 28 days after casting. Standard potable water was used for all concrete and mortar curing and was drained and replenished at 28-day intervals.

6.2.4. Hardened Properties Testing

Prior to the respective compressive ($f'c_7$ and f'_{c}) or splitting tensile strength (f'_{ct}) testing dates, the surface of the cylindrical concrete specimens was ground smooth using a standard concrete grinder to ensure a uniform loading surface, as shown within Figure 45. It should be noted that grinding of the top and bottom surfaces of the concrete specimens was only conducted for the cylindrical concrete specimens. The cubic mortar specimens were oriented such that the smooth faces were in contact with the top and bottom platens of the testing apparatus.

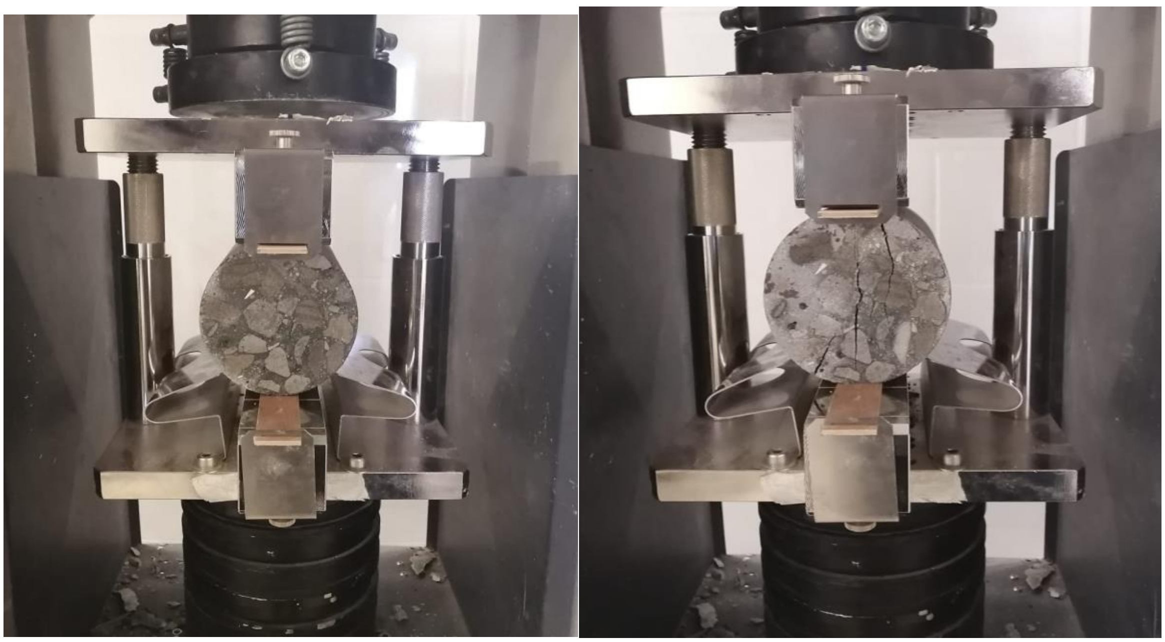
Figure 45-Grinding of concrete cylinders faces

After grinding of the concrete surfaces (cylindrical specimens only), the compressive strength (concrete and mortar specimens) or splitting tensile strength (concrete specimens only) were then tested based on the provisions outlined in CSA A23.2-9C [3] for the compressive strength-concrete cylinders or CSA A23.2-13C [3] (splitting tensile strength) of the cylindrical concrete specimens. Regarding the cubic mortar specimens, standards outlined within ASTM C109 [177] were followed regarding cubic compressive strength testing. Images of the compressive strength testing for the cubic and cylindrical specimens are shown in Figure 46, while images of splitting tensile strength testing for the concrete cylindrical specimens are shown in Figure 47.

It should be noted that given the differences within the dimensions of the various cylindrical specimens due to grinding of the top and bottom faces (refer to Figure 45), prior to compressive and tensile strength testing, the actual dimensions (height, diameter, weight) were taken to determine the actual strength values of the various specimens based on their actual dimensions.

(a) *(b)* *(c)*

Figure 46-Visualization of Concrete Cylinder and Mortar Cube Compressive Strength Testing (a)- Cylindrical Compressive Strength Test-Before, (b) - Cylindrical Compressive Strength Test-After, (c) - Cubic Compressive Strength



(a) (b)

Figure 47-Visualization of Splitting Tensile Strength Testing

(a)- Splitting Tensile Strength Test-Before, (b) - Splitting Tensile Strength Test -After failure

A summary of the testing procedures and parameters for the compressive strength and tensile strength testing of the concrete and mortar specimens is provided below in Table 18.

Table 18-Overview of Testing Procedures for Concrete and Mortar Hardened Properties Testing

Testing Property	Compressive Strength (f'_c): Cylindrical	Compressive Strength (f'_c): Cubic	Splitting tensile Strength (f'_{ct}): Cylindrical
Testing Standard	CSA A23.2-9C [3]	ASTM C109 [177]	CSA A23.2-13C [3]
Diameter (mm)	100	-	100
Height (mm)	200	50	200
Loading rate (MPa/s)	0.259	0.4 **	0.017

*Note: Actual specimen dimensions measured prior to testing,
**Loading corresponds to rate of 1KN/s

7. MECHANICAL PROPERTIES ASSESSMENT

The second stage of the experimental laboratory program consisted of the mechanical properties testing of three series of various concrete and mortar mixtures (Series A, B, and C) developed with various combinations of LCC materials and using several mixture design methods as outlined within Chapter 6. The Series A mixtures were developed to systematically assess the effect of LCC materials on the fresh and hardened mechanical properties and the governing strength properties (i.e., governing strength mechanisms) of concrete and mortar specimens. The Series B mixtures were developed to investigate the mechanical properties of LCC mixtures incorporating high percent replacement of natural materials with LCC materials that were designed with novel mixture optimization methods. The design of the Series C mixtures was based on the findings observed within the Series A and B mixtures. As a result, the Series A and B mixtures are discussed first, followed by the mixture development and optimization of the Series C mixtures.

7.1. Series A and B Concrete Mixtures: Results and Discussion

The fresh and hardened properties of the Series A and B concrete and mortar mixtures (slump, compressive strength, splitting tensile strength and hardened density) are summarized in Table 19. It should be noted that the properties of the RNC-E-B-50 mixture were not omitted as the mixture was found to be unworkable and unable to be compacted into cylindrical specimens for further testing.

Table 19-Fresh and hardened concrete properties-Series A and B Mixtures

Mix-Series	Concrete Properties (MPa)							Mortar Properties (MPa)			% LCC Materials **
	w/cm	Slump (mm)	f'c7 (MPa)	f'c (MPa)	f'c7/f'c	f'ct (MPa)	Density (kg/m³)	f'c7 (MPa)	f'c (MPa)	f'c7/f'c	
NNC-A-30*	0.58	90	20.6	34.2	0.60	3.48	2464	27.7	37.6	0.735	0
RNC-A-30		75	21.2	28.8	0.74	3.25	2293	-	-	-	47.0
NRC-A-30		165	15.3	20.7	0.74	2.63	2266	15.0	18.3	0.823	30.7
RRC-A-30		130	13.6	17.8	0.77	2.19	2111	-	-	-	83.1
NNS-A-30		110	21.9	34.9	0.63	3.82	2398	37.7	44.8	0.842	7.1
RRS-A-30		150	9.8	17.3	0.57	1.97	2075	19.1	22.6	0.845	91.7
RNC-E-B-30		5	4.0	8.4	0.48	0.96	1322	-	-	-	66.2
RNC-M-B-30		15	17.4	25.8	0.68	2.88	2293	-	-	-	52.4
RRC-M-B-30		50	14.4	18.6	0.77	2.17	2129	-	-	-	86.1
RRS-M-B-30		55	11.0	17.8	0.62	2.38	2124	-	-	-	93.0
NNC-A-50*	0.42	105	44.7	56.8	0.79	4.05	2446	46.3	63.0	0.735	0
RNC-A-50		65	27.1	33.4	0.81	3.18	2257	-	-	-	48.0
NRC-A-50		130	28.3	36.5	0.77	3.49	2323	37.8	43.9	0.859	20.5
RRC-A-50		145	22.7	31.7	0.72	3.01	2201	-	-	-	72.1
NNS-A-50		130	36.2	52.0	0.70	4.37	2371	51.0	56.8	0.898	12.1
RRS-A-50		150	20.2	29.6	0.68	2.62	2098	34.3	37.9	0.905	86.2
RNC-E-B-50		0	-	-	-	-	-	-	-	-	67.3
RNC-M-B-50		25	29.9	36.1	0.83	3.39	2296	-	-	-	53.7
RRC-M-B-50		15	25.1	31.0	0.81	2.85	2217	-	-	-	76.9
RRS-M-B-50		45	22.0	29.3	0.75	3.07	1841	-	-	-	88.5

*Control mixture per strength designation,
** LCC materials by weight

7.1.1. Fresh Concrete Properties

The slump values for all of the various concrete are presented in Table 19. Based on the results, a comparison of the Series A and B mixtures indicated that the use of LCC materials and modified mixture design methods led to significant workability fluctuations, which led to a wide variety of slump values among the Series A and B mixtures

7.1.1.1. Effect of CRCA Replacement and Mix Design Methods

The measured slump values for mixtures involving 100% replacement of NCA with CRCA (i.e., RNC-A-30 and RNC-A-50 Series A mixtures) were 17 to 38% lower than the respective control mixtures. It should be noted that despite the larger quantities of additional water added to the RNC-A-30 and RNC-A-50 mixtures relative to the respective control mixtures to compensate for the greater absorption capacity of the CRCA, the observed slump values indicate that the use of 100% CRCA led to reduced slump values. Comparing the findings to those reported in the literature indicates similar slump reductions also reported for mixtures developed with CRCA [37,38,82,110,111]. Many studies have reasoned that the morphology (i.e., presence of residual mortar) and higher water absorption capacity of the CRCA sources may result in significantly faster water absorption rates compared with the NCA, which may contribute to decreased free-water content and reduced slump values as observed [38,82,110]. Additionally, further studies have also found that the reduced slump values for the LCC mixtures comprised of CRCA may also be attributed to the increased angularity and roughened surface texture of the CRCA particles compared with the NCA particles. As a result, CRCA usage may have increased inter-particle friction within the fresh concrete mixtures, resulting in the reduced slump values compared with control mixtures comprised of NCA [37,111]. Visual comparison of the coarse and fine aggregates from the NCA and CRCA sources supports previous findings stating that the RCA's increased angularity and aggregate properties may have negatively reduced the fresh properties of concrete mixtures [37]. Further comparison of the aggregate properties, especially residual mortar content and increased water absorption capacities of the CRCA relative to the NCA, highlight how the higher absorption properties of the CRCA sources may significantly impact the fresh concrete properties of mixtures given the increased water absorption characteristics of the CRCA.

In terms of the Series B mixtures, the sole use of CRCA within the RNC-E-B-30, RNC-E-B-30 (30 MPa mixtures) and RNC-E-B-50, RNC-E-B-50 (50 MPa mixtures) also led to significant slump reductions which were between 83 and 95% lower compared with the respective control mixtures. Although aggregate morphology (i.e., residual mortar), increased absorption capacity, and surface angularity/texture [37,38,82,110,111] may have impacted the slump values, the reduced slump values of the Series B mixtures can be primarily attributed to free-water content reductions from EMV/M-EMV proportioning [44,50,52,107] as well as the nature (i.e., process) of the TSMA utilized during mixing. Compared with the absolute volume mixture proportioning method used to develop the Series A mixtures, EMV/M-EMV proportioning for the Series B mixtures led to a significant reduction in the required free-water content of the mixtures. As a result, it can be reasoned that this reduction in free water content contributed towards the reduced workability of the mixtures regardless of LCC material incorporation (i.e., CRCA, FRCA or GGBFS usage).

Results within literature have also found that the reduced free-water content within EMV/M-EMV proportioned mixtures leads to reduced slump values, often requiring super-plasticizing agents or high-range water-reducing admixtures (HRWA) to improve workability and mixture compaction [44,50,52,107]. The use of TSMA, in addition to the reduced free-water content from EMV/M-EMV proportioning, further reduced the workability values of the Series B mixtures by allowing for further water absorption by the aggregates during the mixing process. As stated, the TSMA requires mixing the in-situ aggregates, followed by adding 50% of the total water content, cementitious materials, and lastly, the remaining 50% of the total water content, with mixing intervals in-between successive material addition [53]. The initial mixing of the aggregates with a fraction of the total water proportions results in reduced free-water contents within the fresh mixtures due to absorption of the initial water by the aggregates [53]. In contrast, the CSA A23.2-2C [3] mixing methods used when batching the Series A mixtures involve the simultaneous mixing of all mixture materials (aggregates, cement/GGBFS and water), limiting the amount of water absorbed by the aggregates (RCA and NA) during mixing. Within the CSA A23.2-2C mixing method, the subsequent introduction of the cement/GGBFS has been observed to effectively seal aggregate pores, limiting water absorption and resulting in higher workability values [92]. As a result, the increased water absorption by the aggregates within the Series B mixtures led to significant slump reductions. In contrast, the Series A LCC mixtures presented increased slump values than the conventional concrete mixtures despite the same theoretical free-water contents due to the limited water absorption by the aggregates during the mixing process. It can be reasoned that while the Series B mixtures presented reduced slump values, the use of TSMA led to improved water absorption as well as improved free-water content/mixture proportion accuracy given the improved water absorption of the RCA compared to the Series A mixtures.

7.1.1.2. Effect of FRCA Replacement and Mix Design Methods

Regarding the mixes containing FRCA (i.e., NRC-A, RRC-A, RRS-A, RRC-M-B and RRS-M-B) for both strength designations, unlike the mixtures solely containing CRCA, it was found that the use of FRCA resulted in slump values that were 24 to 83% higher than the respective control mixtures. In addition, higher slump values were also found for mixtures containing both coarse and fine RCA relative to mixtures only containing CRCA or FRCA, except for RRC-M-B-50, which can be attributed to slight delays within slump readings after mixing (i.e., 2-3 minutes) resulting in further absorption by the aggregates. Based on the experimental observations, it can be reasoned that the increase in slump for FRCA mixtures can be attributed to the additional free-water content within the fresh concrete mixtures due to inaccuracies within the quantities of additional water added within the mixtures to compensate for aggregate absorption and the amount of water absorbed by the aggregates during mixing.

Such phenomenon can be explained based on the total absorbed moisture findings for the FRCA and NFA sources reported in Chapter 5.3.2. Experimental testing revealed that, when submerged in water, the NFA sources did not significantly absorb water beyond a period of five minutes, indicating that the NFA were able to achieve 100% of their total absorption (i.e., AC_{24} =1.51%) during typical concrete mixing periods. This property then ensures the attainment of desired free-water content and w/cm values. In contrast, the total absorbed moisture results for the FRCA indicated that the FRCA sources continually absorb water beyond the duration of typical concrete mixing (i.e., 5 to 15 mins), requiring 24 hours to achieve saturated moisture conditions (refer to Figure 41). As a result, additional water proportioned to compensate for aggregate absorption of the FRCA does not truly represent the quantity of water that the FRCA can absorb during mixing. As a result, the free-water content of the mixtures incorporating FRCA was reasoned to be greater than the anticipated free-water value, resulting in increased slump values that were observed relative to the mixtures containing only CRCA. It can also be reasoned that the higher free-water content of these concrete mixtures led to an increase in the w/cm ratio, which reduced their associated compressive strength and splitting tensile strength.

Given the inability of the FRCA sources to absorb water quantities equivalent to the AC_{24} values, it is recommended that the TSMA or modified water proportioning methods be used when batching concrete mixtures containing FRCA to enable further water absorption and ensure that the actual water absorption properties of the aggregates are accounted for during concrete mixing. Additionally, based on the total absorbed moisture values of the FRCA sources, it is further recommended that the 2-hour absorption values (AC_2) be used in lieu of the AC_{24} values to adequately account for the limited water absorption properties of FRCA during the concrete mixing/setting duration (max of 2 hours), to ensure consistency in the workability and predictable slump values. Additionally, given the observed slump properties for the Series A mixtures, it is suggested that the water compensation/mixing methods specified in CSA A23.2-14 [3] may not be suitable for use in LCC mixtures as they may lead to higher slump values and reduced compressive strength. It is therefore suggested that TSMA be utilized instead.

It should be noted that while further design modifications have been suggested within literature studies to improve workability, such as pre-soaking of the RCA before mixing, previous studies by Mefteh et al. [109] have found that vibration of pre-soaked aggregates may result in excessive bleeding of the resulting mixtures. Further investigation found that bleeding of water within the mixtures lead to a weakened interfacial transition zone (ITZ) between the RCA and the cementitious matrix by locally increasing the w/cm at the ITZ [109], which resulted in reduced mechanical strength performance (i.e., compressive strength and tensile strength properties) of such mixtures [109]. As a result, although beneficial for slump, presoaking of the aggregates is not recommended; rather, based on the results from the experimental program, it is recommended that use of the TSMA and 2-hour absorption values (AC_2) be utilized to ensure predictable slump values while minimizing the possibility for further mechanical strength reductions.

7.1.1.3. Effect of GGBFS Replacement

Incorporating GGBFS in Series A (i.e., NNS and RRS) mixtures increased the measured slump values by 3 to 24% compared with similar mixes with the same aggregate and water proportions (i.e., comparing NNS with NNC and RRS with RRC). While for the Series B mixtures, despite overall lower slump values, the additional incorporation of 50% slag cement was found to increase slump values by 10 to 66% for mixes with the same aggregate and water proportions (comparing RRC-M-B with RRS-M-B). This improved workability may be attributed to the smooth surface characteristics, improved dispersion characteristics, and increased fineness of the GGBFS particles compared with OPC [36,92].

7.1.2. Hardened Concrete Properties

Based on the hardened properties presented in Table 19, the incorporation of RCA and GGBFS presented large fluctuations in both the f'_c and f'_{ct} with significant reductions from those of the control mixtures observed. The 7- and 28-day compressive strength and 28-day splitting tensile strength results for the concrete specimens of the Series A and B mixture is presented within Figure 48 to allow for visual comparison of the various mechanical properties.

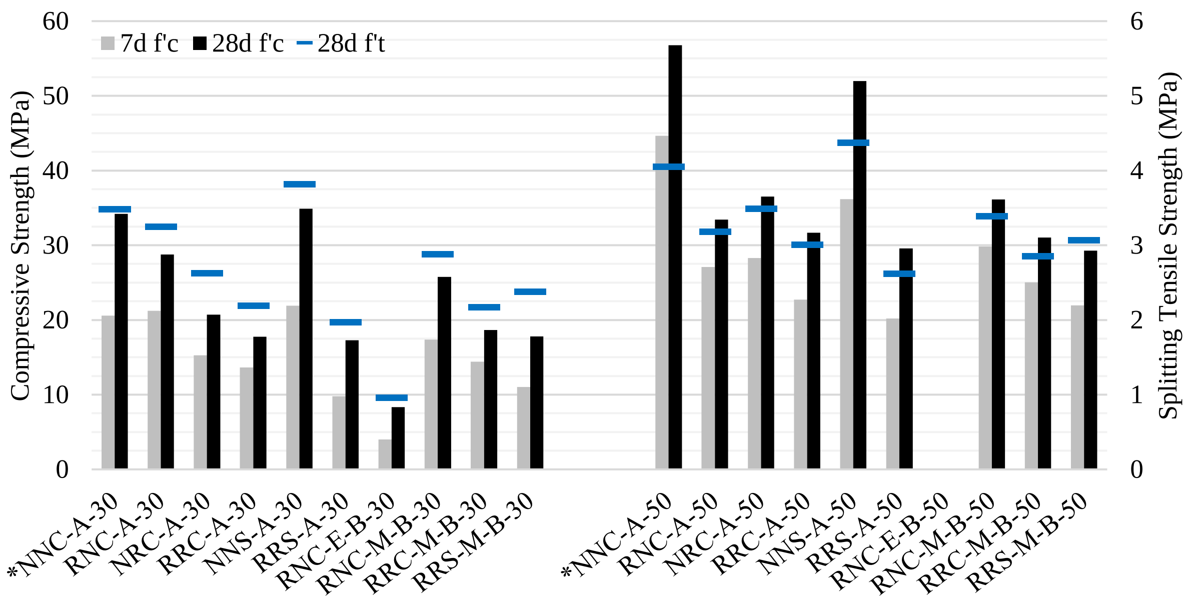


Figure 48-Concrete Compressive Strength (f'_c) and Splitting Tensile Strength (f'_{ct}) Results

**Control Mixtures per strength designation*

7.1.2.1. Compressive Strength

7.1.2.1.1. Effect of RCA

The effect of RCA on the compressive strength properties was highly dependent on both the target strength class of the concrete (30 or 50 MPa) and the respective mixture proportioning method. For the 30 MPa targets strength mixtures, the sole use of CRCA (RNC-A-30 and RNC-M-B-30) resulted in up to 3% higher f'_{c7} values, while marginally lower f'_{c} values ranging between 15 to 25% lower were observed relative to the control mixtures. For the 50 MPa target strength mixtures, the use of CRCA regardless of proportioning method within the Series A and B mixtures (RNC-A-50, RNC-M-B-50) resulted in significantly f'_{c7} and f'_{c} reductions ranging from 33 to 41% lower than those reported for the respective control mixtures.

In terms of the mixtures containing 100% FRCA, it was observed that the effect of FRCA was also highly dependent on the target compressive strength of the developed mixtures (30 or 50 MPa). For the 30 MPa targets strength mixtures, the isolated use of FRCA (NRC-A-30) resulted in f'_{c7} and f'_{c} reductions up to 26% and 39%, respectively. Significant compressive reductions were also observed for the 50 MPa target strength mixtures, similar to those reported for NRC-A-50. However, as noted previously within Chapter 7.1.1, the observed slump increase within the Series A mixtures containing FRCA (NRC-A-30 and NRC-A-50) indicate a lack of absorption by the FRCA despite the significantly higher water absorption properties of the aggregates and the proportioning of the additional mixing water based on the AC_{24} values of the FRCA (as required within the current CSA A23.2-14 mixing practices [3]). Consequently, the increased free-water contents of the mixtures can be reasoned to have also impacted the strength properties by increasing the w/cm ratio of the mixture (due to higher free-water contents), leading to reduced mechanical strength properties of the concrete mortar.

Further analysis of the compressive strength properties of the mortar specimens for the Series A LCC mixtures made with FRCA (i.e., NRC-A-30 and NRC-A-50) further support that the increased slump values of the mixtures (attributed to the increased free-water contents) also led to reduced mortar compressive strength values given the increased w/cm ratios of the various mixtures (refer to Table 19).

In terms of mixtures containing both CRCA and FRCA, further reductions in f'_{c7} and f'_{c} were observed regardless of target strength class relative to the RNC-A and NRC-A mixtures for both target strength classes. For the 30 MPa target strength class Series A mixtures (RRC-A-30), the combined incorporation of CRCA and FRCA lead to minor reductions in compressive strengths beyond that observed within the mixtures containing only FRCA (NRC-A-30); however, given the magnitude and variability within results, such findings can be considered to be insignificant and attributed to variability mixture proportions (i.e., water absorption). In terms of the 50 MPa target strength class Series A mixtures (RRC-A-50), the incorporation of CRCA and FRCA did not significantly impact the compressive strengths compared with mixtures containing only CRCA (RNC-A-50), although significant reductions were observed relative to compressive strength values presented within the NRC-A-50.

Based on the experimental findings, it can be reasoned that specific to each strength class, the further incorporation of additional LCC materials (by weight) does not necessarily result in further compressive strength reductions. Further, CRCA and FRCA usage was observed not to constitute further reductions; instead, the isolated use of either aggregate fraction (based on the target strength class) governed the resulting strength properties of the mixtures as the further incorporation of RCA did not present reductions beyond those observed for the NRC-A-30 mixture (30 MPa target strength class) or RNC-A-50 (50 MPa target strength class).

7.1.2.1.2. Effect of GGBFS

Regarding mixtures containing portions of Portland cement and GGBFS (50% by weight each), marginal compressive strength reductions were measured regardless of strength class. It was observed that 2% higher f'_c values were observed within the NNS-A-30 concrete mixtures, although such changes can be considered insignificant in terms of a structural-design standpoint. It was found that the use of GGBFS did lead to reduced f'_{c7} values, which can be attributed to the slower strength development properties of GGBFS compared with OPC [36,134].

When comparing the effect of various mixture proportioning methods, the measured compressive strength of the Series B mixtures indicates contrary to results presented within the literature, use of EMV or M-EMV proportioning, combined with the TSMA did not lead to significant compressive strength increases. Specific to the mixtures prepared with the EMV, it was observed that EMV proportioning (i.e., RNC-E-B-30 and RNC-E-B-50) led to uncharacteristic compressive strength properties, which were found to result in the lowest compressive strength values regardless of the targets strength class of the mixtures. Consideration of both the workability and compressive strength properties indicates that the compressive strength reductions within the EMV proportioned mixtures can be attributed to the poor compaction quality and excessive voids present within each of the mixtures. It can be reasoned that the limited free-water content (113-136 kg/m^3) and high CRCA content (i.e., 1413 and 1416 kg/m^3) of the EMV proportioned mixture led to very ‘coarse mixtures' which attributed to the lack of mixture workability due to the limited mortar volumes of the mixtures (i.e., the sum of V_{water}, V_{cement} and $V_{fine\ agg.}$) as reported previously within Table 3. As a result, the RNC-E-B-30 and RNC-E-B-50 mixtures were found to lack cohesion between coarse aggregate particles with excessive voids, honeycombing and limited strength properties observed within the prepared cylinders, resulting in the limited (RNC-E-B-30) or lack of quantifiable compressive strength properties (RNC-E-B-50). Given the uncharacteristically poor compressive strength properties observed, the RNC-E-B-30 and RNC-E-B-50 mixtures were not considered within further sections of the analysis given the poor quality of the mixtures and lack of use within any structural setting.

7.1.2.1.3. Effect of Novel Mix Design Methods-Series B Mixtures

With regards to the M-EMV proportioned mixtures, it was observed that in the case of the 50 MPa target strength mixtures, use of M-EMV proportioned along with the TSMA during mixture preparation of the respective Series B mixtures did lead to 8% higher compressive strength values within the mixtures containing CRCA (RNC-M-B-50 relative the RNC-A-50). With regards to the further Series B mixtures, no compressive strength benefits were observed using M-EMV proportioning and TSMA methods, given the similarities between the reported compressive strength values and those of the Series A mixtures were achieved. It should be noted that from a sustainability perspective, the reduced cement contents of the Series B mixtures and similar compressive strength performance as the companion Series A mixtures demonstrate the sustainability benefits provided by the use of the M-EMV and TSMA.

7.1.2.2. Splitting Tensile Strength

In terms of splitting tensile strength, similar findings as those observed for compressive strengths were also found. Regarding the use of CRCA or FRCA, it was found that the effect of RCA usage was highly dependent on the target strength class (30 or 50 MPa) of the concrete mixtures regardless of the mix design method.

Within the 30 MPa target strength class, the sole use of CRCA within the Series A mixtures (RNC-A-30) was found to result in minor tensile strength reductions of 6.6%, while the further use of FRCA within the Series A mixtures (NRC-A-30, RRC-A-30) resulted in tensile strength reductions of 24.4 % and 37.1% respectively relative to the control mixture. By comparison, within the 50 MPa target strength class, reductions up to 21.4% were measured for mixtures with CRCA only (RNC-A-50), while tensile strength reductions ranging from 13.8% and 25.6% were observed within the Series A mixtures containing FRCA (i.e., NRC-A-50 and RRC-A-50). It should be noted that while the combined use of CRCA and FRCA did lead to further tensile strength reductions regardless of the strength class of the mixture, similar to the compressive strength for the 30 MPa target strength mixtures, the incorporation of CRCA and FRCA (RRC-A-30) did not present significantly lower tensile strengths beyond that observed within the mixtures developed with just FRCA (NRC-A-30). While for the 50 MPa target strength mixtures, the incorporation of CRCA and FRCA (RRC-A-50) did not significantly further reduce tensile strengths beyond that observed within the mixtures developed with just CRCA (RNC-A-50), indicating that the further incorporation of LCC materials (by weight) does not necessarily result in further tensile strength reductions.

Regarding the use of GGBFS, it was generally found that the replacement of 50% cement with GGBFS within the Series A mixtures reduced tensile strength further for mixtures containing RCA, tensile strengths that were found to be 7.9% to 9.7% higher for mixtures containing NA (i.e., NNS-A) relative to the control mixtures. In the case of the Series B mixtures, it was generally found that while the use of M-EMV and TSMA methods did not lead to compressive strength values improvements; the Series B mixtures presented improved tensile strength values relative to the Series A mixtures despite no significant compressive benefits observed within the Series B mixtures.

Further analysis was also conducted to evaluate the relationship between the square root of compressive strength properties ($\sqrt{f'c}$) and the tensile strength ($f'ct$) for the various LCC mixtures within the Series A and B mixtures shown within Figure 49. It should be noted that the square root of compressive strength properties were utilized given the existing relations expressed within the current CSA A23.3-14 [68] and ACI 318-14 [5] concrete design standards with regards to the modulus of rupture (i.e., Equation 2 and Equation 3), which relate the modulus of rupture values to the square root of compressive strength properties (CSA A23.3-14: Cl 8.6.4 [68] and ACI-318-14: Cl 19.2.3 [5]).

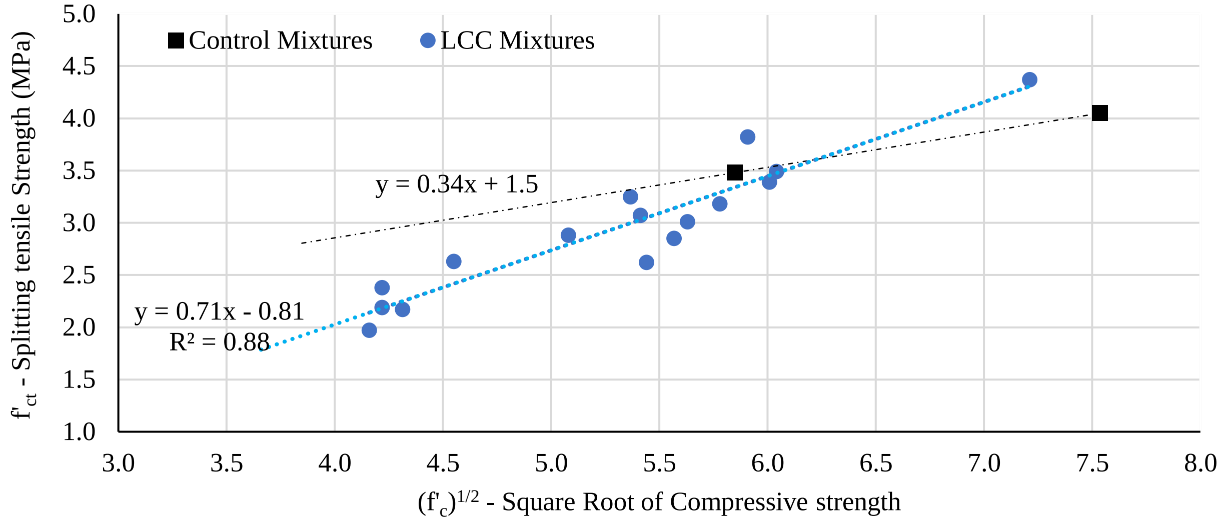


Figure 49-Relationship between f'_{ct} and the $\sqrt{f'_c}$

The results indicate that regardless of the differences within the mechanical properties, mix design methods or LCC material usage (CRCA, FRCA or GGBFS incorporation), a linear relationship between f'_{ct} and $\sqrt{f'_c}$ was observed as shown within Figure 49. It was observed that while the use of LCC materials may impact the resulting compressive and splitting tensile strengths, the linear relationship between the f'_{ct} and $\sqrt{f'_c}$ properties as expressed within the current CSA A23.3-14 [68] and ACI 318-14 [5] concrete design standards may still be applicable for LCC concrete mixtures. Such findings indicate that despite substituting conventional concrete materials with LCC material alternatives, LCC presents similar mechanical strength relations as those observed within conventional concrete mixtures, reasoning that the use of existing conventional concrete relations may be applicable and valid regarding the design of LCC concrete elements. It should be noted that the $f'_{ct} – \sqrt{f'_c}$ slope for the LCC mixtures is steeper relative to the control mixtures', indicating that the splitting tensile strength of LCC mixtures may be more sensitive to $\sqrt{f'_c}$ (and f'_c) changes compared with mixtures proportioned with conventional materials.

7.1.3. Governing Failure Mechanisms

Regarding the governing failure mechanisms of the reported LCC mixtures, the Series A mixtures allow for a systemic and logic-based assessment of the impact of various LCC materials given the systematic mixture development method and isolated and combined incorporation of individual multiple LCC materials. As the effect of individual LCC materials can be logically determined and assessed based on their effect on the governing failure/strength mechanisms of the observed LCC mixtures. Therefore, regarding the governing failure/strength mechanisms, the following observations present the governing mechanical strength behaviour of the 30 and 50 MPa target strength classes.

Regarding the 30 MPa target strength concrete mixtures, it was observed that the isolated incorporation of CRCA led to insignificant and otherwise minor implications on the mechanical properties, while the isolated use of FRCA or combined use of FRCA with CRCA presented significant mechanical strength reductions. Further inspection of the mechanical strength findings for the mixtures comprised with FRCA only and the combined use of CRCA and FRCA indicate that regardless of the further incorporation of additional LCC materials (i.e., CRCA and FRCA) does not lead to progressive mechanical strength reductions beyond those observed with the isolated incorporation of FRCA. Based on the findings, it can be reasoned that regardless of the inferior aggregate quality and aggregate properties of the CRCA source relative to NCA, the mortar fraction of the hardened concrete mixture serves as the limited strength contributor and governs the failure mechanisms of the 30 MPa target strength mixtures.

Analysis of the compressive strength properties of the mortar specimens further indicates that FRCA usage results in significant compressive strength reductions relative to the control mixtures. As a result, using a logic-based systematic analysis, it can be proposed that with regards to the 30 MPa target strength mixtures, the strength properties are governed by the strength of the mortar phase and are adversely affected by the incorporation of FRCA.

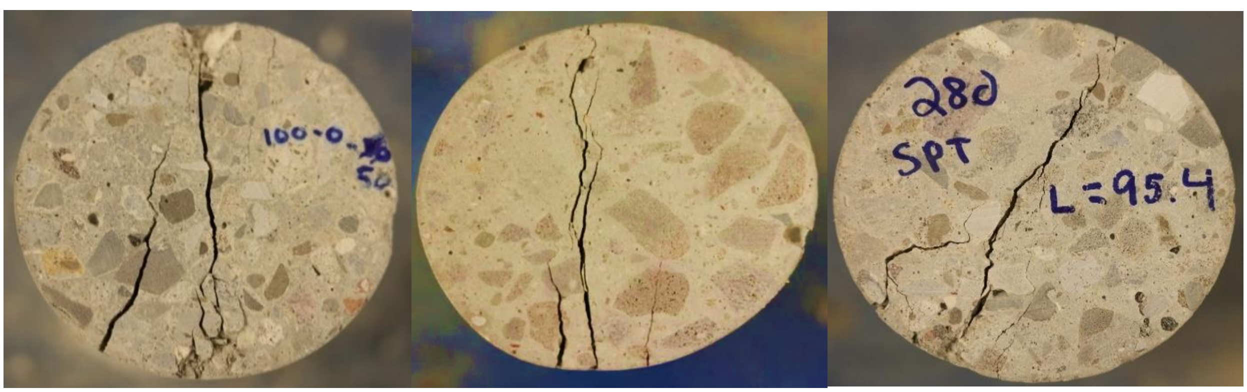
In the case of the 50 MPa target strength class mixtures, opposite to the 30 MPa target strength class, significant compressive and splitting tensile strength reductions were observed regarding mixtures with the isolated incorporation of CRCA (RNC-A-50). In the case of FRCA incorporation, comparatively higher strength properties were observed as in the case of the NRC-A-50 mixture, although reductions were still observed with regards to the control mixture (i.e., NNC-A-50), however with regards to the combined use of CRCA and FRCA (RRC-A-50) no further mechanical strength reductions were observed beyond those presented within the NRC-A-50 mixture despite the combined use of both CRCA and FRCA. Comparison of the compressive strength properties of the mortar specimens for the 50 MPA target strength class further indicates that relative to the control mixtures, the use of FRCA did not present any significant compressive strength reductions. It should be noted that while minor compressive strength reductions were observed with regards to the mortar and concrete specimens using FRCA (i.e., NRC-A-50), such reductions can be attributed to increased higher free-water contents, thus increased w/cm ratios as evident by the increased slump values presented. It should be reiterated that although the slump values of the mortar specimens were not tested (due to the lack of further structural implications), identical mixture proportions used in the preparation of companion concrete and mortar mixtures indicates that attributing factors towards the increased slump values of the concrete mixtures can also be applied to the companion mortar specimens. Given the significant mechanical strength reductions presented within the RNC-A-50 concrete mixtures, the lack of further reductions presented within the RRC-A-50 mixture and supporting f'$_c$ of the mortar specimens indicate that the mechanical properties (50 MPa target strength class) were governed by the strength characteristics of the coarse aggregates, and adversely affected CRCA usage.

Further qualitative visual inspection was conducted on the fracture patterns/paths observed within the splitting tensile specimens for the 30 and 50 MPa target strength class mixtures as shown within Figure 50 and Figure 51, respectively, to further assess the failure mechanisms presented within the Series A mixtures.

(a) (b) (c)

Figure 50-Crack Patterns: 30 MPa Mixtures (a) RNC-A-30, (b) NRC-A-30 (c) RRC-A-30

Note: Primary fracture path observed to occur around coarse aggregates and through concrete mortar.



(a) (b) (c)

Figure 51-Crack Patterns: 50 MPa Mixtures, (a) RNC-A-50, (b) NRC-A-50 (c) RRC-A-50

Note: Primary fracture observed to occur through the coarse aggregate.

Inspection of the crack patterns within the 30 MPa target strength mixtures (Figure 50) found that a strong aggregate-weak mortar strength mechanism was present within the tested mixtures (RNC-A-30, NRC-A-30 and RRC-A-30) as the observed tensile cracks were found to propagate around the coarse aggregate primarily. Within Figure 50, it can be seen that mortar of the various mixtures is prone to fracture under loading, regardless of coarse aggregate source, further reaffirming the presence of a weak-aggregate-strong mortar strength mechanism with the 30 MPa strength mixtures. In contrast, within the 50 MPa target strength mixtures (Figure 51), a weak aggregate-strong mortar strength mechanism was observed within the tested mixtures (RNC-A-50, NRC-A-50 and RRC-A-50) as the observed tensile cracks were found to propagate through the coarse aggregate fractions, regardless of the use of NCA or CRCA usage. The observed cracking indicates that the coarse aggregates govern the resulting strength properties and can be considered the weak link that governs the mixture's strength properties. Similar observations have also been reported within literature, with studies by Fathifazl et al. [51] finding that compressive strength properties depended on the strength of mortar and ITZ. While other studies have reported that for w/cm ratios above 0.45, the effect of the inclusion of CRCA on the compressive strength properties becomes negligible while at lower w/cm ratios (approximately 0.40 as found within other studies) [92], the strength properties of the ITZ (CRCA) governs the strength properties of the mixture [31,54,77,78,92].

Based on these results, to limit the negative impact of various LCC materials on the structural performance of LCC mixtures, it is recommended that CRCA be limited to concretes where the compressive strengths are not governed by the coarse aggregate strength and in the case of the experimental findings, w/cm ratios of 0.58 or higher. Although other recommendations are presented within literature such as those discussed previously, given the propensity for CRCA fracture at applied stresses beyond 35 MPa (as observed within the experimental findings) as well as the observed weak aggregate-strong mortar strength mechanisms outlined above, it advised that CRCA be limited to mixtures with target strengths ≤ 30 MPa. It should be noted that while compressive strengths upwards of 35 MPa were achieved for the RNC-M-B-50 mixture (f'_c =36.1 MPa), given the variable nature of RCA sources, the impact of CRCA on the mechanical properties as well as the less than ideal curing conditions within industrial applications (i.e., air-curing or wet), CRCA incorporation be limited to mixtures with relatively high w/cm ratios (0.58 or higher based on experimental findings). It should be re-emphasized that given the unknown nature and strength properties of CRCA characteristic of RCA sources, the conclusions provided may not be suited for all CRCA sources, rather shall be used a general guideline based on the results specific to the current experimental program as evident by contrasting results presented among existing literature [31,54,77,78,92].

Regarding the use of FRCA, based on the results observed within the experimental findings, it is recommended that FRCA be suitable for use within mixtures where the mortar fraction does not govern the compressive strengths as in the case of mixtures with ‘high’ target compressive strengths and low w/cm ratios (≤ 0.42 based on experimental findings). Given the weak mortar-strong aggregate governing strength mechanism and the negative impacts of FRCA usage at high w/cm ratios, it is recommended that mixtures incorporating FRCA be proportioned to ensure that the mortar's strength does not govern the resulting f’c properties unless sufficient strength (target strengths) can be developed before failure. Based on the results presented within the experimental program, mixtures proportioned with w/cm ratios ≤0.42 would ensure suitable strength within the mortar fraction and minimize the negative influence of FRCA on the mechanical properties of the proportioned LCC mixtures, evident by the compressive strength properties of the mortar specimens.

It should be clarified that while compressive and tensile strength reductions were observed within the mixtures proportioned with FRCA, such reductions can be attributed to the increased free-water contents and higher w/cm ratios of the mixtures due to the limited water absorption by the aggregates during mixing. Therefore in terms of mixture modifications to compensate for the lack of accuracy regarding the water absorption characteristics of FRCA and effect on the mechanical properties, the use of lower w/cm ratios or the partial replacement of FRCA may effectively be used to compensate for any reductions due to FRCA and further LCC material incorporation on the mechanical properties of LCC mixtures as found within numerous studies [26,28,30,32,35,46,116].

It should be highlighted that while reductions of the w/cm ratio and partial replacement of RCA may lead to improved mechanical properties of the resultant LCC mixtures, such design methods may reduce the overall sustainability benefits and GHG/CO_2 savings attributed to LCC material incorporation, contradicting the entire design philosophy associated with LCC mixtures. Additionally, it should be noted that the modification of the mixtures through the modification of the w/cm ratios and partial replacement of LCC materials may further introduce unnecessary variability within the mixture properties (fresh and hardened properties).

7.1.4. Sustainability Considerations

In terms of a sustainability perspective, the results presented within Table 19 can be used to provide a basic understanding of the sustainability properties of various LCC mixtures. Given the proposed failure mechanisms found to govern the mechanical strength properties, it can be concluded that the further incorporation of CRCA and FRCA (RRC-A-30 or RRC-A-50) does not result in compressive or tensile strength reductions beyond those observed with FRCA (NRC-A-30) or CRCA (RNC-A-50) (i.e., 30 and 50 MPa strength class respectively). From a sustainability perspective, increased LCC materials contents can be utilized to improve the sustainability aspects of the mixture without a progressive reduction within mechanical properties. The experimental findings indicate that increasing RCA content does not necessarily impact the mechanical properties of the mixtures further and can be utilized to improve the recycled material content with the mixtures and improve the overall sustainability properties in terms of carbon emissions and energy demand perspective. Similar conclusions can also be drawn for the mixtures incorporating 50% GGBFS (RRS-A-30 and RRS-A-50) with limited further reductions observed despite substituting half the total cement content with GGBFS in each of the respective mixtures.

In terms of mix design methods-in terms of mixture proportions, the Series B mixtures proportioned with the M-EMV method presented considerably lower cement contents than the Series A mixtures proportioned with the CSA standards mix proportioning method (i.e., CSA A23.1-14 [3]). Additionally, amongst companion mixtures with the Series A and B mixtures, those proportioned with the M-EMV method presented the highest LCC materials contents (by % weight) as indicated within Table 19 (i.e., comparison of RRS-A with RRS-B, etc...). As noted within Table 3, the EMV-based methods treat the RM fraction of the CRCA source as a cement replacement. Although the M-EMV method introduces an S-factor considering a portion of the RM fraction [45,51], such mixtures were still proportioned with significantly lower cement quantities relative to the Series A mixtures (i.e. absolute volume method) and were able to achieve comparable mechanical strength properties to the Series A mixtures despite lower overall cement contents.

Although the benefits of the M-EMV proportioned mixtures from a cement usage perspective are significant, the specific examination of the cement quantities exclusively does not provide an overall indication regarding the sustainability of the mixture given the limited consideration of the strength properties (i.e., f'_c or f'_{ct}) of the mixtures. Therefore, to provide an adequate measure of the environmental sustainability of the concrete while providing considerable of the mechanical strength properties, as shown in Figure 52, the cement: compressive strength ratio was utilized to provide a detailed analysis of both the mixture proportions and compressive strength properties of the various mixtures developed within the experimental program. Developed by Hayles et al. [107], the cement: compressive strength ratio (also referred to as ‘cement efficiency’ provides a simple metric to effectively assess the relationship between the cement content (in mass) used in a concrete mix design and performance associated with cement usage (i.e. kg/m^3 of cement per MPa) [107], without the need for a detailed and resource-exhaustive life-cycle assessment.

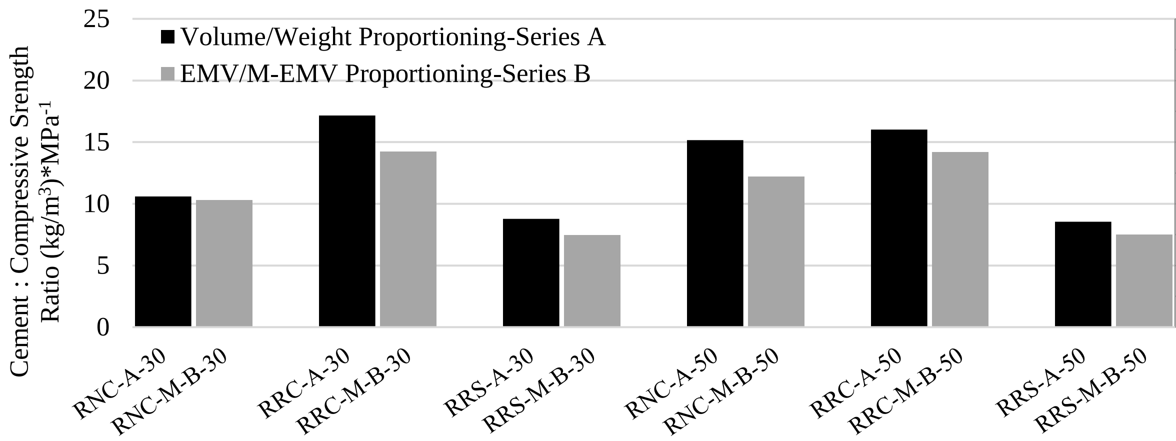


*Figure 52-Comparison of Cement: Compressive Strength Ratio Select Series A and B mixtures (*For clarity: Lower values = improved mixture sustainability)*

Inspection of the findings presented within Figure 52 illustrates that the cement efficiency values of the prepared mixtures within the experimental program ranged from 7-18 for those presented within Figure 52. Hayles's previous analysis determined that cement: compressive strength ratios under 10 ($kg/m^3 * MPa^{-1}$) were a preferable threshold and indication of favour cement efficiency values [107]. Inspection of the values within Figure 52 indicates that cement: compressive ratios below ten (10) were only achieved for the mixtures incorporating CRCA for the 30 MPa target strength class (i.e., RNC-A-30), and those mixtures developed using 50% GGBFS (i.e., RRS-A-30, RRS-M-B-30, RRS-A-50 and RRS-M-B-50). Mixtures for the 30 and 50 MPa target strength classes with both CRCA and FRCA were observed to present the highest cement: compressive strength ratios (i.e., lowest cement efficiency properties), which can be attributed to the principal compressive strength reductions observed within each of the respective mixtures regardless of differences within mixture proportioning method (i.e., CSA or M-EMV proportioning). It should be noted that despite the comparable compressive strength properties of the RRS-A and RRS-M-B mixtures to that of the RRC-A and RRC-M-B mixtures, respectively, the use of GGBFS significantly improves the cement efficiency values of the mixtures leading to reduced cement: compressive strength ratios (i.e., for clarity: lower cement: compressive strength ratio =better) and improved mixture sustainability.

In the case of the M-EMV proportioned mixtures (shown in grey), relative to the companion CSA proportioned mixtures (shown in black), the M-EMV proportioned mixtures presented improved cement efficiency values, evident by the reduced cement: compressive strength values shown within Figure 52 given the reduced cement content and similar compressive strength performance (refer to Table 19). However, despite the reduced cement proportions and comparable performance of the M-EMV proportioned mixtures to their CSA method proportioned counterparts, the replacement of OPC with 50% GGBFS considerable reduces cement: compressive strength ratio, and hence the overall carbon footprint of the mixtures far greater than made possible by M-EMV proportioning.

In the case of the M-EMV proportioned mixtures with 50% GGBFS, while improved cement efficiency values were observed relative to the Series A mixtures, further consideration should be given to the observed workability reductions, increased mixture design complexity, and lack of observable mechanical strength improvements relative to the CSA proportioned mixtures (i.e., Series A mixtures) as presented. From a mix design perspective, although minor improvements in terms of tensile strength properties were observed, the limited workability, lack of compressive strength improvement and increased mix design complexity of the M-EMV proportioned mixtures limit the use of such proportioning methods from further use without extensive optimization (i.e., water proportioning methods) or mixture modification (i.e., modified water contents, use of super-plasticizing agents or high-range water-reducing admixtures).

Therefore, given the improved mixture workability, comparable cement : compressive strength ratios of the developed mixtures as well as the simplicity in the mix design process without the need for complex design equations or further aggregate testing (RM content determination), it is advised that the absolute volume proportioning methods (i.e., CSA A23.1-14 [3] mixture proportioning method as used within the Series A mixtures) be utilized within future LCC research investigations/optimization of mixtures. Based on the experimental findings, it is also advised that the replacement of 50% cement with GGBFS be used in future mixture proportioning to reduce cement requirements further and improve the mixture sustainability without any negative impacts on compressive or tensile strength.

It should be noted that the presented conclusions are based on the experimental findings observed within the current research program. As a result, the use of increasing SCM (as well as RCA) contents may be suitable and allow for the development of LCC with suitable structural grade mechanical properties. However, further research investigation is recommended for such mixture modifications.

7.2. Compressive Strength-Based Mixture Optimization – Series C Concrete Mixtures

Based on the findings from aggregate absorption rate testing, Series A and B mixture properties, and analysis of the corresponding failure mechanisms, optimized mixtures were developed to maximize the resulting concrete compressive strengths to achieve the respective 30 and 50 MPa targets. In total, two separate strength-optimized mixtures were developed. RNS-C-30 and NRS-C-50 mixtures were proportioned using the absolute volume method similar to Series A mixtures, while the 2-hour absorption properties (AC_2) were used to effectively consider the absorption properties of the RCA while the AC_{24} was used for the NA. Additionally, given the highly variable absorption of the FRCA, the w/cm ratio of the NRS-C-50 mixture was reduced to 0.36, while the TSMA was also employed for both mixtures to ensure attainment of desired free-water content and w/cm ratios. Water-reducing admixtures (WRA) were also added to improve workability as required (refer to Table 20). Despite the reduced w/cm ratio for the NRS-C-50 mixture, the free-water content was also reduced to ensure that the total binder proportions were the same as the Series 50 MPa mixtures. The mixture proportions for the optimized (Series C) concrete are presented in Table 20, while a summary of the fresh and hardened mechanical properties of the Series C concrete mixtures are presented in Table 21. The Series A control mixtures (NNC-A-30 and NNC-A-50) were also included for comparison purposes.

Table 20-Summary of concrete mixture proportions- Series C Mixtures

Mix	Mixture Proportions (kg/m^3)									% LCC Materials ****
	w/c ***	Water (Free)	Water (Agg.)	Cement	GGBFS	NCA	NFA	CRCA	FRCA	
NNC-A-30*	0.58	177	24	305	0	1035	752	0	0	0
NNC-A-50*	0.42	213	21	507	0	1035	505	0	213	0
RNS-C-30	0.58	177	45	153	153	0	876	859	0	50.4
NRS-C-50**	0.36	183	69	254	254	1015	0	0	502	37.3

**Control mixture per strength designation (presented for comparison purposes),*
***60 ml of super-plasticizer used (2600 ml/m^3)*
****Effective water-to-cementitious materials ratio,*
****Amount of LCC materials (CRCA, FRCA and GGBFS) by weight %, excludes water,*

Table 21-Fresh and hardened concrete properties-Series C Mixtures

Mix-Series	Concrete Properties								
	Slump (mm)	f'_{c7} (MPa)**		f'_c (MPa)**		f'_{c7}/f'_c	f'_{ct} (MPa)		Density
NNC-A-30*	90	20.6	-	34.2	-	60.2	3.48	-	2464
NNC-A-50*	105	44.7	-	56.8	-	78.7	4.05	-	2446
RNS-C-30	75	17.3	-16.0%	29.1	-14.9%	59.4	3.39	-2.6%	2273
NRS-C-50	220 ***	38.3	-14.3%	49.8	-12.3%	76.9	4.40	+8.6%	2328

**Control mixture per strength designation,*
***Expressed as a % change from respective control mixture,*
****Excess slump due to operator error, excessive super-plasticizer added*

7.2.1. Fresh Concrete Properties

The slump values for the RNS-C-30 were within the permissible target slump limits (100 ± 25 mm) despite modifications to the proportioned water absorbed by the aggregates (i.e., through the use of the AC_2 values used for the CRCA). For the NRS-C-50 mixture, reduced free-water content values (proportioned to ensure same total cementitious materials as Series A mixtures with a lower w/cm ratio) did lead to significant slump reductions, requiring the use of 60 ml of a water-reducing admixture (WRA) (i.e., 2600 mL/m^3 concrete –

proportioned for 850 ml per 100 kg of cement). However, due to operator error, excessive portions of the water-reducing admixture were added to the mixture in one application (rather than progressive addition until desired slump values), resulting in slump values exceeding the target slump values (slump value of 220 mm). Despite the higher slump properties, segregation or settlement of the coarse aggregates was not observed in the fresh concrete mixture or during further inspection of the cylinders during compressive strength testing, indicating that the use of unintended WRA quantities did not negatively impact the viability (i.e., workability and strength) of the mixture.

Additionally, as noted within the Series A mixtures, the partial replacement of cement with 50% GGBFS may have further improved workability results given enhanced dispersion characteristics and increased fineness of the GGBFS particles compared with OPC [36,92].

7.2.2. Hardened Concrete Properties

In terms of compressive strength, it was observed that the RNS-C-30 and RNS-C-50 mixtures both presented marginal f'_{c7} and f'_{c} reductions relative to the respective control mixtures with reductions up to 16% observed. Despite the observed reductions, both Series C mixtures achieved f'c within ±1 Mpa of the target compressive strength for each class. It was noted that even within the partial replacement of GGBFS, both the Series A (control mixtures) and Series C mixtures presented nearly identical strength gain properties (f'_{c7}/f'_{c}) for each target strength class (30 and 50 MPa strength class) despite GGBFS usage, differences within the mixture proportions, materials and mix design methods of the Series A and C mixtures.

In terms of splitting tensile strength, both RNS-C-30 and NRS-C-50 mixtures reached similar tensile strengths as the control mixtures regardless of strength class. In the NRS-C-50 mixture, 8.6% higher tensile strength values were observed compared with the NNC-A-50 mixture. The improved tensile strength properties can be partially attributed to the use of GGBFS, which in the case of the Series A mixture led to improved tensile strength values in some cases (i.e., tensile strengths of NNS-A relative to NNC-A, refer to Table 19). However, it should be noted that unlike the tensile strength values of the Series A mixtures (i.e., RRS-A-30 and RRS-A-50), which was found to be reduced for mixtures proportioned with RCA and GGBFS; the f'_{ct} properties for the Series C mixtures were found to be significantly improved despite RCA and GGBFS incorporation. The differences within the tensile strength behaviour of the Series A and Series C mixtures with RCA and GGBFS may be attributed to the difference within the microstructure characteristics of the hardened concrete structure given the difference within the mix design of the mixtures and use of optimization methods within the Series C mixtures. Therefore, it can be reasoned that the optimization of the Series C mixtures due to optimized water proportioning methods (i.e., use of AC2 values for RCA), use of the TSMA, restriction of LCC materials (i.e., CRCA omitted from 50 MPa strength class) and modifications to the w/cm ratio may have led to a densification of the microstructure, leading to f'_{ct} and f'_{c} properties relative to the Series A mixtures.

Based on the results presented, the performance of the Series C mixtures further validates the proposed governing strength mechanisms and the governing mechanism of FRCA and CRCA as previously discussed, validating the proposed weak aggregate-strong mortar strength mechanism at low w/cm ratios and the weak mortar-strong aggregate governing strength mechanism at high w/cm ratios. As a result, the Series C mixtures indicate that omittance of either the coarse or fine RCA as per the governing failure mechanism combined with the mixture design methods suited to the RCA can effectively produce, structural grade LCC with compressive strengths comparable to conventional concrete can be produced while incorporating a sustainable portion of recycled and secondary materials (up to 50.4%) by weight.

Given these promising results, it is recommended that further mixtures be developed to evaluate the further usage of additional LCC materials within the mix design of LCC mixtures within further studies (i.e., incremental adjustments to LCC materials such as CRCA FRCA and SCM contents). It is recommended that using the optimized mix design methods discussed within the Series C mixtures, additional LCC materials be studied to investigate the possibility of producing LCC with even further amounts of LCC materials without any significant effect on the mechanical properties (e.g., 25% CRCA added to the NRS-C-50 mixture).

7.3. Summary

The following conclusions were obtained based on the experimental findings observed within the Series A, B and C mixtures:

Fresh properties

- CRCA was found to reduce slump values by 17-38% relative to the control mixtures within the Series A mixtures. The reduced slump values can be attributed to the cumulative effects due to differences within aggregate morphology (i.e., RM fraction), higher AC_{24} properties leading to faster water absorption and increased angularity/surface roughness of the CRCA.
- FRCA usage was found to increase slump values by 24-83% with the Series A mixtures, with similar findings also observed for mixtures comprised of CRCA and FRCA. The increased

workability of the mixtures was attributed to the additional free-water content within the fresh concrete mixtures due to the relatively limited absorption by the aggregates (i.e., a fraction of total absorbed moisture).

- GGBFS was found to increase slumps by 3-24% relative to mixtures comprised entirely with OPC, given the smooth surface characteristics, dispersion characteristics, and particle fineness.
- Series B mixtures were found to have 83-95% lower slump values, attributed to the free-water content reductions from EMV/M-EMV proportioning and the increased aggregate absorption due to the use of the TSMA during mixing.
- It is recommended that the TSMA or modified water proportioning methods be used for LCC mixtures containing FRCA to improve water absorption and ensure that the absorption properties of the aggregates accounted represent the actual water absorption characteristics of the FRCA.

Hardened Properties

- The use of CRCA (RNC-A-30 and RNC-M-B-30) resulted in up to 3% higher f'_{c7} values and 15-25% lower f'_c values for the 30 MPa target strength class mixtures. While CRCA usage led to 33-41% lower f'_{c7} and f'_c values within the 50 MPa target strength class mixtures. Similar findings were also observed for splitting tensile strengths
- Significant mechanical strength reductions were also observed for mixtures with FRCA, attributed to the increased w/cm ratios of the mixtures given the higher free-water content values given the increased slump values of the mixtures, although in the case of the 50 MPa strength class, higher f'c values were observed relative to the RNC-A-50 mixture. Analysis of the compressive strength properties of mortar cubes further supports such conclusions
- The combined use of CRCA and FRCA did not present further reductions relative to LCC mixtures prepared within FRCA (30 MPa strength class) and CRCA (50 MPa target strength class), indicating that the further incorporation of additional LCC materials (by weight) does not necessarily result in progressive compressive strength reductions.

Governing failure mechanisms and mixture optimization

- Assessment of the mechanical strength properties found that within the 30 MPa target strength mixtures, the mortar fraction of the hardened concrete mixture serves as the limited strength contributor and governs the failure mechanisms. Assessment of the mechanical properties, fracture patterns and compressive strength properties of mortar cube specimens found that FRCA negatively impacts the mortar strength properties of the mixture with fractures observed to propagate through the mortar fractions and around the coarse aggregates regardless of coarse aggregate source.

- Assessment of the mechanical strength properties found that within the 50 MPa target strength mixtures, the coarse aggregate fraction of the hardened concrete mixture serves as the limited strength contributor and governs the failure mechanisms. Assessment of the mortar strength properties found that regardless of fine aggregate usage, mortar strength properties were significantly higher than those observed during concrete testing. Systematic evaluation of the mechanical strength properties of the hardened concrete mixtures found that CRCA usage limits the resulting strength properties, with fractures observed to propagate through the coarse aggregate fractions regardless of the fine aggregate source.

8. FLEXURAL EVALUATION OF REINFORCED CONCRETE BEAMS

Based on the fresh and hardened properties testing of the various concrete mixtures tested within the Series A, B and C mixtures presented within Chapter 7, the final stage of the experimental research program involved the flexural testing of low carbon concrete reinforced beams. The purpose of this experimental testing stage was to examine further the influence of novel mix design procedures and various combinations of CRCA, FRCA, and GGBFS within the concrete mixtures on the flexural properties of steel-reinforced concrete beams. Experimental maximum moment values were compared against values obtained through code-based equations based on the current CSA A23.3-14 [68] design standards. In terms of serviceability properties, the experimental deflection values were compared with CSA A23.3-14 code-based equations. Further examination of the cracking patterns and evaluation of the cracking moment (M_{cr}) was also conducted to evaluate differences in the behaviour of the LCC beams and the control, conventional reinforced concrete beams. The applicability of the existing CSA structural concrete design standards for use in the design and analysis of reinforced LCC beams is also presented.

8.1. Test Setup, Instrumentation and Procedure

8.1.1. Test Frame Overview and Procedure

Experimental testing consisted of the 4-point flexural testing of several reinforced concrete beams using a four-column loading frame with a centrally mounted servo-hydraulic actuator and load cell. A loading plate centred on the beam's midspan, with a clear spacing of 300 mm from roller to roller (applied loads) was used to distribute the concentrated actuator force to the top surface of concrete test beams, as shown within Figure 53. The loading was applied under displacement control at a 1 mm/min loading rate and was stopped upon a 10% reduction from the peak load (note this value was modified to 15% for some tests). The beams were 2250 mm in length and were simply supported with a clear spacing (L_n) of 2000 mm.

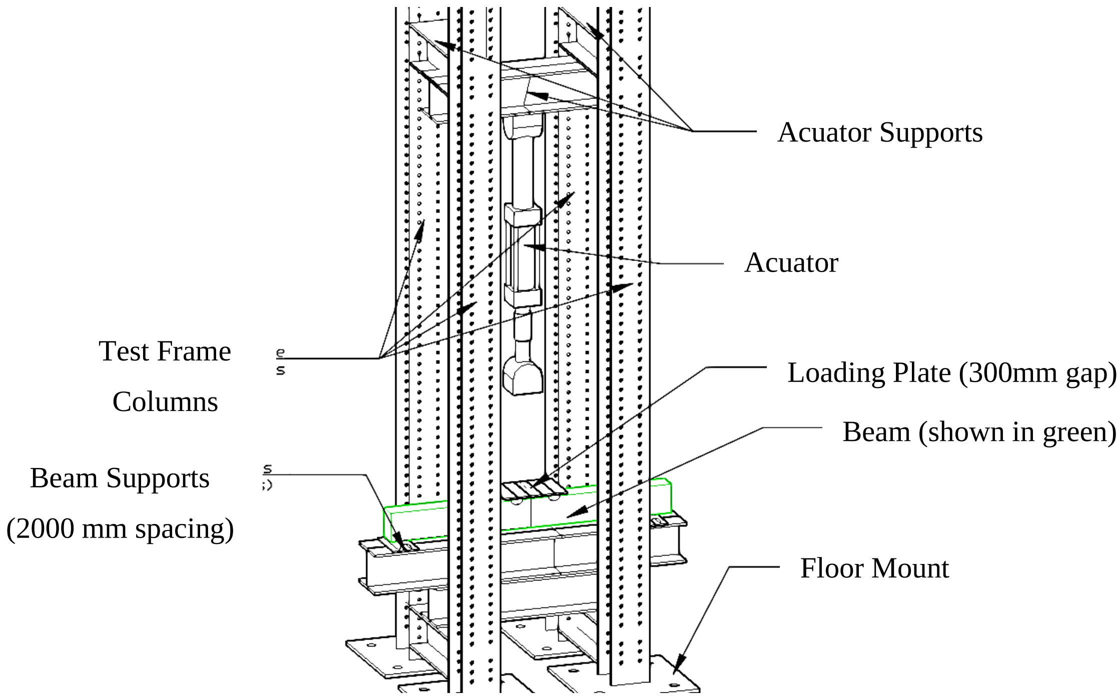
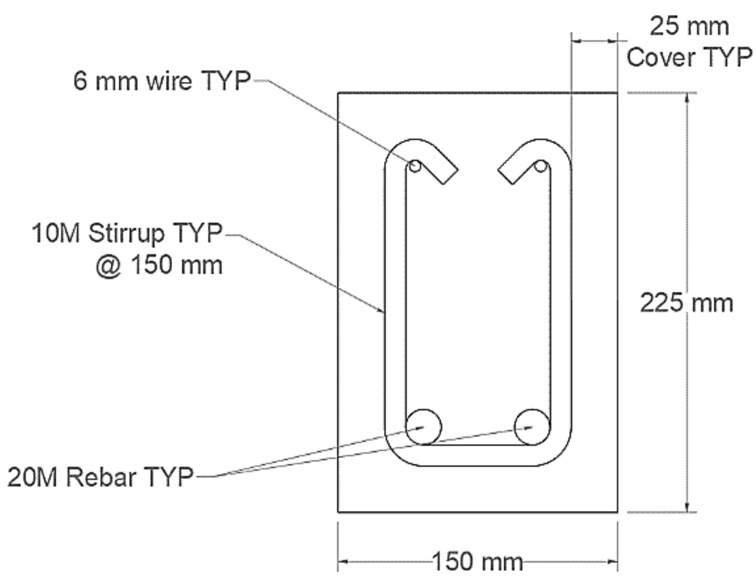


Figure 53-Test-Frame Visualization

8.1.2. Beam Detailing and Instrumentation

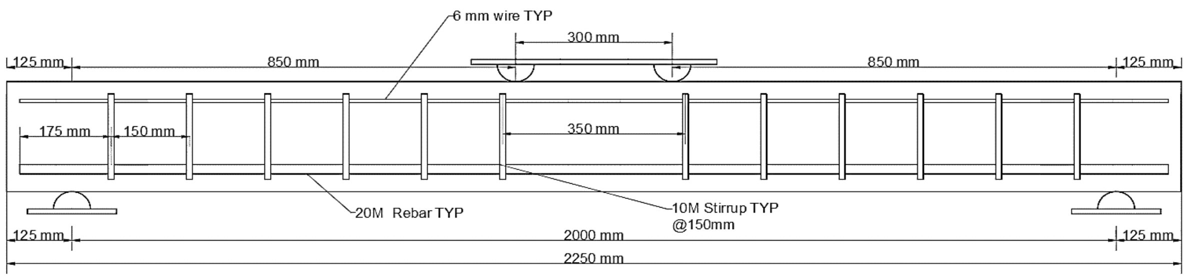
All beams were singly-reinforced and designed with a rectangular cross-section (150 x 225 mm), as shown



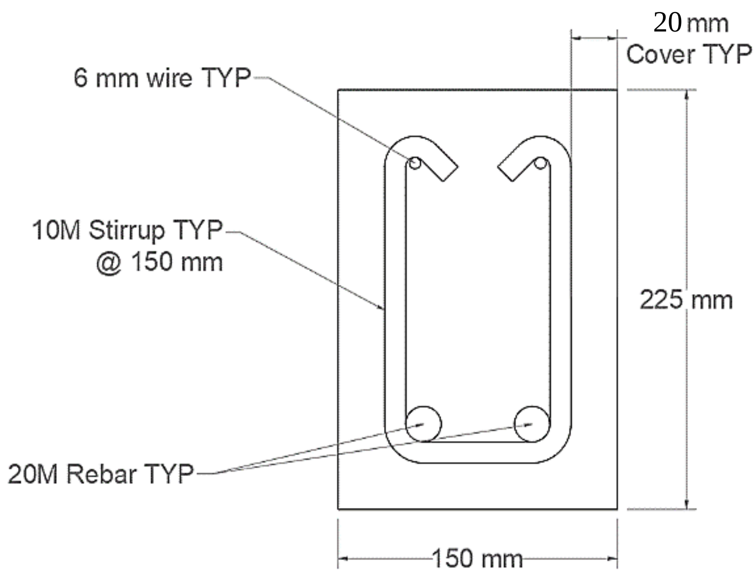
in

(b)

Figure 54(b). Beams were designed per CSA A23.3-14 standards. The longitudinal steel reinforcement consisted of 2-20M bars (f_y =400 MPa) placed within the tension zone and 10M stirrups (f_y = 400 MPa), spaced at 150 mm centres. A clear cover of 20 mm was used throughout; note that that underside cover was achieved using plastic ‘chairs,’ which were placed under each of the 20M longitudinal reinforcement bars at each end of the beam. Constructability tolerances of ± 2.5 mm were used for the construction of the beam frame and steel cage; additionally, the actual yield stress values (f_y) of the steel reinforcement (longitudinal and stirrups) were not tested (i.e., via steel coupon testing or similar testing method), rather, the yield stress values were provided as per design specifications by the manufacturer.



(a)

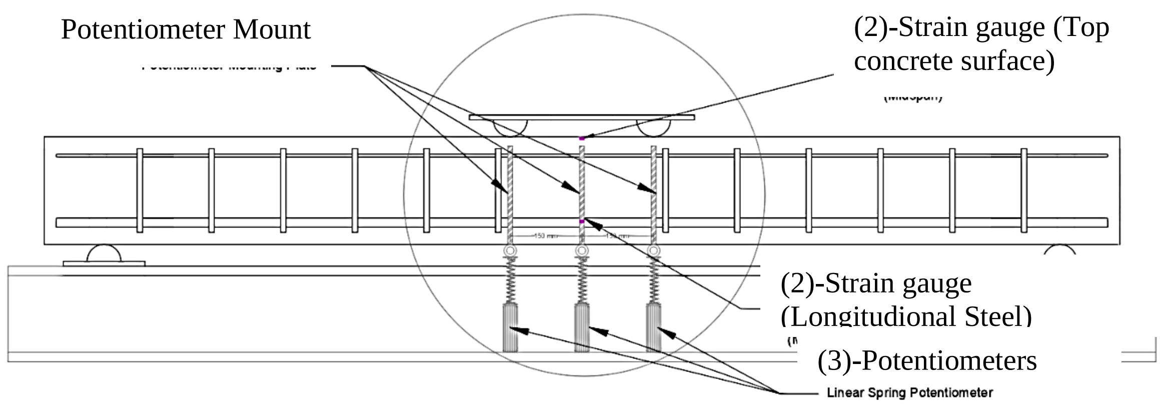


(b)

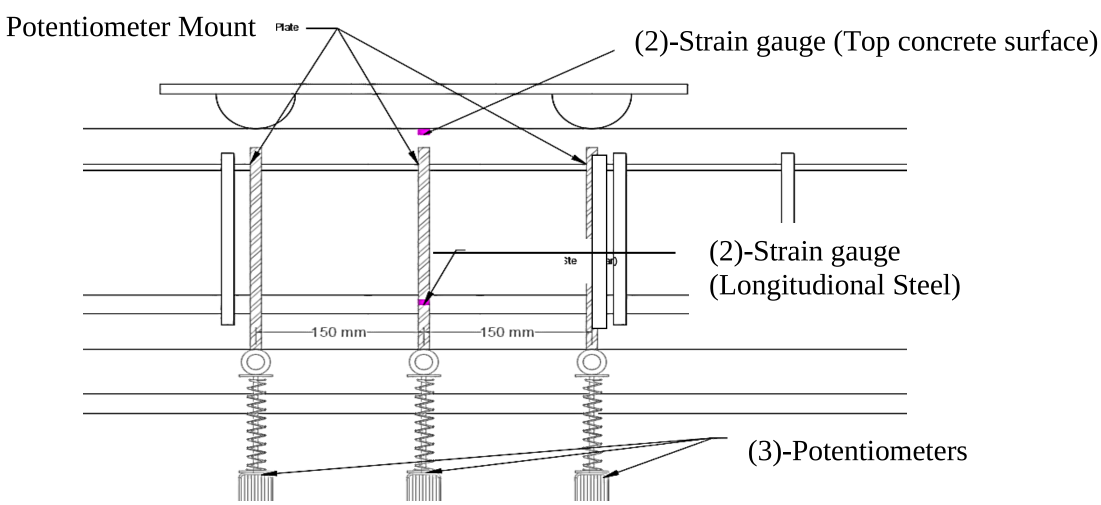
Figure 54-Beam Detailing (a) Plan View, (b) Cross-section of Beam

To monitor the vertical displacement of the beams during testing, linear/string potentiometers were mounted at midspan and each of the loading points, 150 mm from the midspan point of the beam. Electrical-based strain gauges were mounted on the longitudinal steel and top concrete faces prior to casting/testing to measure strain. Strain gauges with a gauge length of 5- or 10-mm and a resistance of 120 Ω were installed at the midspan of each of the 20M steel bars (1 per bar) as well as on the top surface of the concrete (2 per beam) using superglue and covered with a protective epoxy-based adhesive coating prior to beam casting. It should be noted that the multiple sizes of strain gauges were due to logistical limitations and were assumed to serve the purpose without any assumed impact on the experimental findings.

Rigid steel mounting plates were mounted on the surface of each of the concrete beams using hot glue to provide a reaction surface for the linear potentiometers. Figure 55 a/b illustrates the location of the various strain gauges and potentiometers within the beams. The actual instrumentation setup is presented in Figure 56.



(a)



(b)

Figure 55-Visualization of Beam Instrumentation Overview

(a) Cross-sectional View, (b) Further zoom of circled section

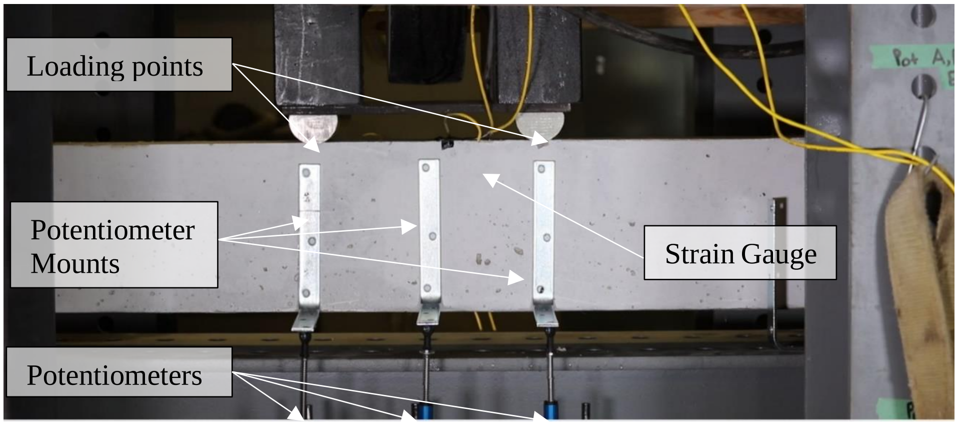


Figure 56-Beam Instrumentation Overview (shown within Test Frame)

Note: Longitudinal steel and concrete mounted strain gauges (far size of the beam) not visible

A summarization of the various design properties of the tested concrete beams are shown below in Table 22:

Table 22-Summarization of beam properties

Property	Value	Note
Beam Dimensions		
Length (L)	2250 mm	
Clear Span (L_n)	2000 mm	125 mm overhang each side
Distance from support to loading point (x)	850 mm	
Distance between loading points (a)	300 mm	
Width (b)	150 mm	
Height (h)	225 mm	
Clear cover	20 mm	Uniform throughout entire beam
Longitudinal Steel		
Rebar Type	2-20M	D_b = 19 mm
Yield Strength (f_y)*	400 MPa	*Values supplied by the manufacturer
Effective Depth (d)	183.95 mm	
Reinforcement Ratio (ρ_s)	2.1745	Based on beam dimensions
Stirrups		
Rebar Type	10M	D_b = 11.3 mm
Yield Strength (f_y)*	400 MPa	*Values supplied by the manufacturer
Effective Shear Depth (d_v)	165.375 mm	Max (0.9d, 0.72h)
Typical Spacing (s)	150 mm	*Spacing of 350 mm at midspan** *
Hanger Bars* *		
Rebar Type	6 mm wire	
Yield Strength (f_y)*	400 MPa	*Values supplied by manufacture
Strain gauges and Potentiometers		
Number of gauges on the top concrete face	2	*Located at midspan*
Number of gauges embedded on steel	2	*1 per 20M bar, located at midspan*
Strain gauge length****	5 or 10 mm	*Gauge resistance:* 120 Ω
Number of Active Potentiometers*****	3	*Locations: Midspan, left loading point, right loading point.*

**Values supplied by manufacture specifications*
***Stirrups within the zero-shear region, negligible impact on resultant shear resistance properties*

**** Used for constructability purposes, assumed not to contribute any strength properties*
***** Secured to the testing surface using glue and epoxy coating*
****** Deflection values from potentiometer located at midspan exclusively presented*

8.2. Concrete Mixture Proportions Selection

Based on the mixtures developed within Chapter 7, three different series of mixtures were selected to cast the LCC beams. Mixture proportions were selected to evaluate the effect of CRCA, FRCA and GGBFS usage and varying mixture design methods. An overview of the composition and mix design methods used within the various concrete mixes tested within the experimental program is provided in Table 23, while the mixture proportions for the various concrete mixtures used within beam testing are provided in Table 24. It should be noted that the mixture proportions of the six selected mixtures are the same as those listed in Chapter 7; however, minor modifications were made to the mixing water amounts to account for aggregate absorption.

Table 23-Overview of mixture characteristics of tested concrete specimens

Mix	Mixture Characteristics					
	w/c	Coarse Agg.	Fine Agg.	Binder	Proportioning Method	Mixing Method
NNC-A-30*	0.58	NCA	NFA	OPC	Absolute Volume Method**	CSA **
NNC-A-50*	0.42	NCA	NFA	OPC	Absolute Volume Method **	CSA **
RRC-A-50	0.42	NCA	NFA	OPC	Absolute Volume Method**	CSA **
RRS-A-50	0.42	CRCA	FRCA	50% GGBFS, 50% OPC	Absolute Volume Method**	CSA **
RRS-M5-B-50	0.42	CRCA	FRCA	50% GGBFS, 50% OPC	M-EMV	TSMA
NRS-C-50	0.36	NCA	FRCA	50% GGBFS, 50% OPC	Absolute Volume Method***	TSMA

**Control mixtures*
***Based on CSA A23.1-14 standards,*
****Modifications to water proportioning, optimized for highest compressive strength values (refer to Chapter 7)*

Table 24-Concrete mixture proportions

Mix	w/c	Mix Proportions (kg/m^3)								% LCC Materials ***
		Water (Free)	Water (Agg.)	Cement	GGBFS	NCA	NFA	CRCA	FRCA	
NNC-A-30*	0.58	177	23	305	0	1035	752	0	0	0
NNC-A-50*	0.42	213	21	507	0	1035	505	0	0	0
RRC-A-50	0.42	213	63	507	0	0	0	929	382	72.1
RRS-A-50	0.42	213	91	254	254	0	0	836	490	86.2
RRS-B-M5-50	0.42	185	91	220	220	0	0	1086	382	88.5
NRS-C-50**	0.36	183	69	254	254	1015	0	0	502	37.3

**Control mixtures*
***2600 ml of super-plasticizer (ml/m3) used*
****Percentage of LCC materials (CRCA, FRCA and* GGBFS*) by weight, excludes water*

Within the selected mixtures, both the 30 and 50 MPa concrete control mixtures (NNC-A-30 and NNC-A-50) were chosen to serve as a reference point to evaluate the flexural behaviour of the LCC beams. The two control mixtures were also used as a reference point for further beam testing (i.e., comparison to the LCC beams) as well as evaluate the validity of the theoretical predictions presented within the current CSA A23.3-14 [68]- concrete flexural theory models/equations for conventional concrete mixtures as well as allow for the effect of various concrete compressive strengths to be evaluated without additional variability due to LCC material incorporation or mix design modifications (proportioning or mixing methods). Two LCC Series A mixtures (RRC-A-50 and RRS-A-50) were selected to systemically assess the influence of LCC material usage on the flexural performance of reinforced concrete beams. The RRC-A-50 mixture was chosen to evaluate the effect of the complete replacement of coarse and fine RCA, while the RRS-A-50 mixture was chosen to investigate the further replacement of 50% of cement with GGBFS. The RRC-A-50 and RRS-A-50 mixtures were also chosen to assess further the applicability of the absolute volume method and CSA mixing standards on the flexural performance of reinforced concrete beams. The final set of mixtures consisted of the casting and further assessment of the RRS-M-B-50 and NRS-C-50 mixtures; such mixtures were chosen given their highest incorporation of LCC materials (by % weight) (RRS-M-B-50) amongst the various LCC mixtures, equivalent compressive strengths to the 50 MPa control mixture (NRS-C-50), as well as to investigate further the influence of novel mixture design methods such as M-EMV and TSMA (RRS-M-B-50) and modified water proportioning/compensation methods (NRS-C-50).

8.2.1. Specimen Preparation

Two identical beam specimens were cast for each of the six (6) concrete mixtures, providing 12 beams. The same batch and casting methods were utilized for each pair of beams to minimize beam-to-beam mixture variability as much as possible. Based on both initial mixer capacity limitation concerns and, i.e., safety considerations, the NNC-A-30 mixture was split into two mixtures. As such, the findings for each of the NNC-A-30 mixtures trials (denoted with (1) and (2)) are provided separately.

An industrial ‘shear action’ concrete pan mixer with a capacity of 300 L was used for all concrete mixing. Prior to discharging the mixtures into a wheelbarrow for transport to the location of the beam forms, the discharged mixtures were manually mixed for approximately 30 seconds to ensure uniformity prior to casting. Although specific mixing practices were utilized during the preparation of the various beams (i.e., NMA or TSMA), manual mixing was conducted after mixture discharging to reduce segregation within the fresh mixture and ensure uniformity during beam casting; therefore, it was assumed that any impact from manual mixing was negligible on the resulting concrete strength or flexural/serviceability properties.

Immediately following mixing, the fresh concrete slump values were determined as per CSA A23.2-5C standards [3] (refer to Chapter 6.2.2). The fresh concrete was then cast into the formwork, consolidated using a tamping rod and rubber mallet, and then the top surface of the concrete was finished using a trowel (refer to Figure 57).

(a) *(b)* *(c)*

Figure 57-Casting of concrete beams

(a)-Placement of concrete within formwork, (b) tamping by use of rod, (c) finishing surface with trowel

Six cylindrical specimens (100 mm x 200 mm) were also cast for each mixture and cured until 28-day f'_c or f'_{ct} testing. All concrete specimens (beams and cylinders) were de-moulded after one (1) day of curing and then covered with damp burlap sheets and sealed until 28-testing (cylindrical and beam specimens). The beam and cylindrical specimens were watered periodically to ensure continuous moist-curing conditions. Prior to testing the cylindrical and beam specimens, the loading surfaces (cylindrical-top/bottom face, beam-top face) were smoothed over by grinding/sanding. To avoid stress concentrations within the loading surface of the beam, imperfections such as air bubbles, voids, and surface unevenness were filled by the use of an industrial concrete repair compound (i.e., hydro-stone).

8.3. Concrete Fresh and Hardened Properties

The mechanical properties of the tested concrete mixtures (slump, compressive strength, splitting tensile strength and hardened density) are presented in Table 25. Seven (7)-day compressive strength (i.e., f'_{c7}) was not assessed for any mixtures. Furthermore, the empirically predicted concrete modulus of elasticity (E_c) for each concrete specimen was calculated using Equation *5*-(Cl 8.6.2.2 -CSA A23.3 [68]).

Table 25-Fresh and Hardened Concrete Properties of mixtures used in beam production

Mix ID	f'_c (MPa)	f'_{ct} (MPa)	Density (kg/m^3)	Slump (mm)
NNC-A-30 (1)*,**	36.8	4.12	2401	175

NNC-A-30 (2)*,**	37.4	4.03	2375	175
NNC-A-50*	50.0	3.98	2351	175
RRC-A-50	35.9	3.21	2174	205
RRS-A-50	34.7	2.89	2109	190
RRS-M5-B-50	38.4	3.20	2174	75
NRS-C-50	51.9	4.19	2261	140

Note: f'_c, f'_{ct} and density values were obtained from testing of cylindrical specimens for each mixture
**Control Mixtures*
***NNC-A-30 beams made with separate batches as shown (Trial 1 and 2)*

8.3.1. Fresh Properties

The measured slump values, presented in Table 26, significantly exceeded those previously reported for the same mixtures presented in Chapter 7 for the small-scale companion batches.

Table 26-Comparison of slump values (small scale batches to large scale batches)

Mix ID	Slump-Small Scale (mm)**	Slump-Beams (mm)***
NNC-A-30 (1) *	90	175
NNC-A-30 (2) *	90	175
NNC-A-50*	105	175
RRC-A-50	145	205
RRS-A-50	150	190
RRS-M5-B-50	45	75
NRS-C-50	220****	140

*Control Mixtures
**Slump values as noted within Chapter 7- mixture made in 30 L batches,
***Slump values for mixtures used in beam casting, 178 L batches.
****Excessive slump due to excessive super-plasticizer volumes

The higher slump values may be attributed to the differences between the mixer types (i.e., shear-based pan mixer-beams versus rotary drum mixer), which may have modified the workability values of the concrete due to differences within mixing action. At the same time, the same overall trends were observed within the slump values for the mixtures used within the beam casting, as found within Chapter 7. CRCA and FRCA usage still led to higher slump values (RRC-A-50) relative to the control mixtures, while the additional incorporation of GGBFS (RRS-A-50) further increased slump values. It was also found that while the use of the pan-mixer with increased mixture volumes increased the mixtures' slump values, M-EMV proportioning (RRS-M5-B-50) still produced reduced slump values relative to the control mixtures. The observed slump values of the RRS-M5-B-50 mixture were found to be within the target slump specifications of 100 ± 25 mm despite significant reductions relative to the control mixtures (NNC-A-30 and NNC-A-50). Additionally, it was found that the slump values of the trial 1 and trial 2 mixtures of the NNC-A-30 mixture displayed the same slump values indicating that despite production within separate batches, similar fresh properties were observed. Similarities within the fresh properties affirm that minimal differences/variability may be present between the two batches regardless of different batches.

8.3.2. Hardened Properties

Regarding the hardened concrete properties of the concrete mixtures, although similar trends were reported as those found within the small-scale batches as noted within Chapter 7, differences within the values reported for the batches used in the beam preparation relative to the small-scale batch produced within Chapter 7 were reported. Differences within hardened properties of the mixtures developed within the small-scale batches, and those used for beam production are presented within Table 27, along with the % change values.

It was observed that the mixtures used for beam production (Beams) presented higher compressive strength values compared with those observed within the small-scale batches (Small-scale). Up to 31% higher compressive strength values were observed (RRS-M5-B-50), with an average increase of 10.1% for the mixtures used in the beams compared with the small-scale batches. Similarly, splitting tensile strength improvements were also observed within the beam mixtures; however, reduced f'_c values up to 4.8% lower (NRS-C-50) were also observed.

Similar to the fresh properties, the differences within the reported compressive strength and splitting tensile strength values of the mixtures used for beam casting and of the small-scale batches may be attributed to the difference within the mixing process (i.e., use of pan mixer-beams, drum mixer-small scale batches) as well as the increased batch size of the mixtures used for beam casting (177 L batches used for beam casting relative to 30 L batches used for small scale testing within Chapter 7).

Table 27-Comparison of hardened properties- cylindrical specimens and beam preparation

Mix ID	f'_c (MPa)			f'_{ct} (MPa)			Density (kg/m^3)		
	Small Scale	Beams	% Change	Small Scale	Beams	% Change	Small Scale	Beams	% Change
NNC-A-30 (1) *	34.2	36.8	7.5	3.48	4.12	18.4	2464	2401	-2.6
NNC-A-30 (2) *	34.2	37.4	9.4	3.48	4.03	15.8	2464	2375	-3.6
NNC-A-50*	56.8	50.0	-12.0	4.05	3.98	-1.7	2446	2351	-3.9
RRC-A-50	31.7	35.9	13.3	3.01	3.21	6.6	2201	2174	-1.2
RRS-A-50	29.6	34.7	17.2	2.62	2.89	10.3	2098	2109	0.5
RRS-M5-B-50	29.3	38.4	31.0	3.07	3.2	4.2	2217	2174	-1.9
NRS-C-50	49.8	51.9	4.2	4.4	4.19	-4.8	2328	2261	-2.9

**Control mixture per strength designation.*
Note: % Change denotes differences within properties of small-scale mixture and (chapter 7) and mixtures used for beam production mixtures

Additionally, the differences within curing methods such as damp burlap relative to moist curing should be considered. At the same time, the variability within the LCC materials sources (RCA quality/properties and deleterious material quantity) may also be accountable for the observed differences reported for the various concrete mixtures. Regarding the anticipated flexural strength values, the similarities amongst the f'c of the various mixtures (i.e., grouped into either 30 MPa or 50 MPa strength class) ensure that the observed flexural and serviceability findings are observed can be assessed without the further influence of compressive strength. Regarding the hardened density of the mixtures, despite minor variability within the reported values, an average change of less than 4% was reported for all mixtures, which were considered insignificant.

8.4. Flexural and Serviceability Results and Discussion

The load-midspan deflection plots for the 12 concrete beams are summarized in Figure 58a. Individual load-displacement plots for the two control beams (NNC-A-30 and NNC-A-50) are provided in Figure 58b, while the LCC beams are provided within Figure 58c. The midspan displacement at peak load ($P_{n\text{-}exp}$) for the beam specimens are summarized in

Table 28. Additionally, the applied moment values (M_n) and maximum applied shear forces ($V_{n\text{-}exp}$) based on the peak loading values ($P_{n\text{-}exp}$) are also displayed in

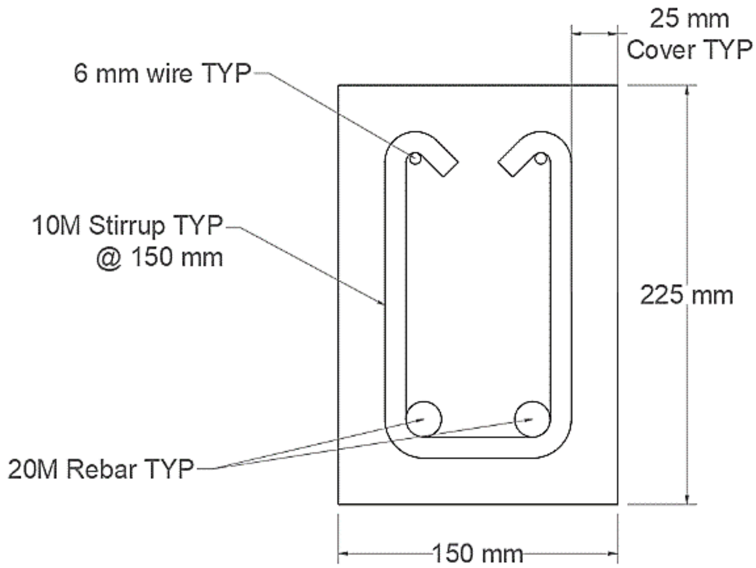
Table 28 and were computed based on elastic beam theory using Equation 17 and Equation 18.

$$M_{n-exp} = \frac{P_{n-exp}(L-a)}{4} \quad \text{Equation 17}$$

$$V_{n-exp} = P_{n-exp}/2 \quad \text{Equation 18}$$

It should be noted that in Equation 17 and Equation 18, the maximum applied moment values ($M_{n\text{-}exp}$) and applied shear force values were calculated based on the total applied load ($P_{n\text{-}exp}$) observed during testing;

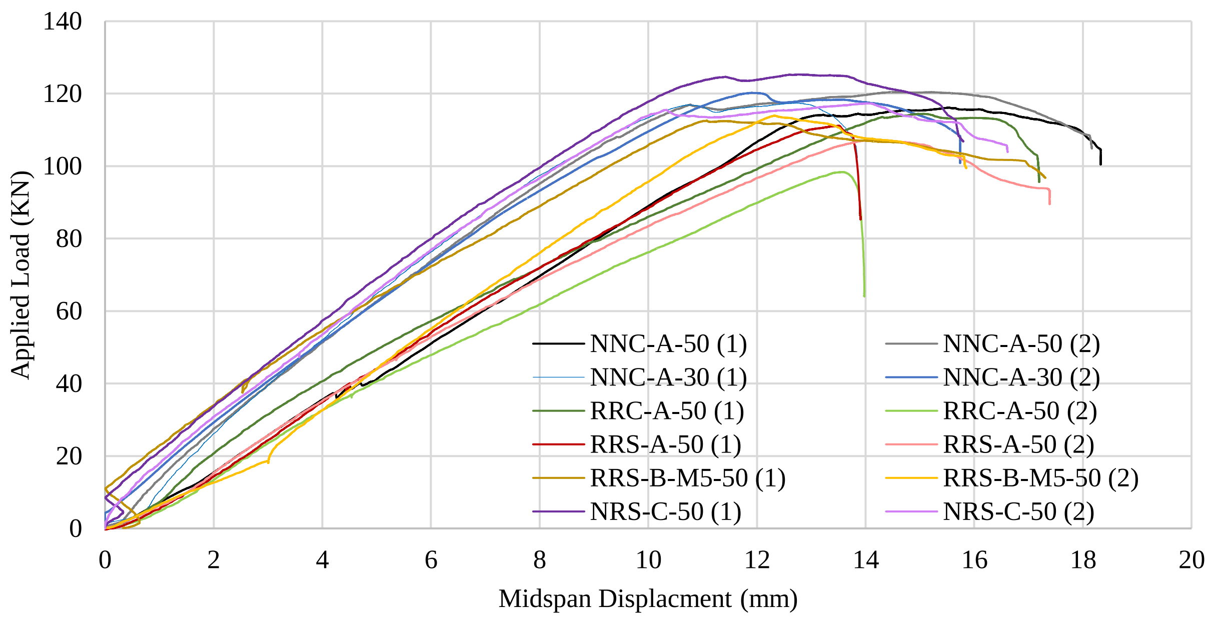
while clear span distances between supports (L) of 2000 mm) and between loading points (a) (i.e., 300



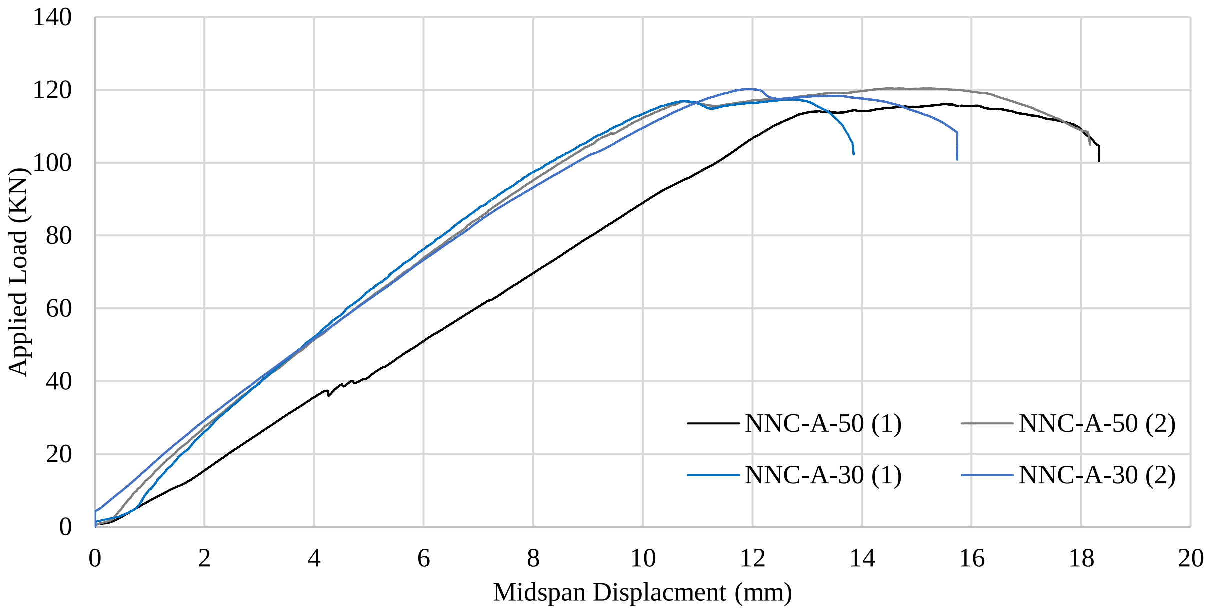
mm) (refer to

(b)

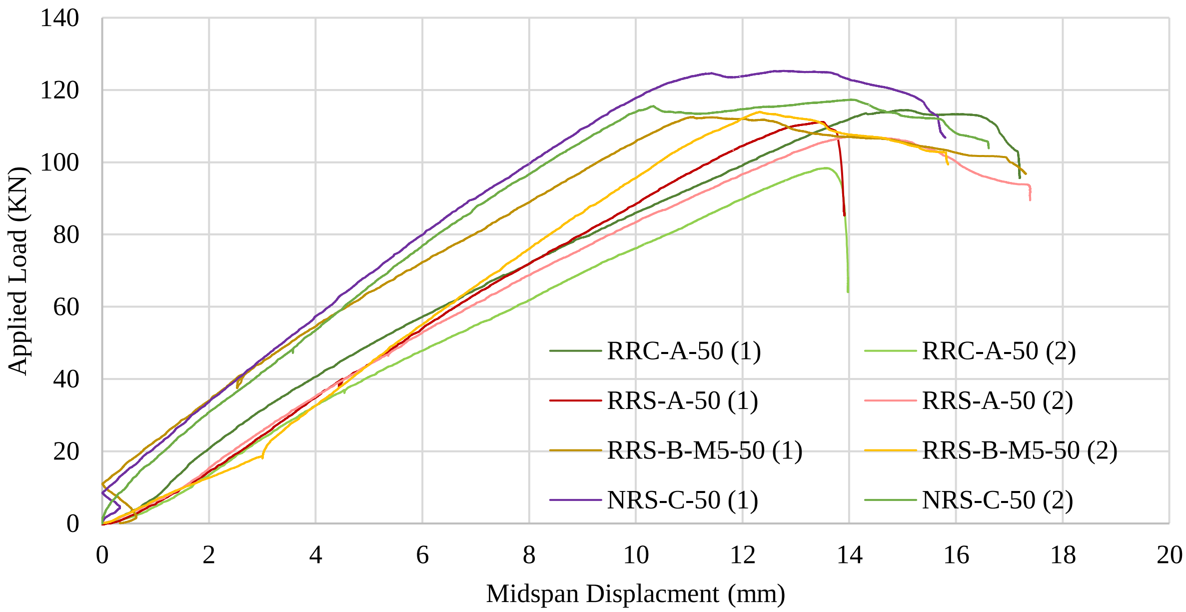
Figure 54 for further beam dimensions and detailing) were used for all calculations.



(a)



(b)



(c)

Figure 58-Load-displacement chart

(a)All beams, (b) Control mixtures, (c) LCC mixtures

Table 28-Loading, strain and displacement values at peak load

Mix ID	Trial	P_n (kN)	M_n (kNm)	V_n (kN)	$\Delta_{mid, ult}$ (mm)	ε_s (μm/m)****		ε_c (μm/m) ****	
						1	2	1	2
NNC-A-50	1	116.18	49.38	58.09	16.54	2971	7055	-2616	-2144
	2	120.42	51.18	60.21	17.98	*	7379	-3268	-2270
NNC-A-30	1	117.40	49.90	58.70	14.89	*	2914	-2196	-2188
	2	120.24	51.10	60.12	12.90	2352	2536	-1972	***
RRC-A-50	1	114.43	48.63	57.22	14.83	2356	2133	-2678	-3209
	2	98.37	41.81	49.19	13.67	2103	1769	-1154	-1442
RRS-A-50	1	111.13	47.23	55.57	14.82	1759	1632	-1378	-1792
	2	107.42	45.65	53.71	15.81	2405	1978	-485	-973
RRS-M5-B-50	1	112.55	47.83	56.28	13.92	2000	2169	-1629	-1604
	2	113.95	48.43	56.98	15.11	2037	2259	-1624	-2350
NRS-C-50	1	125.30	53.25	62.65	15.15	6439	13675	-2382	-1486
	2	117.32	49.86	58.66	16.08	5164	**	-1057	-1617

**Strain gauge failure prior to reaching peak load. Strain values above 2000 μm/m reported at pre-peak loads*
***Strain gauge failure prior to peak load*
**** Strain gauge failure prior to testing*
*****Dual strain gauges mounted: 2 on top concrete face at midspan, 1 on each longitudinal steel bar at midspan*

Where:

P_n *: Nominal load*
M_n *: Nominal moment*
V_n *: nominal shear resistance,*
$\Delta_{mid, ult}$ *: midspan deflection at peak load*
ε_s *: Steel Strain at peak load*
ε_c *: Concrete Strain at peak load, Note: negative values denote compression strain*

8.4.1. Flexural Properties-Maximum Moment

The various reinforced concrete beams' flexural load properties are shown in Figure 58 and

Table 28. In terms of peak loading, it was observed that all beams (control and LCC) generally presented similar P_n values, ranging from 98-125 kN. It was found that the control beams (NNC-A-50 and NNC-A-30) both presented similar P_n (average values: 118.3 and 118.8 kN respectively) values despite the differences in f'_c values of the mixtures (i.e., 50.0 MPa and 37.1 MPa, respectively), with minimal variability between duplicate specimens. Regarding the LCC beams, it was found that regardless of LCC material content, most of the LCC beams demonstrated similar flexural strength performance comparable to the control beams despite differences in compressive strength and mixture composition. Both the RRS-M5-B-50 and NRS-C-50 beams achieved similar peak loading values (± 4 kN) despite a 13.54 MPa difference in concrete compressive strength (refer to Table 27 for f'_c values). In addition, the RRS-M5-B-50 and NRS-C-50 beams achieved similar performance as the control mixtures despite the incorporation of 100% CRCA,

100% FRCA and 50% GGBFS, lower overall cementitious material content (refer to Table 24) and reduced compressive strength values.

The similar flexural performance of the control and LCC mixtures can be attributed to the reductions within the reinforcement ratio ρ_s (%) and minimal longitudinal reinforcing steel, A_s (mm^2) used in the design of the beams (i.e., A_s = 600 mm^2, ρ_s = 2.1745 %, refer to Table 22). To illustrate the effects of the reduced steel reinforcement within the beams, Equation 19 presents the CSA A23.3-14 [68] formulation used to calculate the nominal moment (M_n) for singly reinforced beams (as in the case of the beams designed within the experimental program).

$$M_n = \Phi_s A_s f_y d(1 - \frac{\Phi_s A_s f_y}{2\Phi_c \alpha_1 f'_c bd}) \qquad \text{Equation 19}$$

Where,

A_s : area of steel within the beam cross-section (mm^2),
f_y : yield strength of the reinforcing steel (MPa),
b : width of the beam (mm),
d : effective depth of the reinforcement, i.e., distance from top concrete surface to the centroid of reinforcing steel, (mm),
α_1 : rectangular concrete stress distribution factor, based on the compressive strength (f'c)
ϕ_s and ϕ_c : material resistance factors for concrete and steel reinforcing bars (ϕs = 0.85 and ϕc = 0.65).

Regarding M_n calculations, material resistance factors were modified to (i.e., $\phi_s = \phi_c = 1$) to allow for adequate comparison of experimental values with theoretical calculations (in the case of typical concrete design, the factored moment resistance of the beams (M_r) would be computed where material resistance factor values of $\phi_s = 0.85$ and $\phi_c = 0.65$ would be utilized).

Based on the formula provided within Equation 19, it can be observed that while the M_n properties of the concrete are impacted by the f'_c and material resistance factors, the A_s, f_y and d values have the largest effect on the M_n values. As a result, given the minimal steel reinforcement within the various beams, it was expected that the beams would exhibit similar flexural strength performance despite differences in compressive strengths of the various concrete mixtures. Plotting of the nominal moment versus area of tension reinforcement for various compressive strengths (i.e., 25, 30 and 50 MPa) indicates that in the case of under-reinforced beams with total area reinforcing steel values (i.e., A_s) under 800 mm^2, relatively similar M_n values can be observed amongst all of the beams irrespective of concrete compressive strength. In the case of the beams developed within the experimental program for A_s values of 600 mm^2, theoretical M_n

values at compressive strengths of 25 and 55 MPa were 34.5 kNm and 39.38 kNm (4.9 kNm difference: 12.5%).

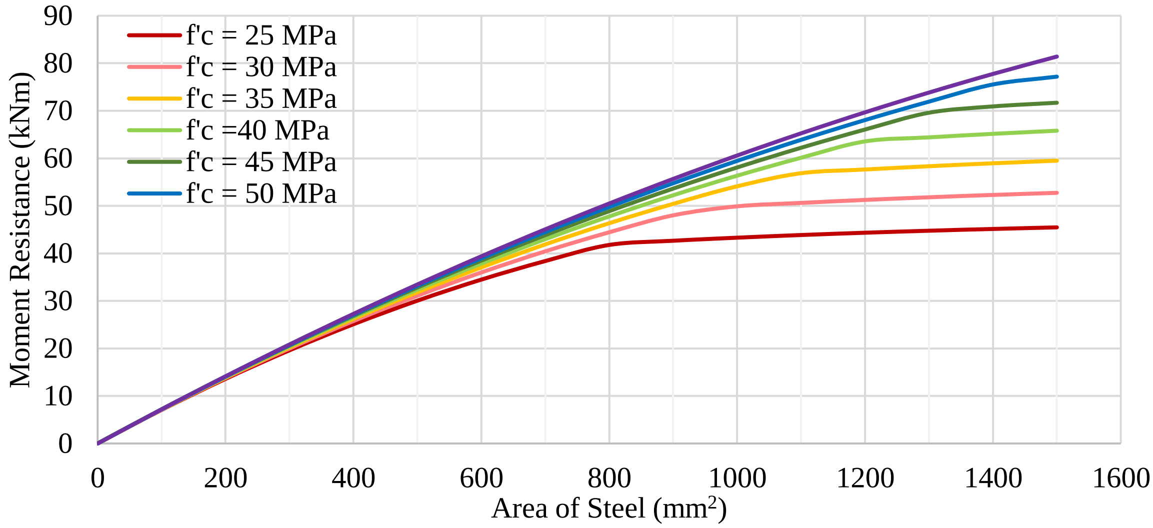


Figure 59-Effect of concrete f'c on M_n based on A_s of beams

Note: For all plots b: 150 mm, h: 225 mm, d: 183.05 mm, f_y = 400 MPa

For clarity, the area of reinforcement at the balance point (i.e., the onset of concrete controlled failure mechanisms), ($A_{s,bal}$) for concrete compressive strengths ranging from 25-50 MPa based on the beam specifications within the experimental program (i.e., b, h, d, f_y) are provided below in Table 29.

Table 29-Steel reinforcement at balance point-based on concrete compressive strength

f'_c (MPa)	A_s,bal (mm^2)
25	947
30	1111
35	1266
40	1413
45	1552
50	1683
55	1806
Corresponding beam properties: b: 150 mm, h: 225 mm, d: 183.05 mm, f_y = 400 MPa	

Based on the findings presented within Figure 59, it can be reasoned that the low quantity of reinforcing steel (i.e., use of 2-20M bars, A_s = 600 mm^2) minimized the impact of differences in concrete compressive strength and led to similar M_n among the majority of the tested beams. While most of the LCC beams presented experimental findings in line with theoretical predictions as per CSA A23.3-14 [68] design standards (i.e., Equation 19), the code-based equations were developed based on empirical data that assumed conventional concrete. As a result, the assumptions, rectangular stress-strain distribution, and stress block approximations utilized within the CSA A23.3-14 flexural strength formulations may not necessarily suit flexural elements containing LCC.

In particular, several of the CSA A23.3-14 design relations used to model the flexural behaviour of concrete elements such as strain compatibility and the modified Hognestad stress-strain relation may need to be re-evaluated regarding their applicability for LCC flexural elements. Other design assumptions utilized within the existing CSA A23.3-14 [68] design standards such as limiting concrete strain values of 0.0035 and zero contribution of the tensile strength of concrete with design calculations may need to be reevaluated given the differences within the composition and properties of LCC materials, including the effect of deleterious substances/materials. Regardless of the lack of mention within the current CSA A23.3-14 [68] design standards regarding the applicability of current codes/standards with LCC, the experimental maximum moment values (M_{n-exp}) indicate that both LCC and control beams present similar member resistances despite varying compressive strengths or amount of recycled materials usage.

Previous studies have also observed similar findings, concluding that reinforced LCC beams containing 100% CRCA had similar flexural capacities as conventional concrete beams [50,58,141,142]. Further studies found that for LCC beams, flexural strength was affected primarily by the reinforcement ratio (ρ) rather than the compressive concrete strength value when suitable tensile reinforcement is utilized and yields prior to concrete crushing (i.e., under-reinforced behaviour) [58,59]. Various studies have found that longitudinal tension-steel yielded first for LCC beams designed with existing code-based equations, followed by concrete crushing. Many such studies have found that the flexural behaviour of reinforced LCC beams are not affected by the presence of RCA-concrete [143] and demonstrate suitable flexural strength properties for use in structural concrete applications [146], with further studies noting that current ACI 318 design code limitations on ductility and maximum reinforcement ratios are applicable for LCC and ensure adequate ductile behaviour [59].

Concerning the experimental study, the beams were designed to undergo ductile flexural behaviour, where yielding of the reinforcing steel was designed to theoretically (as per CSA A23.3-14 [68] standards) occur prior to crushing of concrete, regardless of the concrete compressive strengths of the respective mixtures. The strain gauge readings corresponding to peak load (P_n) of the beams presented within

Table 28 corroborate that prior to failure, the steel strains (ε_s) (with the exception of the RRC-A-50 (2) and RRS-A-50 (1) beams) beams exceeded 2000 μm/m ($\varepsilon_s = 0.002$) corresponding to the assumed yield strain value (ε_y) of the longitudinal reinforcement provided by the manufacturer. Given the presented steel strains values, it was stated that within the majority of LCC beams, the longitudinal 20M steel reinforcement had yielded prior to peak loading (and hence failure of the beams due to concrete crushing). The observed experimental values further validate the use and applicability of the current CSA A23.3-14 standards with regards to ductility behaviour and maximum reinforcement ratios for the design of LCC flexural elements.

With regards to the RRS-A-50 (1) and RRC-A-50 (2) beams however, strain values below yielding (i.e., $\varepsilon_s < \varepsilon_y$) were reported in addition to reduced M_n values relative to the other beams. Further visual inspection of the corresponding load-displacement plots (Figure 58) also indicated the occurrence of a brittle (over-reinforced) failure, given the sudden drop in load capacity without any yielding of the reinforcement observed. To emphasize the observed brittle (over-reinforced) failure, the corresponding load-displacement plots of the RRS-A-50 (1) and RRC-A-50 (2) beams are shown in Figure 60. Note that the load-displacement plot of the respective compansion beams (i.e. RRC-A-50 (1) and RRS-A-50 (2)) are also included for comparison purposes.

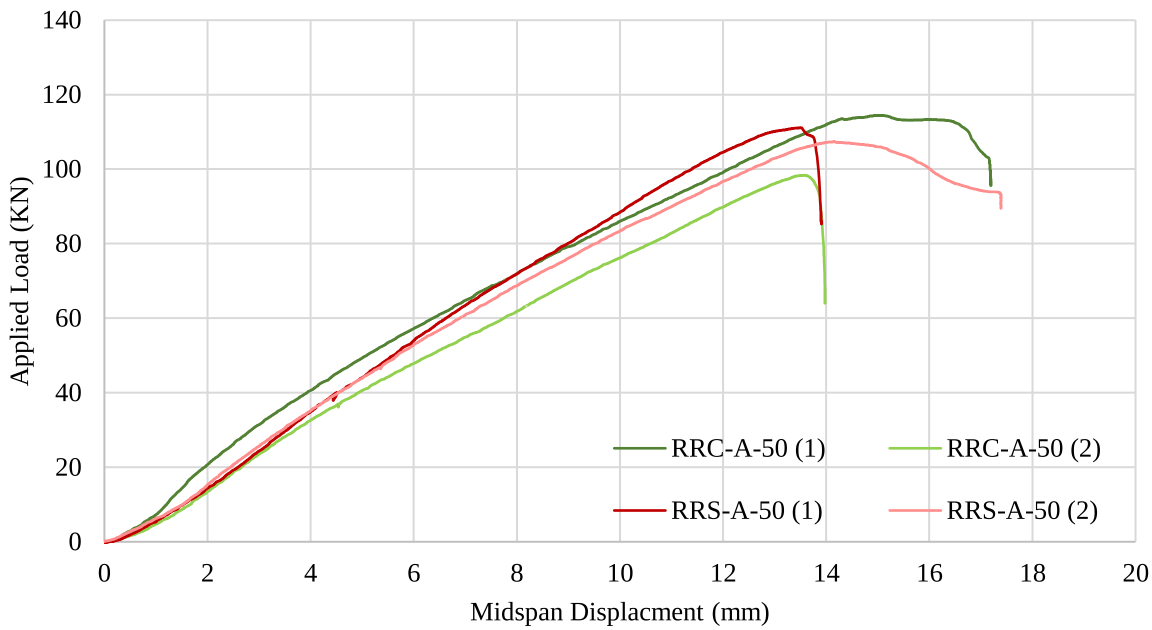


Figure 60-Load-displacement chart: Over-reinforced Behaviour

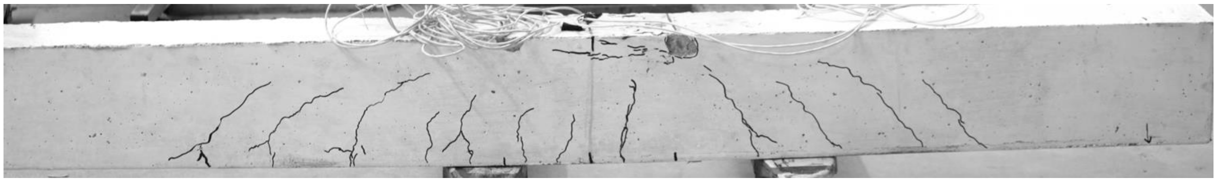
Note: Companion beams included for comparison purposes.

Based on the load-displacement plot, it was observed that upon reaching peak load, both the RRC-A-50 (2) and RRS-A-50 (1) beams displayed brittle behaviour exhibited by the sudden drop in applied loading at a midspan displacement of approximately 14 mm. Compared to the load-displacement plots of the other tested beams, the RRC-A-50 (2) and RRS-A-50 (1) beams do not present post-peak yielding behaviour or any indication of a steel-controlled failure as observed within the companion beams. The brittle failure of the RRC-A-50 (2) and RRS-A-50 (1) beams indicate a lack of steel yielding, which was confirmed upon inspection of the strain gauge values for both the RRC-A-50 (2) (i.e., ε_s = 2103, 1769 μm/m) and RRS-A-50 (1) beams (i.e., ε_s = 1759, 1632 μm/m) for the longitudinal steel as reported in

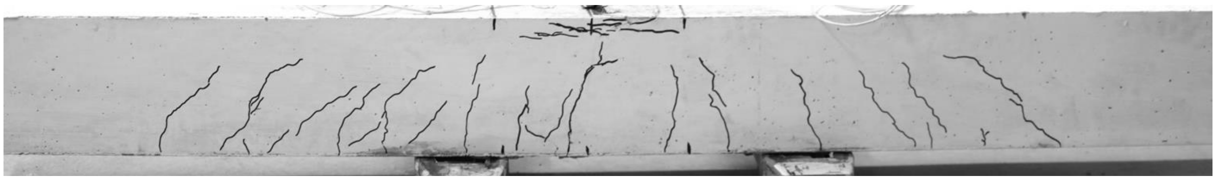
Table 28. However, it should be noted that the strain gauge readings at the top-face of the concrete at midspan were below those assumed to cause concrete crushing. As per Cl 10.1.3 in the CSA A23.3-14 standards [68], the maximum strain at the extreme compression fibre of 3500 μm/m (i.e., ε_{cu} = 0.0035) was assumed at the onset of crushing failure. However, the recorded strain within the gauges mounted on the top concrete face ranged from 1000 to 1500 μm/m at peak loading for the RRC-A-50 (2) and RRS-A-50 (1) beams. Further comparison of the second trial (i.e., companion) beams for the RRC-A-50, and RRS-A-50 mixtures indicate that over-reinforced/brittle behaviour was not observed as per the load-displacement plots (refer to Figure 58). Further, the recorded steel strain values at peak load for the second companion beams were also found to exceed the ε_y values (i.e., 2000 μm/m) for the longitudinal bars (refer to

Table 28). Therefore, given the same mixture proportions and beam design (i.e., reinforcement arrangement), it can be reasoned that the mix designs of RRC-A-50 and RRS-A-50 may not be responsible for the observed brittle failure mechanisms observed within the RRC-A-50 (2) and RRS-A-50 (1) beams.

Further visual examination of the cracking patterns found that while flexural, flexural-shear, and shear-based cracks generally occurred in all of the beams, in the case of the RRC-A-50 (2) and RRS-A-50 (1), noticeably larger shear-based cracks were visible. The cracking patterns at failure for the beams are presented in Figure 61-Figure 66.

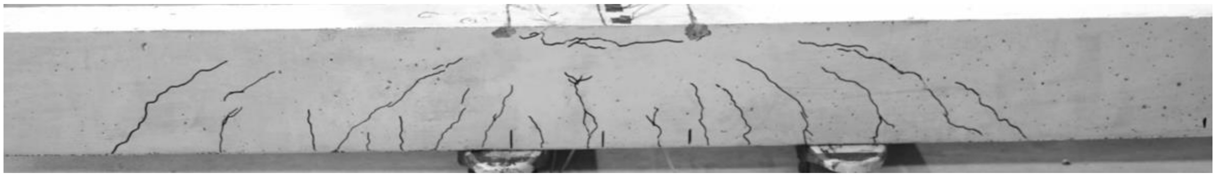


(a)

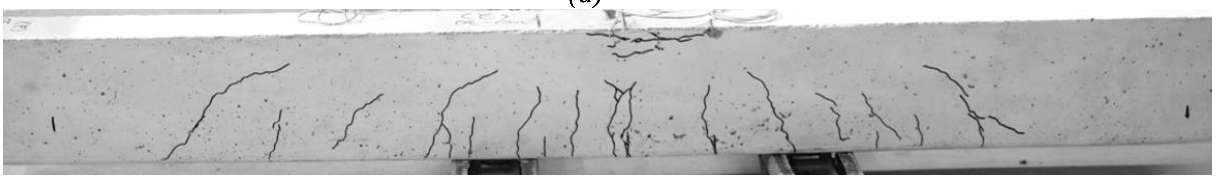


(b)

Figure 61-Crack Patterns (a) NNC-A-50 (1), (b) NNC-A-50 (2)

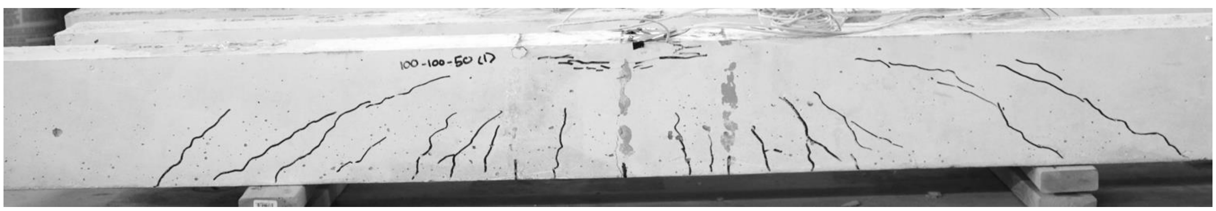


(a)

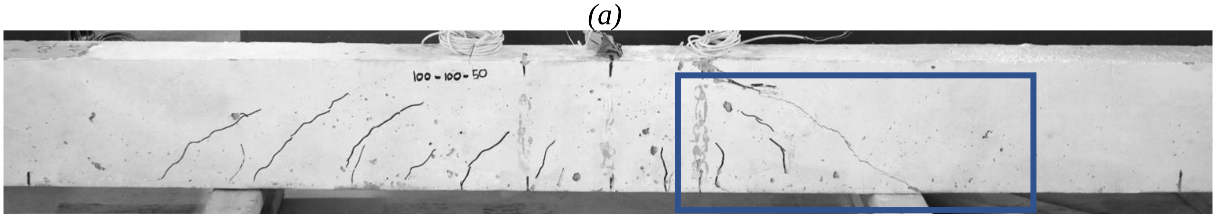


(b)

Figure 62-Crack Patterns (a) NNC-A-30 (1), (b) NNC-A-30 (2)



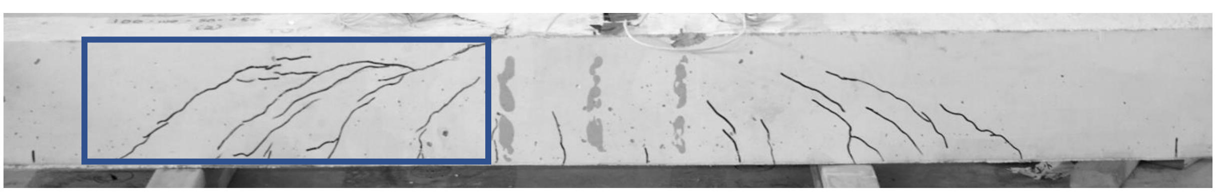
(a)



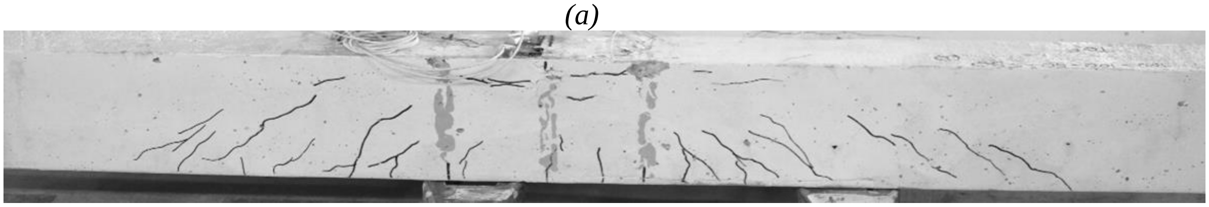
(b)

Figure 63-Crack Patterns (a) RRC-A-50 (1), (b) RRC-A-50 (2)

Significant Shear cracking highlighted for clarity



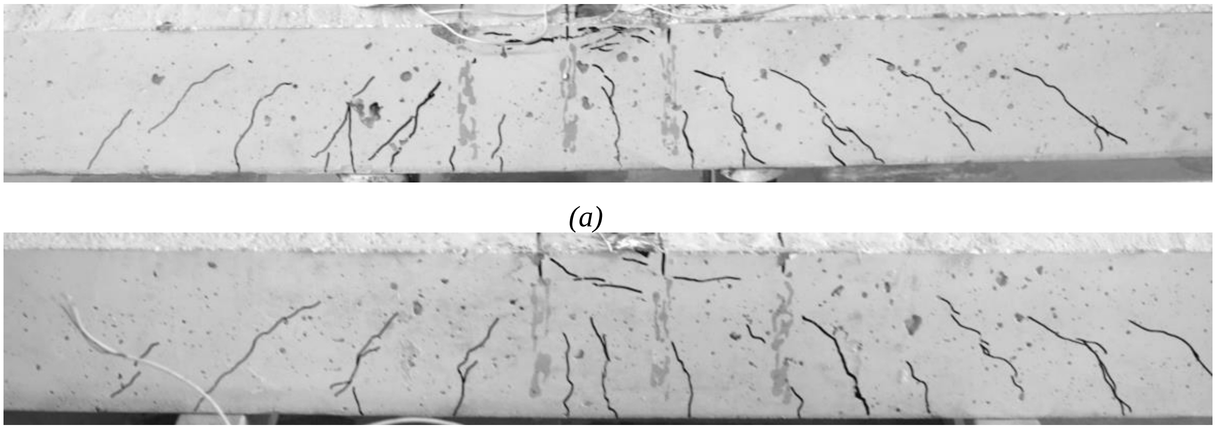
(a)



(b)

Figure 64-Crack Patterns (a) RRS-A-50 (1), (b) RRS-A-50 (2)

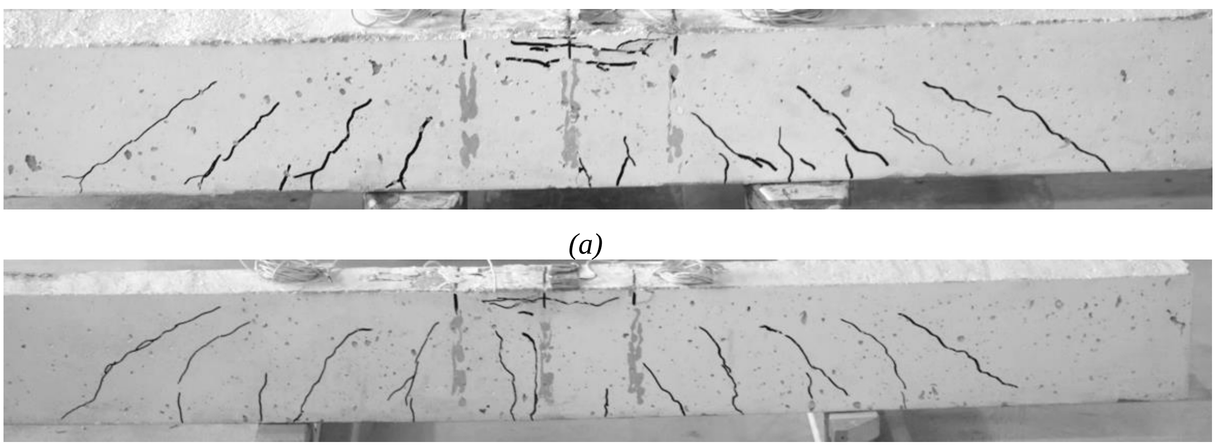
Significant Shear cracking highlighted for clarity



(a)

(b)

Figure 65-Crack Patterns (a) RRS-M5-B-50 (1), (b) RRS-M5-B-50 (2)



(a)

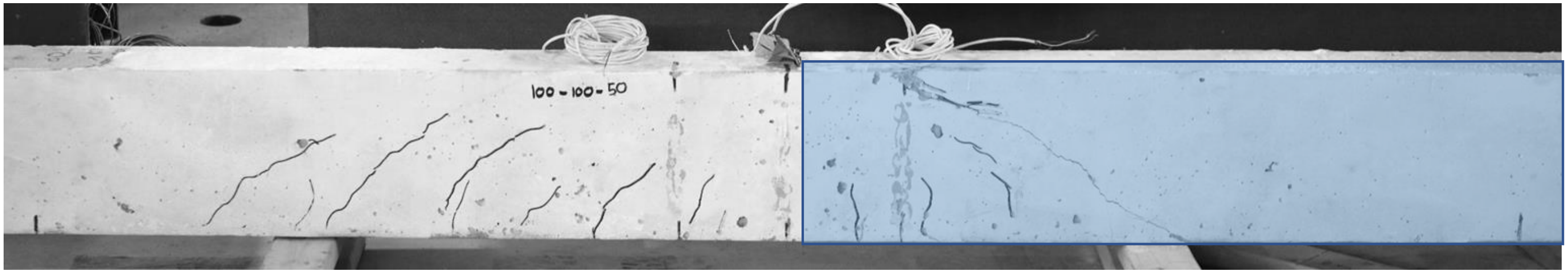
(b)

Figure 66-Crack Patterns (a) NRS-C-50 (1), (b) NRS-C-50 (2)

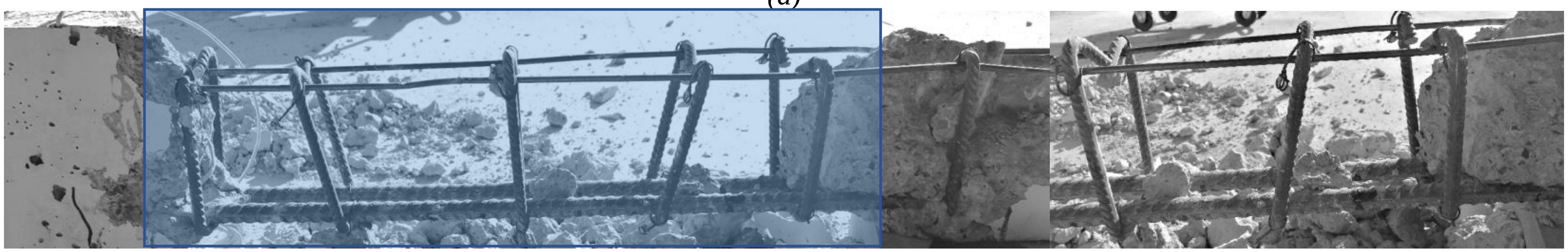
Note Shear cracking has been annotated for select beams for added clarity

As observed for the various beams (except those of the RRC-A-50 (2) and RRS-A-50 (1) beams), flexural cracking (at midspan) and flexural-shear-based cracks occurred in each of the beams regardless of differences in peak loading values and concrete compressive strengths of the various beams. The tensile and shear-flexural-based cracking observed near the midspan within the side face profiles of the majority of the beams and the limited shear cracking (i.e., angled from loading point to bottom supports) indicate that flexural-based action was the predominate failure within the tested beams. While the minimization of observable shear cracking further indicates that the transverse stirrups within each of the various beams provided sufficient shear resistance (i.e., $V_n > V_f$). In the case of the tested beams, visual indication of the crack patterns provides evidence to support further that shear resistance properties of the beam exceeded the applied shear forces given the limited shear-based cracking and extensive flexural cracking and ductile behaviour observed within the P-Δ plots of the beams. Thus, it can be reasonably concluded that the strength of the beams (with the exception of the RRC-A-50 (2) and RRS-A-50 (1) beams) was governed by flexural action (i.e., governed by yielding of the longitudinal reinforcement).

In the case of the RRC-A-50 (2) and RRS-A-50 (1) beams however, an inspection of the crack patterns presented in Figure 63 and Figure 64 indicate a shear-dominated failure, given the lack of observed flexural cracking and extensive magnitude of shear-based cracking within the cracking profiles of the beams respective to the other beams within the experimental program. To further investigate the observed experimental behaviour of the RRC-A-50 (2) and RRS-A-50 (1) beams, a detailed forensic examination of the beams' longitudinal and transverse reinforcement arrangements was conducted. Using a manual hand-held concrete jackhammer, the surrounding concrete within the vicinity of shear-based crack propagation was carefully chipped away to reveal the embedded longitudinal and transverse reinforcement. Visuals of the concrete sections before concrete removal, exposed reinforcing steel after concrete removal and spacing of the transverse reinforcement are provided within Figure 67, Figure 68 for the RRC-A-50 (2) beam and Figure 69 and Figure 70 for the RRS-A-50 (1) beam.

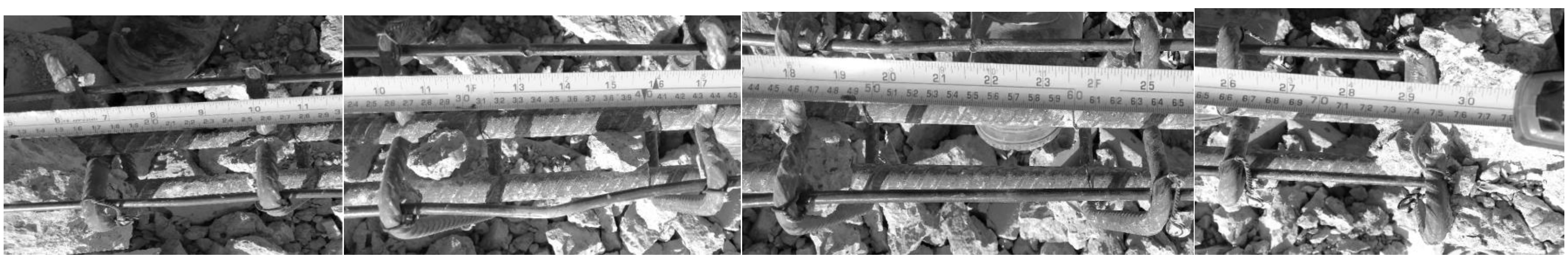


(a)



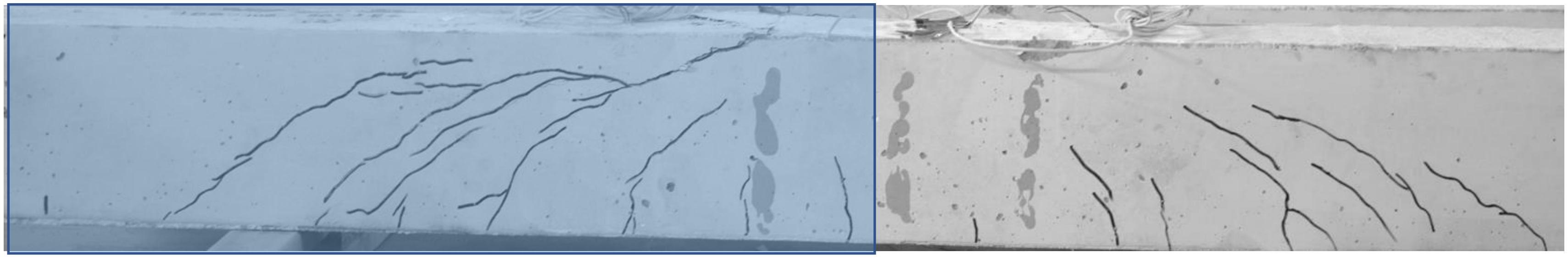
(b) *(c)*

Figure 67-Forensic Investigation Overview: RRC-A-50 (2)
(a) Before Investigation-after testing (Note: significant shear cracking on the right side), (b) Exposed stirrups after concrete removal, (c) Visualization of angled/bent stirrups. Location of forensic investigation shown in blue for clarity



(a) *(b)* *(c)* *(d)*

Figure 68-Forensic Investigation - Stirrup spacing: RRC-A-50 (2)
(a) Spacing: 90 mm, (b) Spacing: 170 mm, (c) Spacing: 175 mm, (d) Spacing: 85 mm (Notes spacing values shown are at the top of the stirrup-at the 6 mm wire)



(a)

(b)

Figure 69-Forensic Investigation Overview: RRS-A-50 (1)

(a) Before Investigation-after testing (Note: Significant shear cracking on the left side), (b) Exposed stirrups after concrete removal and visualization of angled/bent stirrups. Location of forensic investigation shown in blue for clarity

(a) *(b)* *(c)* *(d)*

Figure 70-Forensic Investigation - Stirrup spacing: RRS-A-50 (1)

(a) Spacing: 185 mm, (b) Spacing: 130 mm, (c) Spacing: 160 mm, (d) Spacing: 155 mm (Notes spacing values shown are at the top of the stirrup-at the 6 mm wire)

Based on the forensic investigation, it was found that for both the RRC-A-50 (2) and RRS-A-50 (1) beams, the transverse reinforcement located where the shear-based cracking had occurred was either bent (i.e., non-perpendicular to the longitudinal bars) or spaced incorrectly.

Further investigation of the shear strength properties of the beams with the increased shear spacing of the stirrups as presented within indicates that with the increased stirrups spacing within the RRC-A-50 (2) and RRS-A-50 (1) beams (up to 185 mm), the nominal shear strength values provided by the stirrups greatly reduces. The CSA A23.3-14 [68] shear strength equations for reinforced concrete elements (i.e., Cl 11.3.3, Cl 11.3.4 and Cl 11.3.5) are provided in Equation 20-Equation 22.

$$V_r = V_c + V_s \qquad \text{Equation 20}$$

$$V_c = \Phi_c \lambda \beta \sqrt{f'_c} b_w d_v \qquad \text{Equation 21}$$

$$V_s = \frac{\Phi_s A_v f_y d_v cot\theta}{s} \qquad \text{Equation 22}$$

Where:

V_c : Shear resistance provided by concrete (kN)
V_s : Shear resistance provided by reinforcing steel (kN)
A_v : area of shear reinforcement within typical stirrup spacing (mm^2),
f_y : yield strength of the reinforcing steel (MPa),
b_w : width of the beam (mm),
d_v : effective shear depth, larger of 0.9d or 0.72h (mm),
s : typical stirrup spacing (mm)
θ : angle of inclination of diagonal compressive stress to the longitudinal axis of member (provided by CSA A23.3-Cl 11.3.6)
ϕ_s and ϕ_c : material resistance factors for concrete and steel reinforcing bars (ϕ_s = 0.85 and ϕ_c = 0.65)

Based on Equation 22, as the spacing of the stirrups (s) increases, the shear strength provided by the steel (V_s) steadily decreases and lowers the overall shear strength values of the reinforced concrete section (V_n) as provided within Equation 20. To illustrate the shear strength reductions with increased stirrup spacing, Table 30 provides the shear strength values for various stirrups spacings (V_s) as well as the shear strength provided by the concrete (V_c) for both the RRC-A-50 (2) and RRS-A-50 (1) beams.

Table 30-Nominal shear strength properties of RRC-A-50 (2) and RRS-A-50 (1) beams

Stirrups spacing (mm)	*V_s (kN)	**V_c : RRC-A-50 (2) (kN) (f'c =35.9 MPa)	**V_c : RRC-A-50 (2) (kN) (f'c = 34.7 MPa)
150	98.24		
155	95.07		
160	92.10		
165	89.31		
170	86.68	30.6	30.1
175	84.20		
180	81.86		
185	79.65		
190	77.56		

*Assume stirrups perpendicular to longitudinal bars/do not account for angled positions of stirrups
** Values based on cross-section of tested beams within experimental program (150 x 225 x 2250 mm) (b x h x l)

Note: A_v : 200 mm^2, d_v: 165.375 mm, f_y: 400 MPa, θ: 42^o (0.733 rad), β: 0.21, λ: 1 (both beams)
Steel (V_s) and concrete (V_c) shear strength contribution presented separately-nominal values shown

Therefore, despite the increased stirrup spacing up to 185 mm, the cumulative shear strength of the beams (V_r) (based on Equation 20) still exceeds the applied shear force (V_n) values for both RRC-A-50 (2) and RRS-A-50 (1) beams (refer to

Table 28). However, based on the forensic investigation, several of the stirrups were found to be oriented on an angle relative to the applied loads (i.e., stirrups not perpendicular to longitudinal bars), which may have further impacted the shear strength values reducing the actual shear resistance of the beams further than the values presented within Table 30. Clause 11.3.5.2 of the CSA A23.3-14 [68] standards presents empirical equations to calculate the steel shear strength (V_s) for flexural concrete members with transverse reinforcement inclined to the longitudinal axis as in the case of the RRC-A-50 (2) and RRS-A-50 (1) beams. However, given the variable spacing and orientation (i.e., inclination angles) of the stirrups within the RRC-A-50 (2) and RRS-A-50 (1) specimens, such equations are difficult to apply without significant assumptions. For completeness, the Clause 11.3.5.2 equations presented within CSA A23.3-14 [68] are presented below within Equation 23.

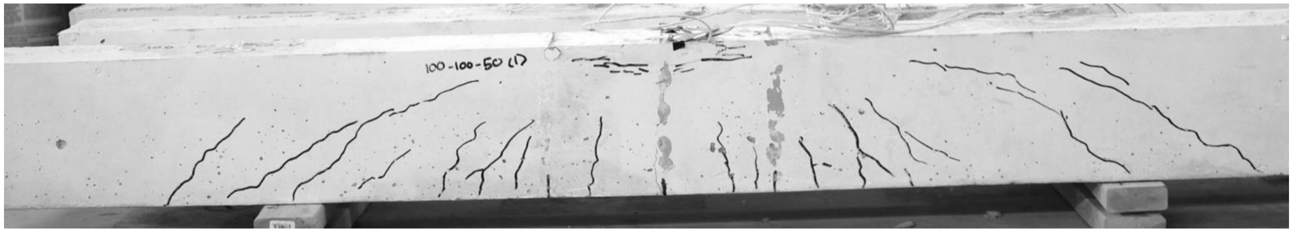
$$V_s = \frac{\Phi_s A_v f_y d_v (cot\theta + cot\alpha) sin\alpha}{s} \quad \text{Equation 23}$$

Where,

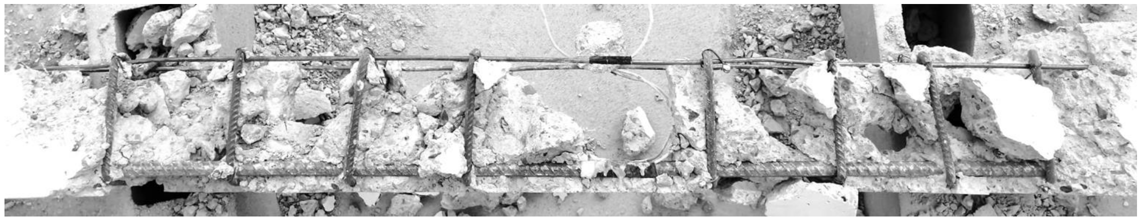
V_s : Shear resistance provided by reinforcing steel (kN)
A_v : area of shear reinforcement within typical stirrup spacing (mm^2),
f_y : yield strength of the reinforcing steel (MPa),
d_v : effective shear depth, larger of 0.9d or 0.72h (mm),
s : typical stirrup spacing (mm)
θ : angle of inclination of diagonal compressive stress to the longitudinal axis of member (provided by CSA A23.3-14: Cl 11.3.6)
α : angle of inclination of stirrups from the longitudinal axis (rad)
ϕ_s : material resistance factors for steel reinforcing bars (ϕ_s = 0.85)

With regard to shear resistance, while the steel shear strength (V_s) may have been impacted, the shear resistance provided by the concrete should also be examined. While Equation 23 (Cl 11.3.4 of CSA A23.3-14 [68]) outlines the concrete shear strength contribution, it should be noted that such relations were developed for conventional concrete mixtures comprised without the LCC materials (i.e., CRCA, FRCA or SCM's). As a result, the applicability of such relations needs to be evaluated to assess further the applicability of the existing design standards for LCC. Given the unknown applicability of the empirically provided V_c values as well as the reduced V_s values due to increased spacing and inclination of the stirrups, explanation of the observed brittle shear failure observed within the RRC-A-50 (2) and RRS-A-50 (1) beams cannot narrowly be determined, rather can be attributed to a cumulation of all factors.

Therefore, based on the experimental values and findings from the forensic investigation, it can be proposed that despite precautions taken during reinforcement cage assembly (i.e., extensive measuring and use of steel ties during cage assembly), poor stirrup construction of the RRC-A-50 (2) and RRS-A-50 (1) beams negatively impacted the resulting shear strength properties of the beams. The inadequate shear resistance (i.e., $V_c + V_s$) of the RRC-A-50 (2) and RRS-A-50 (1) beams led to brittle failure prior to yielding of the longitudinal reinforcement, hence governing the flexural strength (i.e., M_n, P_n) properties. To validate/verify the impact of the transverse rebar construction on the governing strength mechanisms, a further investigation regarding the transverse reinforcement construction of the comparison beams (i.e., RRC-A-50 (1) and RRS-A-50 (2)) was also conducted similar to that conducted for the RRC-A-50 (2), and RRS-A-50 (1) beams. Figure 71 and Figure 72 present the arrangement after the embedded reinforcement within the RRC-A-50 (1) and RRS-A-50 (2) beams after the manual removal of the surrounding concrete. It should be reiterated that care was taken not to deform any of the embedded rebar to accurately assess the rebar conditions of the respective beams during experimental testing.

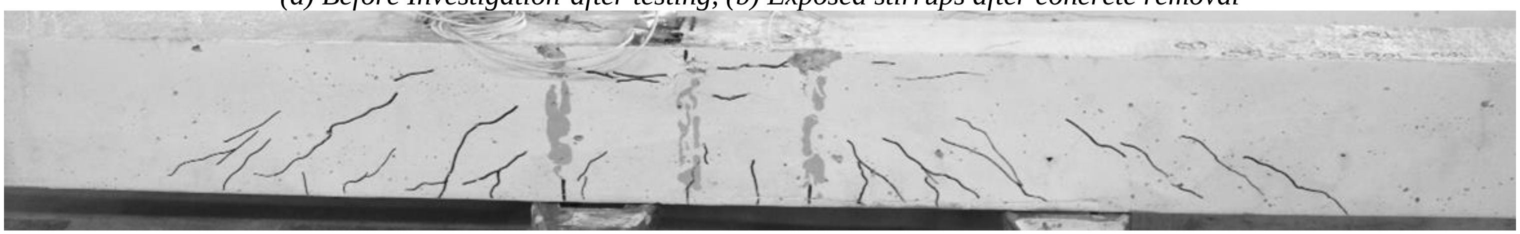


(a)

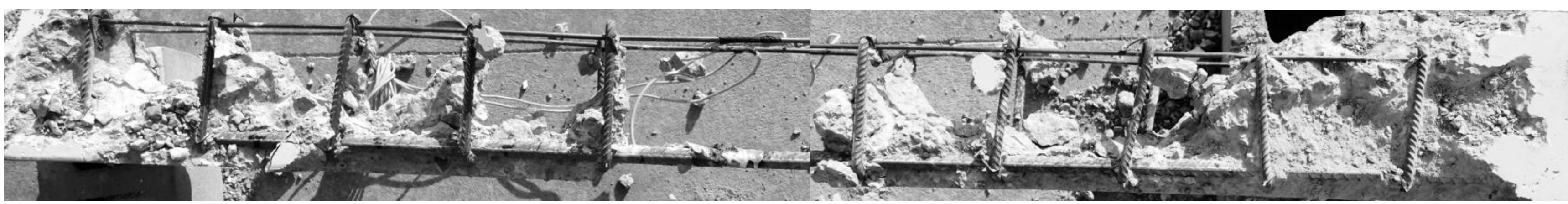


(b)

Figure 71-Forensic Investigation Overview: RRC-A-50 (1)
(a) Before Investigation-after testing, (b) Exposed stirrups after concrete removal



(a)



(b)

Figure 72-Forensic Investigation Overview: RRS-A-50 (2)
(a) Before Investigation-after testing, (b) Exposed stirrups after concrete removal (left and right side presented separately)

The forensic investigation found that the reinforcement arrangement within the RRC-A-50 (1) and RRS-A-50 (2) beams were of substantially higher quality than that of the respective companion beams, with transverse reinforcement found to be equally spaced throughout the entirety of the beams. It was noticed that in the case of the RRS-A-50 (2) beam, select stirrups were marginally inclined (relative to the longitudinal axis), although the spacing of the stirrups was not found to be increased by more than approximately 5-10 mm (i.e., new spacing: 155-160 mm, design spacing: 150 mm).

The experimental observations and forensic investigation both provide a reasonable justification to attribute the brittle failures observed for the RRC-A-50 (2) and RRS-A-50 (1) to the beams' inadequate shear strength due to the stirrups' poor construction quality. The uniform mixture batch and concrete mechanical properties (i.e., f'_c, f'_{ct}) amongst both beams provide practical reasoning to conclude that the improper beam construction due to improper stirrup spacing/orientation of the stirrups served as a limiting factor, governing the resultant properties of the RRC-A-50 (2) and RRS-A-50 (1) beams resulting in brittle failure mechanisms.

Despite such conclusions, it can be further stated that given the significant impact of beam construction accuracy on the results flexural properties, further research investigations are required to accurately assess the applicability of the existing design standards regarding theoretical flexural behaviour with regards to empirical values (i.e., the occurrence of brittle failure within experimental findings). As noted in Table 30, regardless of the increased spacing of the stirrups (i.e., up to 190 mm), theoretical design equations indicate that adequate shear resistance (i.e., $V_{r\text{-new stirrup spacing}} > V_n$) should have been provided given the relatively lower V_n values of the beams (i.e., 41.81 kN and 39.5 kN- refer to

Table 28). Therefore, given the limited accuracy regarding theoretical shear resistance values and experimental findings, further experimental testing and research investigation are required to assess whether existing standards can be safely applied to LCC mixtures given constructability tolerances within modern construction and the significant impacts observed to varying stirrup spacing and beam construction.

8.4.2. Application of CSA A23.3-14 design standards

Regarding the applicability of existing CSA A23.3-14 [68] concrete design standards, the experimental flexural strength values indicate that regardless of LCC usage, experimental flexural strength values exceeded factored and nominal flexural capacity predictions. To illustrate such observations, Table 31 presents the experimental moment resistance ($M_{n\text{-exp}}$) values (moment resistance calculated based on experimental applied loading values (P_n)- refer to Equation 17); theoretical flexural strengths values (nominal-M_n and factored-M_r) obtained from CSA A23.3-14 [68] formulations using Equation 19.

Table 31-Comparison of experimental and theoretical values (peak load and deflection)

Mix	Experimental		Theoretical-Nominal**		Theoretical-Factored**	
	$P_{n\text{-}exp}$ (kN)	$M_{n\text{-}exp}$ (kNm)	M_n	$(M_{n\text{-}exp}/M_n)$	M_r	$(M_{n\text{-}exp}/M_r)$
NNC-A-30 (1) *	117.40	49.90	37.58	1.33	30.22	1.65
NNC-A-30 (2) *	120.24	51.10	37.69	1.36	30.34	1.68
NNC-A-50 (1) *	116.18	49.38	39.19	1.26	32.02	1.54
NNC-A-50 (2) *	120.42	51.18		1.31		1.60
RRC-A-50 (1)	114.43	48.63	37.43	1.30	30.06	1.62
RRC-A-50 (2) ***	98.37	41.81		1.12		1.39
RRS-A-50 (1) ***	111.13	47.23	37.21	1.26	29.82	1.58
RRS-A-50 (2)	107.42	45.65		1.23		1.53
RRS-M5-B-50 (1)	112.55	47.83	37.83	1.26	30.51	1.57
RRS-M5-B-50 (2)	113.95	48.43		1.28		1.59
NRS-C-50 (1)	125.3	53.25	39.36	1.35	32.20	1.65
NRS-C-50 (2)	117.32	49.86		1.27		1.55

**Control Mixtures*
***Theoretical values based on CSA A23.3-14 standards. Nominal: $\Phi_c = \Phi_s = 1$, factored $\Phi_c = 0.65$, $\Phi_s = 0.85$.*
****Beams that displayed brittle failure mechanisms*

Based on the values in Table 31, both control and LCC beams presented displayed significantly higher experimental moment resistance values, with experimental values observed to be 12-36% larger than the nominal strength predictions. It should be highlighted with regards to the factored moment resistances used within conventional concrete design practices (i.e., Φ_s = 0.85, Φ_c = 0.65), the observed experimental moment resistances for both control and LCC tested were found to be up 69% higher than the predicted values calculated by the current CSA A23.3-14 [68] flexural design equations. Analysis of the factored flexural moment resistance of the RRC-A-50 (2) and RRS-A-50 (1) beams also found that despite the observed brittle failure mechanism and lowest experimental peak loading values (i.e., $P_{n\text{-}exp}$), experimental moment resistance values were still 39 and 58 % higher than the factored flexural capacity values; which equate to a 11.75 kNm and 17.41 kNm margin of difference respectively.

As a result, it can be reasoned that despite the use of LCC materials within the various mixtures and the brittle failure mechanisms observed within the RRC-A-50 (2) and RRS-A-50 (1), the experimental moment resistance values provide a minimum margin 1.32 margin of safety with regards to the factored theoretical moment resistance values from existing CSA A23.3-14 design equations (i.e., $M_{n\text{-}exp}/M_r$ = 1.39 minimum). Given the presented findings, regardless of material incorporation (CRCA, FRCA and SCM's) or occurrence of brittle failures (attributed to constructability quality as per forensic investigation), the LCC beams were able to demonstrate sufficient flexural strength capacity similar to those of the control specimens despite differences within compressive strength properties of the various mixtures. The similar flexural performance of the LCC and control specimens provides adequate reasoning to conclude that LCC can be utilized within structural applications while demonstrating a similar margin of safety (i.e., $M_{n\text{-}exp}$ /M_r) flexural behaviour (i.e., under-reinforced behaviour). The comparable flexural strengths amongst control and LCC beams also indicate that the existing CSA A23.3-14 [68] concrete design equations, empirical relations and design assumptions can effectively be utilized to represent the flexural behaviour/characteristics of LCC flexural elements, further indicating the limited effect of LCC material incorporation on the flexural strength properties of reinforced concrete elements.

It should be noted that while such conclusions apply to all of the tested LCC mixtures within the experimental program, the undesirable brittle failures observed within the RRC-A-50 (2) and RRS-A-50 (2) beams due to beam construction (as indicated within the forensic investigation) present increased uncertainty regarding the required quality of beam construction given the impactful effect of poor stirrup construction/arrangement on the flexural strength properties. Therefore, while the findings from the forensic investigations, companion beams (i.e., RRC-A-50 (1) and RRS-A-50 (2)) and mixtures with similar compressive strength values (RRS-M5-B-50) provide practical reasoning to support the suitability of such mixtures and explain the observed flexural behaviours, the observed brittle failure mechanisms within the RRC-A-50 and RRS-A-50 mixtures provide reasonable grounds to question the flexural performance of such mixtures from a design perspective. Although suitable flexural properties (i.e., rebar yielding and moment resistance) were achieved with suitable margins of safety (min of 39%), further testing is advised to assess further the flexural behaviour of the RRC-A-50 and RRS-A-50 mixtures, validate forensic investigation findings and determine whether additional design considerations are required for the flexural design of reinforced LCC elements.

In terms of mix design effect, it was observed within the experimental program that despite differences within the hardened concrete properties of the various mixtures (i.e., f'_c, f'_{ct}) due to varying LCC material incorporation of mix design variability (i.e., M-EMV proportioning), similar findings were observed for all mixtures. Although minor differences within the experimental peak loading values were observed, such differences can be attributed to the variability within the compressive strengths of the various mixtures (or stirrup orientation in the case of the RRC-A-50 (2) and RRS-A-50 (1) mixtures). Additionally, given the similar flexural performance of the various beams despite differences in hardened mechanical properties and mixture proportions, it can be concluded that M-EMV based mixture portioning provides the most significant benefit in terms of mixture sustainability (i.e., minimization of cement content) without any significant effect on mechanical performance. Although optimization of the mixtures led to the highest flexural strength performance amongst all of the tested mixtures (i.e., NRS-C-50), it should be noted that the higher flexural performance of the NRS-C-50 beams can be partially attributed to higher compressive strength values relative to other mixtures. It should be noted that in the case of the RRS-M5-B-50 beams (as well as that of the NNC-A-30, RRC-A-50, RRS-A-50), the similar flexural strength achieved despite the reduced compressive strength values can be attributed to low reinforcement of the tested specimens as previously discussed in Figure 59. As a result, while the RRS-M5-B-50, NNC-A-30, RRC-A-50 and RRS-A-50 beams presented similar flexural strength values, similar findings may not be present for beams with increased reinforcement ratios (ρ) (assuming beams are still designed in an under-reinforced manner).

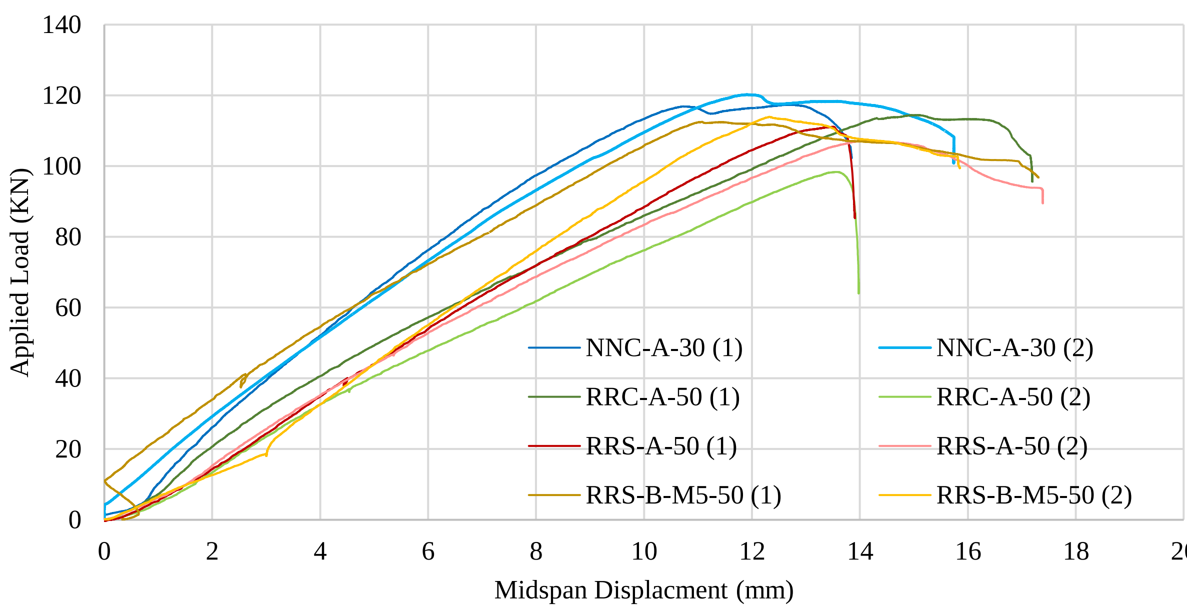
With regard to existing studies, despite limited literature and reported flexural strength properties of LCC with existing studies, the experimental findings align well, with similar experimental findings observed as those reported in past studies. Previous studies have found that LCC beams' experimental nominal flexural strength values were 8- 22% greater than the nominal strength values predicted as per ACI-318 guidelines [50,58,141,144]. While other studies have found that LCC beams demonstrate up to 23% higher nominal flexural strength values than Eurocode 2 predictions, with similar values also reported for conventional concrete beams, further indicating the similarity and applicability of the current conventional concrete design codes with regards to LCC [145]. While such studies present similar findings to those within the current experimental program; such findings have been limited to LCC flexural elements designed exclusively with CRCA [50,58,142,144,145] or FRCA [141], with limited investigation conducted for flexural elements designed CRCA and FRCA [59,146] or with optimized mix design methods (i.e., limited to M-EMV with limited CRCA contents) [50,143]. As a result, the findings from the experimental program provide further experimental precedence to support the structural suitability and use of LCC mixtures with increased LCC material contents (i.e., CRCA, FRCA and SCM’s) as justification for LCC as a comparable alternative to conventional concrete flexural elements. Additionally, the findings from the experimental program further support that the use of existing CSA A23.3-14 [68] design provisions yield conservative theoretical predictions regarding moment resistance values, applicable to LCC mixtures comprised of various mixture design methods, material arrangements compressive strengths ranging from 30-55 MPa.

8.5. Serviceability Properties

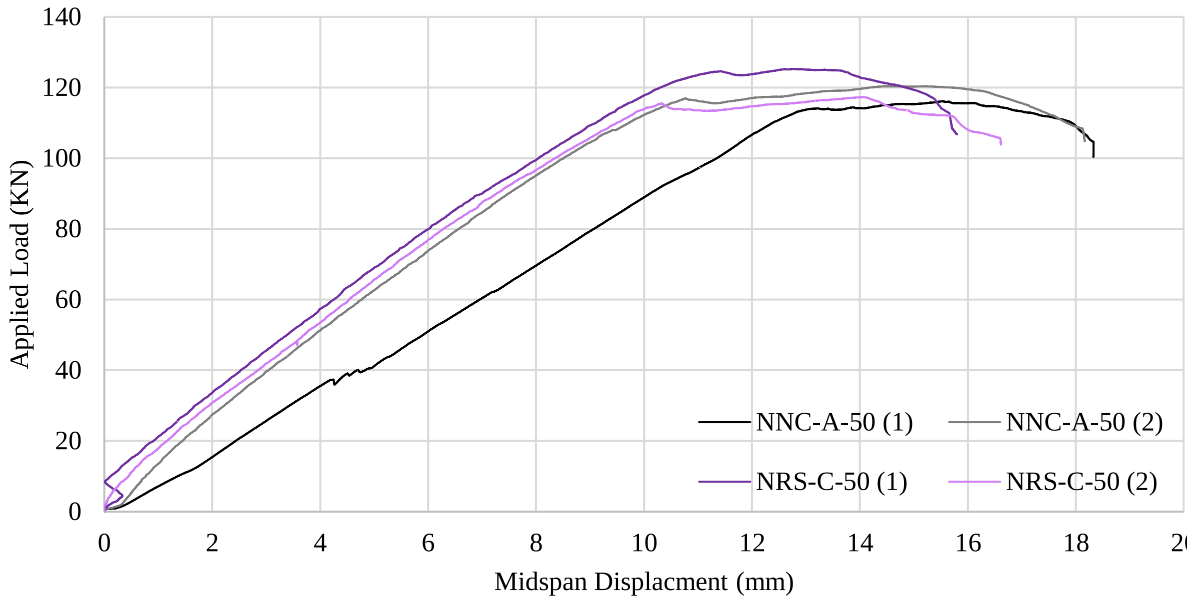
8.5.1. Midspan Deflection at Peak load

Load-displacement plots of the various beams are presented in Figure 58. In terms of midspan displacement ($\Delta_{mid\text{-}exp}$), it was observed that for the majority of the tested beams (except RRC-A-50 (2) and RRS-A-50

(1)), both LCC and control beams presented similar midspan deflection values regardless of differences within material incorporation or hardened properties of the concrete mixtures. It was found that at peak load, the NNC-A-50 mixture presented the largest Δ_{mid} values (average of 17.26 mm), while the NNC-A-30 mixture presented the lowest average values (average of 13.90 mm). Comparatively, it was found that the average midspan displacement value at beam midspan amongst all of the mixtures was 15.14 mm, with the Δ_{mid} values for all of the beams found to be within ± 2.8 mm. In terms of the mixtures with similar compressive strengths, for compressive strengths around 30 MPa (i.e., NNC-A-30, RRC-A-50, RRS-A-50, RRS-M5-B-50), the LCC beams presented marginally higher midspan displacement values at peak load. Comparison of the slope of the load-displacement plots for the 30 MPa strength mixtures as shown within Figure 58 indicates that except for the RRS-B-M5-50 (1) beam, the LCC mixtures displayed reduced stiffness/elastic modulus values (i.e., E_c - indicated by the reduced slope values) compared with the NNC-A-30 control beams. As a result, the reduced stiffness values and similar flexural performance properties (as discussed in Chapter 8.4) led to the LCC beams' marginally higher midspan displacement values. To highlight the differences within the stiffness properties and midspan displacement of the beams, the load-displacement plots of the various beams with tested compressive strengths ranging from 30-40 MPa (i.e., actual compressive strength values, refer to Table 25) are presented within Figure 73a, while the load-displacement plots of the various beams with tested compressive strengths over 40 MPa (i.e., actual compressive strength values, refer to Table 25) are presented within Figure 73b.



(a)



(b)

Figure 73-load-displacement plots

(a) Compressive Strengths < 40 MPa-Note: reduced stiffness of all LCC beams, except RRS-B-M5-50 (1)
(b) Compressive strengths > 40 MPa (Note: Reduced stiffness of NNC-A-50 (1) beam)

Compared with existing literature, previous studies have reported similar findings stating that LCC beams and mixtures often present higher deflection values than conventional concrete beams (regardless of LCC materials or differences within the mixture composition) [58,142,145,146]. Further research investigations have attributed the increased midspan deflection values to the reduced elastic modulus of LCC mixtures relative to conventional concrete mixtures [58,145] due to the reduced elastic modulus of the RCA (i.e., CRCA) used within the LCC mixtures [95]. As summarized by McNeil and Kang [95], the elastic modulus of LCC concrete has generally be reported within numerous studies to be lower than that of conventional concrete; however, significant variations have been reported. Studies by McGinnis et al. [16] and Omary et al. [10] have reported that relative to conventional concrete mixtures, LCC presents up to 34.4% lower stiffness values [16], while further studies by Pedro, de Brito and Evangelista, have also reported similar findings with similar reductions observed, however, extensive variability was reported based on RCA source, with minor elasticity values reported (i.e., 10% reduction with 100% CRCA) [26]. Other studies by Butler et al. [173] and McNeil and Kang [95] have also noted that while the modulus of elasticity of conventional concrete is related to the modulus of elasticity of the NCA, similar relations are also applicable for LCC. Other researchers have also found that the concrete modulus of elasticity (E_c) depends both on the stiffness of the paste and the aggregates, with additional research investigations finding that the higher propensity for deformation of RCA (given the reduced modulus of elasticity) often leads to reduced elastic modulus/stiffness properties for LCC mixtures and increased deformations [26,112].

Additional studies have commented on the cracking patterns for LCC mixtures, stating that LCC beams' lower effective moment inertia (I_e) properties due to increased cracking observed within LCC beams relative to conventional concrete beams may also be attributed to the increased midspan deflection [145]. However, as per visual inspection of the crack patterns of the various beams, the LCC beams did not appear to present any significant differences in terms of crack spacing/crack patterns relative to the conventional concrete beams.

Other studies have found that the counteracting effects due to the reduced tensile strength values (lower applied stresses required to initiate cracking [141,144,145]) and the reduced modulus of elasticity of LCC materials (i.e. increased deformability) may offset each other and lead to similar cracking behaviour and crack spacing [141] as conventional concrete beams. Studies conducted by Butler et al. [22] have noted that the incorporation of LCC materials may act to decrease the bond between longitudinal steel [22], which further studies have noted may result in similar cracking behaviour, crack propagation and failure modes for LCC as conventional concrete beams [50,59,141,144]

Concerning the beams tested within the experimental program, for beams presented within Figure 73(a), it was observed that the various LCC beams (except RRS-B-M5-50 (2)) displayed reduced stiffness values relative to the control specimens (based on the slope of the P-Δ plots) despite the similar flexural performances of the beams (i.e., $M_{n\text{-}exp}$) as indicted within

Table 28. With regard to the observed cracking behaviour (i.e., cracking magnitude and spacing), despite the reduced stiffness of the LCC beams noted within Figure 73a, the observed cracking behaviour of the LCC beams remained comparatively similar to the control beams upon visual inspection of the cracking patterns presented within Figure 62, Figure 63, Figure 64 and Figure 65. Further analysis of the midspan deflection values at peak load (i.e., $\Delta_{mid\text{-}ult\text{-}exp}$) also revealed that while reduced midspan deflection values were observed at peak load (i.e., $P_{n\text{-}exp}$), the LCC beams displayed increased deformations (i.e., $\Delta_{mid\text{-}failure\text{-}exp}$), with significant post-peak plastic deflection observed relative to the control mixtures. In the case of the RRC-A-50 (2) and RRS-A-50 (1), brittle failure mechanisms of the beams resulted in a lack of deflection prior to peak loading with no post-peak plastic deformation observed.

For the beams presented within Figure 73(b), similar observations were also found, although, with regard to the NRS-C-50 mixtures, increased stiffness values relative to any of the other beams (i.e., control or LCC) was observed, as noted in Figure 58 (all beams) and Figure 73(b). The improved stiffness properties can be reasoned to be primarily attributed to the optimization methods used within beam production, such as the TSMA and optimized water compensation and the reduced w/c ratios of the mixture as noted in Table 23 and Table 24-refer to Chapter 7.2 regarding the design methodology for the NRS-C-50 mixture). Therefore, based on the observed stiffness values, the various optimization methods within the NRS-C-50 mixture helped strengthen the microstructure characteristics of the mixture, leading to improved f'_{ct} and increased E_c properties, resulting in reduced deflection values relative to the other tested specimens. It should be noted that improved stiffness properties and reduced deflection values (relative to the control mixtures) were also observed within the RRC-M5-B-50 mixtures (M-EMV proportioning and TSMA). Other studies have also found that EMV/M-EMV proportioning can improve E_c properties and lead to reduced deflections [50].

Despite differences within the properties of the various LCC beams regardless of differences within mixture composition, LCC material incorporation, mix design method failure mechanisms (i.e., in the case of RRC-A-50 (2) or RRS-A-50 (1) beams), all of the LCC mixtures presented comparatively similar deflection properties as the conventional concrete beams with little variability observed amongst duplicate trial beams.

8.5.2. Cracking Moment (M_{cr})

Based on the recorded strain values for the longitudinal reinforcement, curvature (Φ) values were computed for each of the tested beams throughout the entire testing duration using the recorded strain within the steel and concrete based on the formula shown within Equation 24.

$$\Phi = tan^{-1}\frac{\varepsilon_s + \varepsilon_c}{d} \qquad \text{Equation 24}$$

Where:

Φ: Curvature with concrete beam (1/mm)
ε_s : Recorded strain within longitudinal steel
ε_c : Recorded strain within top concrete face
d: Effective depth (mm). Note: 183.95 mm used for all calculations

Based on the computed curvature values, moment-curvature (M-φ) plots were developed and are presented in Figure 74. To aid in visual clarity and comparison purposes, the M-φ plots of the control beams are presented within Figure 75, while the M-φ plots of the LCC beams are presented within Figure 76.

Additionally, the moment-curvature plots for each of the beams during initial loading (i.e., 0-10 kNm) are also presented to highlight the cracking moment (M_{cr}) and cracking curvature (Φ_{cr}).

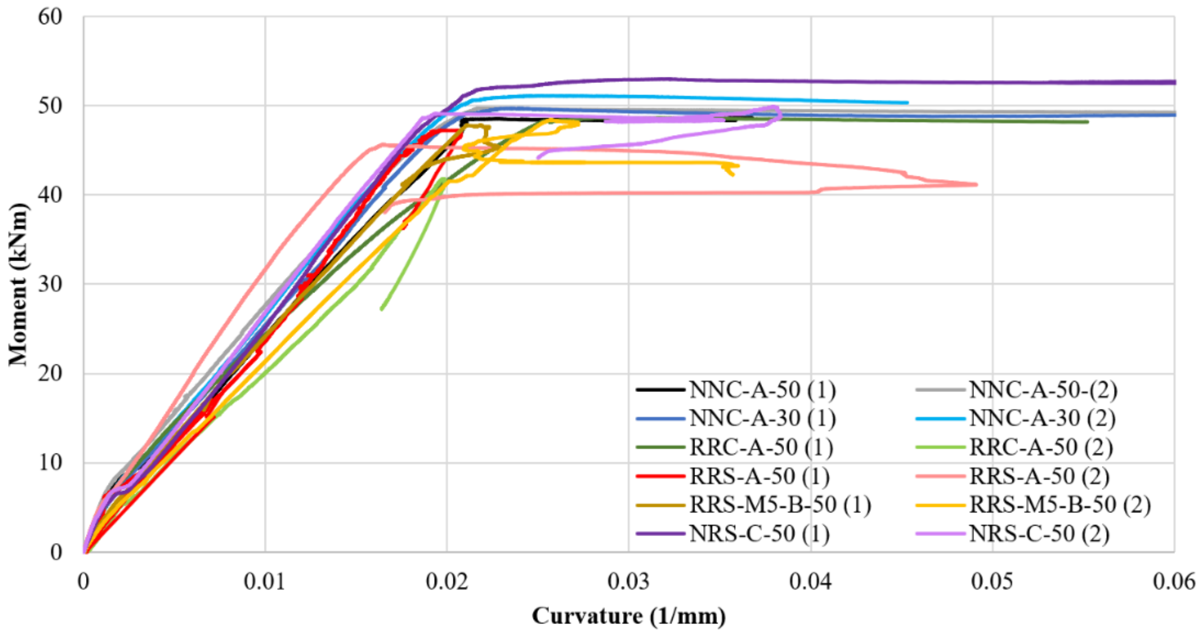


Figure 74-Moment-Curvature Plot: All beams

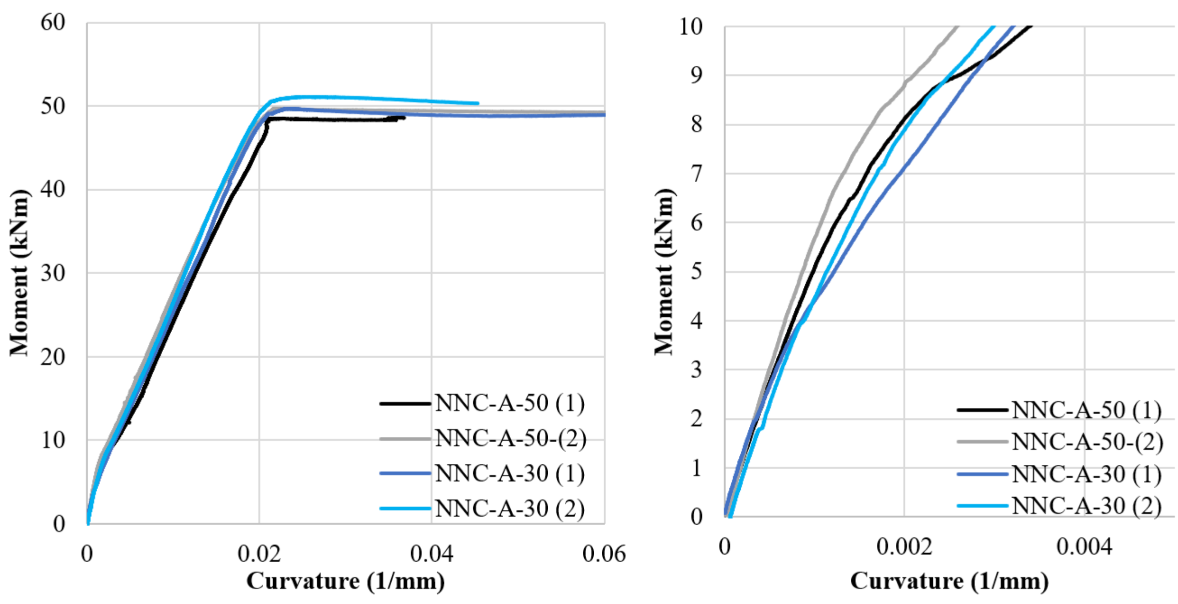


Figure 75-Moment-Curvature Plot: Control beams
(a)-Full Moment Curvature Plot, (b)- Visualization of cracking moment (Mcr)

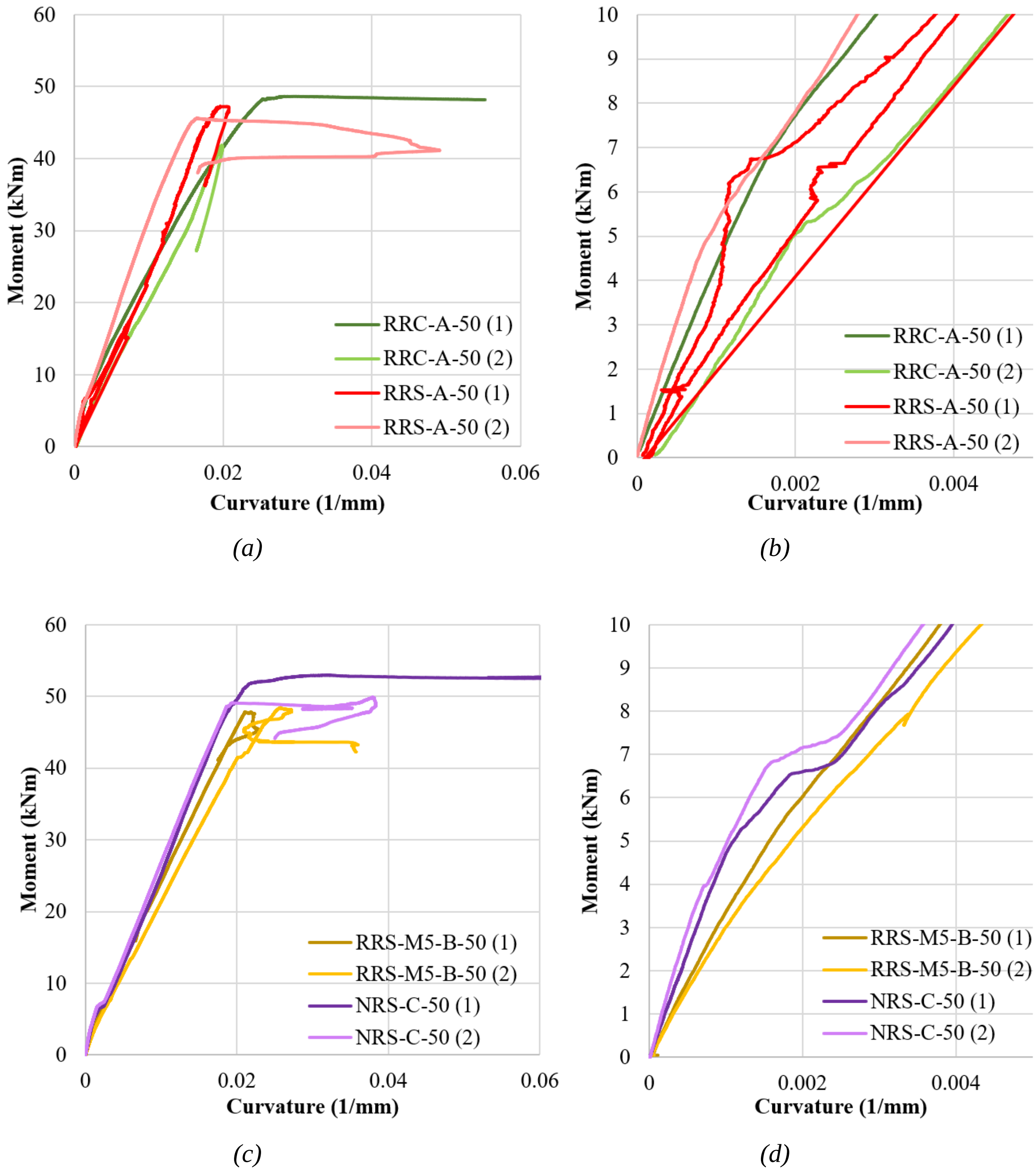


Figure 76-Moment-Curvature Plot: LCC Beams

(Note: Beams separated for clarity, (a)/(c)-Full Moment Curvature Plot, (b)/(d)- Visualization of cracking moment (M_{cr})

Regarding the determination of the M_{cr}, in lieu of methods such as digital image correlation (DIC) or further analysis techniques, tangents were superimposed to the M-φ plots of the various beams during the initial loading of the beam. A data sampling rate of 10 Hz was used for all experimental testing; therefore, exact determination of the M_{cr} was not possible given variability with the recorded values due to minor variations within the recorded values. Therefore, separation of the tangent line from the M-φ plots by ≥10% was used as a standardized reference point to determine the M_{cr} and Φ_{cr} values for the various beams. For illustration purposes, a sample plot of the NRS-C-50 (1) beam is presented within Figure 77 to visualize the determination of the M_{cr} and Φ_{cr}. M-φ plots used to determine the Mcr and Φ_{cr} for the remainder of the beams are presented in Appendix F: Moment Curvature Plots. A summary of the M_{cr} and Φ_{cr} values for all of the tested beams within the experimental program is presented in Table 32.

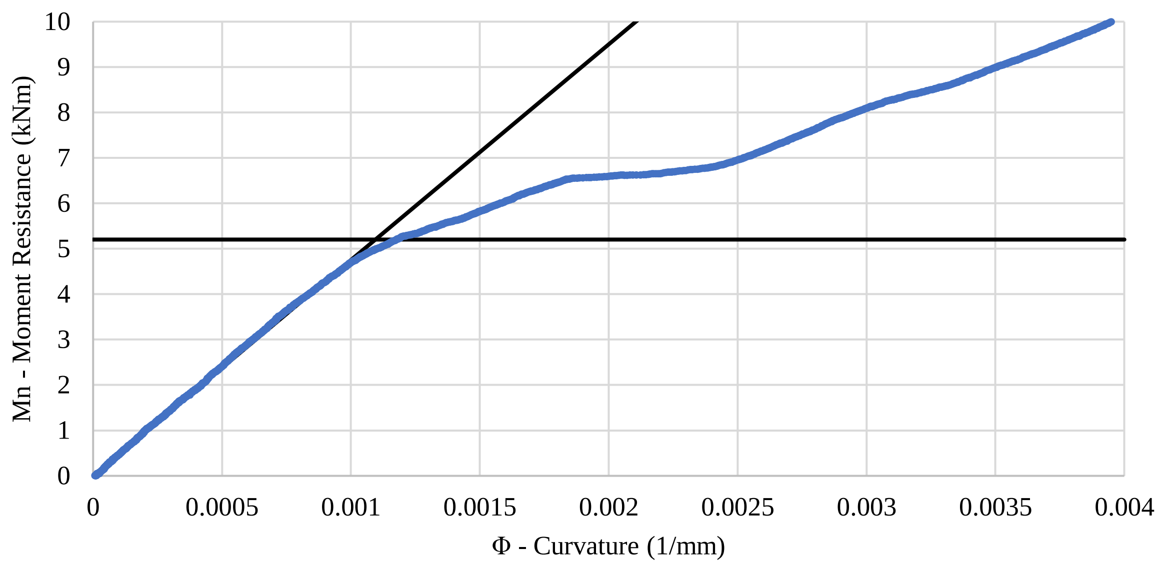


Figure 77-Determination of M_{cr} and Φ_{cr} (Note: NRS-C-50 (1) shown)
Refer to Appendix F: Moment Curvature Plots, for M-φ plots for all beams

For some of the tested beams, a distinct change in stiffness within the M-φ plots at the onset of cracking (i.e., $M_{cr\text{-}exp}$) was not observed. As a result, while M_{cr} values were provided, such values are annotated (**) within Table 32 to indicate the lack of a clearly defined cracking moment. Additionally, for further comparison with existing design codes, the theoretical cracking moment values provided using the CSA A23.3 design equations are also provided within Table 32 to further compare the $M_{cr\text{-}exp}$ values with theoretical predictions. The theoretical M_{cr} values were calculated based on the equations provided within Equation 25-Equation 27 based on the CSA A23.3-14 standards [68].

Regarding theoretical M_{cr} values, the CSA A23.3-14: Cl 8.6.5 [68] specifies the use of a density modification factor (λ) of 0.75-0.85 to account for the effects of low-density aggregates on the tensile strength (i.e. f_r within M_{cr} determination) and the resultant effect on the M_{cr} properties. Although no specific provisions are detailed referencing LCC or RCA, the effect of aggregates on the concrete density in the form of semi-low (λ=0.85) or low-density concretes (λ=0.75) with fine aggregate contents comprised or non-natural sand (fine aggregates besides NFA) are noted. Therefore, regardless of the lack of specific provisions for RCA, given the reduced densities of the LCC mixtures and use of alternative aggregate sources (i.e., RCA), the empirical cracking moments for the LCC mixtures were also provided using λ -factors of 0.85 and 0.75. It should be noted that while the λ were not developed with specific to LCC mixtures with RCA, for comparison purposes, M_{cr} values computed with λ =1, 0.85 and 0.75 were presented in Table 32 to assess further whether LCC beams could be treated similar to conventional concrete mixtures or whether the effect of aggregate density and f_r values should be modified to predict the Mcr of LCC beams to a higher degree of accuracy.

$$M_{cr} = \frac{f_r I_g}{y_t}$$ *Equation 25*

$$I_g = bh^3/12$$ *Equation 26*

$$y_t = h/2$$ *Equation 27*

Where,

M_{cr} : Cracking Moment (kNm)
f_r : Modulus of rupture (MPa)-refer to Equation 2
I_g : Moment of inertia for gross concrete section about centroidal axis (mm^4)
y_t : distance from centroidal axis to extreme tension fibre (mm)
f'_c : Concrete Compressive Strength (MPa)
λ : Modification factor for concrete density (provided by CSA A23.3-14: Cl 8.6.5)
b : beam section width (mm) (Note: 150 mm used for all calculations)
h : beam section height (mm) (Note: 225 mm used for all calculations)

Table 32-Comparison of experimental ($M_{cr\text{-}exp}$) and theoretical (M_{cr}) cracking moment

Mix ID	Experimental values		M_{cr} (kNm)***					
	$M_{cr\text{-}exp}$ (kNm)	Avg	λ= 1	$M_{cr\text{-}exp}/M_{cr}$	λ= 0.85	$M_{cr\text{-}exp}/M_{cr}$	λ= 0.75	$M_{cr\text{-}exp}/M_{cr}$
NNC-A-30 (1)*	3.2**	3.45	4.60	*0.70*		-		
NNC-A-30 (2)*	4.1**		4.65	*0.84*				
NNC-A-50 (1)*	6	5.9	5.37	*1.12*		-		
NNC-A-50 (1)*	5.8			*1.08*				
RRC-A-50 (1)	6.7	6.1	4.55	*1.47*	3.87	*1.73*	3.41	*1.96*
RRC-A-50 (2)	5.5			*1.21*		*1.42*		*1.61*
RRS-A-50 (1)	3.6**	4.3	4.47	*0.81*	3.80	*0.95*	3.36	*1.07*
RRS-A-50 (2)	5			*1.18*		*1.32*		*1.49*
RRS-M5-B-50 (1)	5.2	4.9	4.70	*1.11*	4.00	*1.30*	3.53	*1.47*
RRS-M5-B-50 (2)	4.6			*0.98*		*1.15*		*1.30*
NRS-C-50 (1)	5.3	4.65	5.47	*0.95*	4.65	*1.12*	4.10	*1.27*
NRS-C-50 (2)	4.2			*0.75*		*0.88*		*1.13*
Avg $_{LCC}$	***4.99***	**-**	**-**	***1.06***	**-**	***1.23***	**-**	***1.41***

** Control Mixture*
***Poorly defined cracking moment observed*
**** Predicted values (M_{cr}) based on CSA A23.3-14 standards, density modification factors (λ) applied to f_r values*

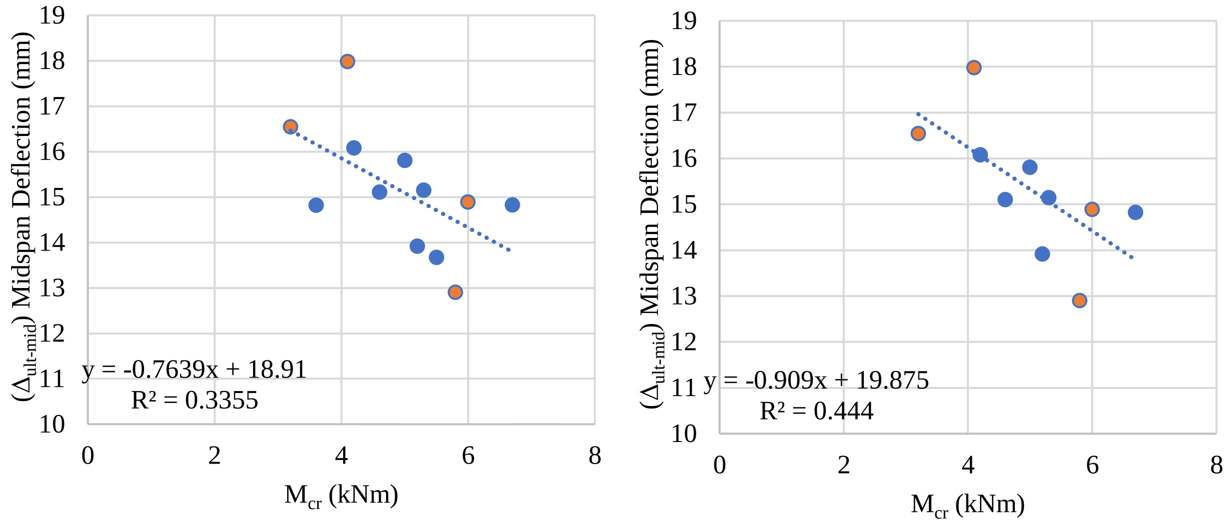
Based on the results presented, it was observed that despite the comparable or improved flexural strength characteristics of the LCC beams relative to the control mixtures and similarities within the observed failure modes for the majority of the beams, it was found that the LCC presented earlier cracking behaviour at lower applied stresses relative to the control beams. It was found that the M_{cr} values for the control mixtures varied between 6-5.8 for the NNC-A-50 beams, while M_{cr} values of 3.9 kNm were observed for the NNC-A-30 beams (note cracking moment was not able to be defined for the NNC-A-30 (1) beam- refer to respective M-φ plots within Appendix F: Moment Curvature Plots). Regarding the LCC mixtures, it was observed that M_{cr} values varied between 3.6-5.2 kNm, except the RRC-A-50 beams, which presented the highest cracking moments amongst all beams ranging from 5.5-6.7 kNm (average values of 6.1 kNm). Comparing the M_{cr} values for the LCC beams to that of the control beams (i.e., NNC-A-30) indicates that the LCC beams presented M_{cr} values that were found to be an average of 10.2 - 56.4% higher on average. However, it should be noted that poorly defined cracking moments were observed for both NNC-A-30 beams (i.e., gradual changes within the M-Φ plots), which may provide an unrepresentative basis for comparison. Upon comparison to the M_{cr} values reported for the NNC-A-50 beams, it was observed that the LCC beams presented up to 27.1% lower M_{cr} values (refer to Table 32) and significant intermixture variability that was not observed within the reported values for the control beams.

With regard to the RRC-A-50 beams, despite the highest average M_{cr} values (i.e., 6.1 kNm), significant intermixture variability was observed, with M_{cr} differing by 1.2 kNm (21.8%) amongst the two companion beams. Similar properties were observed for the remainder of the LCC beams (i.e., RRS-A-50, RRS-M5-

B-50 and NRS-C-50), with intermixture M_{cr} variability ranging from 12.6 - 28% observed within the reported values (refer to Table 32). The inter-batch variability of the LCC beams can be partially attributed to the increased material variability/quality of the LCC materials (i.e., differences within the residual mortar, deleterious materials, construction quality). However, despite the M_{cr} variability amongst the various mixtures, similar cracking behaviour (i.e., crack spacing, cracking type) to those observed within the control mixtures was observed based on the crack patterns presented within Figure 61-Figure 66 for the majority of the tested beams. In the case of the RRC-A-50 (2) and RRS-A-50 (1) beams, it should be re-iterated that although shear-based cracking and brittle failure mechanisms were observed, relatively similar M_{cr} values as those reported for the remaining LCC beams was observed.

Compared with previous studies, it can be observed that similar studies have also found that LCC beams present reduced M_{cr} values relative to conventional concrete mixtures [58,142,144,145]. Previous studies have noted that increasing LCC materials often leads to increasing M_{cr} reductions with reductions ranging from 10-26% observed for mixtures with 100% CRCA [58,142,144]. Further studies have also noted that similar to the experimental findings presented in Table 32, EMV/M-EMV did not present any improvement regarding M_{cr} with up to 28% lower values observed [143].

With regard to the observed M_{cr} and midspan deflection values, previous studies have reasoned that the reduced M_{cr} and deflection values of LCC beams can be attributed to the lower E_c of the RCA relative to NA (i.e., NCA or NFA) [145]. In comparison, further studies have found that the increased microstructural complexity of the RCA structure, namely the ITZ, may lower the resulting mixture stiffness and increased deflection values [143,145]. Therefore to investigate the relationship between deflection and M_{cr} values, Figure 78 presents the M_{cr} and $\Delta_{ult\text{-}mid}$ values for all beams within the experimental program. Given the brittle failure mechanisms of the RRC-A-50 (2) and RRS-A-50 (1) beams and the lack of post-peak yielding/ deflection, Figure 78 (b) also presents the M_{cr} and $\Delta_{ult\text{-}mid}$ values for all of the beams omitting the RRC-A-50 (2) and RRS-A-50 (1) beams.



(a) *(b)*

Figure 78-Determination of M_{cr} and $\Delta_{ult\text{-}mid}$
(a) All Beams, (b) Beams with brittle failure removed, (RRC-A-50 (2) and RRS-A-50 (1) removed), LCC beams shown in blue, conventional concrete control beams shown in orange.

Based on the results presented within Figure 78, it can be seen that an inverse linear relation can accurately be utilized to model the midspan $\Delta_{ult\text{-}mid}$ properties of the beams with regard to the M_{cr} values. As the M_{cr} of the beams increases, the resultant $\Delta_{ult\text{-}mid}$ values were observed to decrease progressively indicating, while the opposite was observed for increasing M_{cr} values of the beams. Based on the experimental findings, it can be concluded that while LCC materials acted to reduce the M_{cr} values, which further reduced the stiffness properties of the beam by lowering the tensile stress developments required to initiate cracking, leading to increased deformability of the beams. Similar findings have also been reported within previous studies [141]. Regarding the control mixtures, similar conclusions can also be drawn as the deflection values were also found to be inversely dependent on the M_{cr} values indicating the reduced tensile strength of the beams (based on M_{cr} values) inversely affected the resultant midspan deflection values of the beams.

8.5.3. Application of CSA A23.3-14 concrete design standards

Regarding applicability of existing CSA A23.3-14 concrete design standards [68], the experimental midspan deflection and cracking moment (M_{cr}) properties indicate that regardless of LCC usage, mixture design method or relation to flexural strength properties, experimental serviceability values often varied significantly from empirical predictions.

In terms of the midspan deflection values, the empirical midspan defection was provided based on simple elastic beam theory, considering the effects of cracking and reinforcement on the member stiffness as specified within Cl 9.8 of the CSA A23.3-14 standards as provided within Equation 28. It should be noted that the deflections were computed using the average moment of inertia-based method, based on Branson 4th power equation, which acts to discretize the member, accounting for both the cracked and uncracked regions within the beam and the resultant effect on member stiffness [68]. As a result, the effective moment of inertia (I_e) was utilized to express the stiffness properties of the member and is provided within Equation 29.

$$\Delta_{mid,pred} = \frac{\left(\frac{P}{2}\right)x}{24E_cI_e}(3L^2 - 4x^2) \qquad \text{Equation 28}$$

$$I_e = I_{cr} + \left(I_g - I_{cr}\right) * \left(\frac{M_{cr}}{M_a}\right)^3 \qquad \text{Equation 29}$$

Where:

P: total applied load (KN),
x : distance between load and supports (i.e., 850 mm based on test setup)
L-clear span (i.e., 2000 mm based on test-setup)
E_c *: Concrete modulus of elasticity (MPa), refer to Equation 4 and Equation 5*
I_e *: Effective moment of inertia* (mm^4),
I_{cr} *: Moment of Inertia of cracked section transformed to concrete* (mm^4)
I_g *: Gross-section moment of inertia* (mm^4)
M_{cr} *: Cracking moment (MPa)*
M_a *: Applied moment (kNm), (i.e., corresponding to experimental loads values)*

Using Equation 28 and Equation 29, the predicted elastic deflection values for each concrete beam were computed and provided in Table 33. With regard to empirical predictions, the experimental applied moment values (M_a) corresponding to the elastic limit were utilized within Equation 29 as required for each of the beams. The M_a values corresponding to the elastic limit were determined based on the experimental steel strain values (i.e., ε_s), in excess of 2000 µm/m, and identified based on an initial increase of 50 µm/m*s^{-1} (note: 10 Hz data sampling rate) within the recorded ε_s values (progressive yielding of the reinforcement). Based on the experimental data sampling rate (10 Hz), an inspection of the recorded strain data during loading (prior to elastic limit) only presented minor deviations (i.e., up to 5 µm/m*s^{-1}). As a result, the rapid increase within the recorded steel strain (i.e., ≥ 50 µm/m*s^{-1}) values indicated progressive straining and yielding of the rebar was utilized to determine the corresponding M_a and deflection values corresponding to the elastic limits of the respective beams. It should be clarified within the experimental ε_s values, a gradual increase with strain values was observed before yielding (i.e. through initial and intermediate stages of testing), while significant ε_s increases observed during advanced stages of testing indicated yielding of the rebar. Comparison of the M-φ plots to the determined elastic limit M_a values further supports that the determined values accurately assessed and determined the elastic limit properties for the various beams. In the case of the RRC-A-50 (2) and RRS-A-50 (1) beams, the peak loading and corresponding moment values were utilized due to the lack of plastic deformation (yielding) observed within the reinforcement.

Additionally, regarding the predicted deflection values, although the experimental M_{cr} values were determined for the various beam (refer to Table 32), the empirically derived values provided by the existing CSA A23.3-14 equations (shown in Equation 25-Equation 27) were utilized to verify the validity of the existing empirical codes and applicability for the LCC beams tested within the experimental program. It should be iterated that, specific to the deflection predictions, the modulus of rupture (f_r) formulation used to determine the cracking moment was reduced by a factor of 0.5 to reflect the presence of tension due to restrained shrinkage that reduces the applied moment, which causes flexural cracking as well as unconservative errors consistent within the representation of the concrete mechanical model of which Branson's equations were based upon-refer to CSA A23.3-14 [68]; as presented within Equation 30.

$$f_r = 0.3\sqrt{f'c} \qquad \text{Equation 30}$$

The f_r values were modified based on provision within the CSA A23.3-14 standards. Further, with regards to the elastic modulus of the member (E_c), CSA A23.3-14 provides two empirical equations used for the determination of the concrete modulus of elasticity, considering only the compressive strength (i.e., Cl 8.6.2.3-shown in Equation *4*) or further considering both compressive strength and hardened concrete density values of the concrete mixtures (i.e., Cl 8.6.2.2- shown in Equation *5*). For comparative purposes, the empirical deflection values were computed for each of the beams using both the “strength-based” (i.e., Equation *4*) and “density-based” (i.e., Equation *5*) E_c formulations.

Table 33-Comparison of experimental and theoretical deflection values (onset of yielding)

Mix	Experimental values at yielding limit			Predicted Mid-span Deflections			
	$P_{y\text{-}exp}$ (kN)	$M_{y\text{-}exp}$ (kNm)	$\Delta_{y\text{-}exp}$ (mm)	$\Delta_{y\text{-}pred.}$ (mm)**	$\Delta_{y\text{-}exp}/\Delta_{y\text{-}pred}$ **	$\Delta_{y\text{-}pred.}$ (mm)***	$\Delta_{y\text{-}exp}/\Delta_{y\text{-}pred}$ ***
NNC-A-30 (1)*	114.81	48.79	12.36	8.92	1.39	8.77	1.41
NNC-A-30 (2)*	117.48	49.93	12.16	9.32	1.30	9.22	1.32
NNC-A-50 (1)*	110.25	46.86	13.41	8.84	1.52	8.89	1.51
NNC-A-50 (2)*	115.55	49.11	11.89	9.04	1.31	9.10	1.31
RRC-A-50 (1)	113.33	48.17	14.18	9.20	1.54	9.51	1.49
RRC-A-50 (2)****	98.37	41.81	13.67	7.99	1.71	8.25	1.66
RRS-A-50 (1)****	92.93	39.50	14.82	7.59	1.95	7.96	1.86
RRS-A-50 (2)	92.82	39.45	14.00	8.75	1.60	9.17	1.53
RRS-M5-B-50 (1)	112.19	47.68	13.93	9.01	1.55	9.33	1.49
RRS-M5-B-50 (2)	102.97	43.76	14.04	8.27	1.70	8.56	1.64
NRS-C-50 (1)	110.82	47.10	11.58	9.33	1.24	9.57	1.21
NRS-C-50 (2)	111.60	47.43	12.21	8.54	1.43	8.76	1.39

** Control Mixture*
*** Predicted values, E_c determined using* Equation *4*
**** Predicted values, E_c determined using* Equation *5*
*****Peak load and corresponding deflection values shown due to beam failure prior reinforcement yielding*

Comparison of the experimental and computed deflection values indicates that the experimental deflection values are significantly larger than empirical predictions for LCC and control mixtures. Analysis of the control mixtures found that the experimental deflection values were between 1.30 – 1.52 times larger than empirical predictions, while 1.21 – 1.95 for the LCC mixtures. Further analysis also indicated that regardless of E_c determination method (i.e., strength-based or density-based, refer to Equation *4* and Equation *5*), only minor variations can be observed between the computed empirical deflection values for each of the various concrete beams. Concerning the design accuracy of the empirical predictions, the reductions within the empirical values indicate that the stiffness of the beams may not be effectively accounted for, leading to the significant variation between empirical and experimental values. It can be reasoned that the inaccuracies within the empirical predictions can be attributed to errors within the computed E_c values of the concrete members and the limited accuracy regarding the actual E_c of the mixtures (due to lack of E_c testing). Additionally, while factors such as f'c and γ_c were accounted for within the determination of E_c, existing code equations presented within CSA A23.3-14 were not developed to account for the differences within materials such as LCC or SCM's. Specifically, the E_c properties depend both on the stiffness of the paste as well as that of the aggregates [26,68,126]; therefore, as noted within the P-Δ plots, the reduced stiffness of the LCC mixtures due to the effect of the various materials may have further lead to the significant differences between experimental and empirical deflection values [126].

As a result, it can be reasoned that the existing code equations provide unrepresentative assessments of the E_c of LCC elements, over-estimating the stiffness properties, leading to unconservative assessments of the computed deflection values. However, supplementary notes are provided within the CSA A23.3-14 standards detailing that due to the general variability within concrete mixtures due to the influence of the aggregate fraction and testing loading rate, E_c values may range between 80-120% of the values specified within Cl 8.6.2.2 and Cl 8.6.2.3 (i.e., Equation *4* and Equation *5* respectively). Despite the specific mention of LCC or LCC materials, Table 34 presents modified empirical deflection values considering 70 - 90% of the E_c values for the various concrete mixtures to illustrate whether the differences between empirical and experimental values can be attributed to the reduced E_c properties of the LCC mixtures. Note, given the improved accuracy of the E_c provide by further taking into account the mixture density; initial E_c values were computed using Equation *5* and then multiplied by a factor of 0.7, 0.8 or 0.9.

Table 34-Effect of reduced elastic modulus values on theoretical deflections (onset of yielding)

Mix ID	$\Delta_{y\text{-exp}}$ (mm)	$\Delta_{y\text{-pred (modified)}}$ (mm)***					
		$0.7E_c$	$\Delta_{exp}/\Delta_{pred.}$	$0.8E_c$	$\Delta_{exp}/\Delta_{pred.}$	$0.9E_c$	$\Delta_{exp}/\Delta_{pred.}$
NNC-A-30 (1) *	12.36	9.94	*1.24*	9.46	*1.31*	9.08	*1.36*
NNC-A-30 (2) *	12.16	10.45	*1.16*	9.95	*1.22*	9.55	*1.27*
NNC-A-50 (1) *	13.41	10.03	*1.34*	9.57	*1.40*	9.19	*1.46*
NNC-A-50 (2) *	11.89	10.26	*1.16*	9.79	*1.21*	9.41	*1.26*
RRC-A-50 (1)	14.18	10.86	*1.31*	10.31	*1.38*	9.87	*1.44*
RRC-A-50 (2) **	13.67	9.43	*1.45*	8.95	*1.53*	8.57	*1.60*
RRS-A-50 (1) **	14.82	9.12	*1.62*	8.65	*1.71*	8.27	*1.79*
RRS-A-50 (2)	14.00	10.52	*1.33*	9.97	*1.40*	9.53	*1.47*
RRS-M5-B-50 (1)	13.93	10.65	*1.31*	10.11	*1.38*	9.68	*1.44*
RRS-M5-B-50 (2)	14.04	9.78	*1.44*	9.28	*1.51*	8.89	*1.58*
NRS-C-50 (1)	11.58	10.82	*1.07*	10.31	*1.12*	9.91	*1.17*
NRS-C-50 (2)	12.21	9.91	*1.23*	9.44	*1.29*	9.07	*1.35*

* *Control Mixtures*
** *Beam failure prior to yielding, deflection values corresponding to peak load shown*
*** *Predicted values, E_c determined using* Equation *5, modification factor of 0.7, 0.8 or 0.9 applied to E_c*

Based on the values presented in Table 34, despite reductions within the E_c properties, there is a significant lack of accuracy between empirical predictions and the experimental values. In the case of the control mixtures, considering $0.7E_c$, experimental deflections were still 1.16-1.34 times larger than theoretical predictions, while 1.07-1.62 times larger for the LCC mixtures, further increasing with higher E_c values (i.e., $0.8E_c$ or $0.9E_c$). Therefore despite minor prediction improvements, the discrepancies between experimental and theoretical deflections indicate that while the E_c values have a significant effect, the limited accuracy within empirical predictions can also be attributed to the cumulative effects due to errors within I_e, M_{cr}, f_r, f'_c, variations amongst elements, localized microstructural imperfections (i.e., nonuniformity within the concrete structure due to air-bubbles, voids), the model of which section stiffness equations were based upon (i.e., specific to I_e) as well as the general variability within concrete construction.

From a serviceability limits states (SLS) design standpoint, the inaccuracy of the computed theoretical deflection values may pose problems in terms of deflection limitations for various structural applications as listed within "Table 9.3" of the CSA A23.3-14 standards (i.e., items, partitions, walls or non-structural elements likely to damage with large deflections). The increased experimental deflections relative to theoretical predictions may also impact occupant/user perceptions in the case of observable deflections or structural cracking, which for some applications may structures non-suitable for use despite sufficient structural capacities (i.e., from a ULS standpoint).

It should be noted that regardless of differences within the experimental and predicted values, similar experimental deflections were found amongst both conventional concrete (control) and LCC mixtures regarding the differences between experimental and theoretical predictions (i.e., $\Delta_{exp}/\Delta_{pred.}$). Therefore, while theoretical predictions poorly predict the deflection properties of all concrete mixtures, similar $\Delta_{exp}/\Delta_{pred}$ variability and experimental deflection values amongst LCC and conventional concrete mixtures indicate that minimal differences exist between LCC and control mixtures from a design stand-point. Therefore, the defection uncertainties with regard to conventional concrete mixtures can also be applied to LCC mixtures. As a result, it can be concluded that regardless of the concrete composition/properties, the existing deflection predictions included within the current CSA A23.3-14 standards provide an unconservative estimation of experimental deflection values for all beams with significant differences up to 95% observed within the experimental testing. It should be noted that except in specific cases, the actual concrete properties (i.e., E_c, f_r, f'_c) are often unavailable to designers/engineers at the start of the design process. As a result, the CSA A23.3-14 standards should be utilized to provide a general estimation of experimental deflection values based on designer specific values (i.e., f'_c), with further consideration of the variability within concrete production/mechanical properties (i.e., f'_c variability, curing methods, temperature, hydration, batch size, the elastic modulus of the aggregates, concrete handling, f_y variability) also to be considered within such analysis/predictions.

In terms of M_{cr}, the empirical values predicted using Equation 25 were found to present accurate predictions relative to $M_{cr\text{-}exp}$ values observed for both conventional concrete and LCC mixtures, as shown in Table 32. Although significant differences up to 47% were observed between $M_{cr\text{-}exp}$ and $M_{cr\text{-}pred}$ for select mixture with the experimental program, the $M_{cr\text{-}exp}$ were found to be an average 1.06 times larger than empirical predictions when no density-modification factor (λ) was applied to the f_r values within the $M_{cr\text{-}pred}$ values (i.e., λ= 1). In the case of the values predicted with λ = 0.75 and 0.85, $M_{cr-exp}/M_{cr-pred}$ values were found to be 1.23 and 1.41 on average, respectively. Therefore, despite the reduced density of the LCC mixtures, the observed $M_{cr-exp}/M_{cr-pred}$ values indicate that the use of RCA and reduced f'_{ct} values of the LCC mixtures had no minimal effect on the M_{cr-exp} values, with no density modification factor required to ensure accuracy between the M_{cr-exp} and $M_{cr-pred}$ values. The empirical findings also indicate that the f'_c properties mixtures within f_r calculation were the primary factor that affected the M_{cr-exp} values (as outlined in Equation 25 24-Equation 27) given the consistent I_g, and y_t properties amongst all of the tested mixtures. As such, it can be reasoned that despite mixture differences, the $M_{cr-pred}$ for LCC mixtures can be conducted similar to conventional concrete mixtures, without the application of λ-factors despite the reduced density and use of non-NFA sources (i.e., FRCA).

However, it should be highlighted that in the case of the RRC-A-50 mixture, unlike any of the other LCC mixtures, the M_{cr-exp} values significantly exceeded $M_{cr-pred}$ values by 21-47%. Additionally, it should be noted that out of the LCC mixtures tested, the RRC-A-50 mixture was the only mixture not comprised with the partial replacement of GGBFS (i.e., 50% of total cementitious materials). Given the lower $M_{cr-pred}$ values for the RRC-A-50 mixtures, compared with M_{cr-exp} values, it is advised that further testing be conducted to evaluate whether the variations within M_{cr-exp} and $M_{cr-pred}$ values can be attributed to general concrete variability or whether the use of GGBFS significantly reduces M_{cr} values. It should be noted that while contradicting trends were observed for the conventional concrete mixtures, further investigation should also be conducted to evaluate the effect of GGBFS on the M_{cr} for mixtures developed with NA (i.e., NCA and NFA). Given the lack of provisions detailed within the existing standards regarding the use of GGBFS and other SCM's on the M_{cr} properties, further investigation is required to assess whether modifications to the existing CSA A23.3-14 equations are required to effectively consider the effect of GGBFS on the stiffness/cracking behaviour and M_{cr} properties of both conventional and LCC mixtures.

8.6. Summary

Based on the flexural and serviceability testing of the various reinforced concrete beams, the following points detailed summary of the over-arching experimental results and findings observed during the experimental program:

Mixture development

- Slump values for all mixtures were significantly higher slump values than reported for small-scale mixtures reported within Chapter 7. The improved slump values were attributed to the differences within the mixer type and higher batch volumes.
- An average 10.1% higher f'_c values were reported relative to the small-scale batch values (i.e., Chapter 7), while marginal f'_{ct} improvements were also reported. The observed changes were attributed to differences within mixer types, batch volumes curing methods.

Flexural Strength Properties-ULS

- Despite f'_c differences amongst all mixtures, similar or higher peak load (P_n) were reported for the LCC beams, while similar cracking behaviour (cracking type and spacing) and ductile failure mechanisms were also observed for both conventional and LCC beams. The similar flexural performance was attributed to the low reinforcement ratio ρ_s (%) constant amongst all beams. The RRC-A-50 (1) and RRS-A-50 (2) beams presented reduced P_n values, with brittle failure mechanisms and significant shear cracking observed.
- Except for the RRC-A-50 (1) and RRS-A-50 (2) beams, all beams displayed yielding of the longitudinal reinforcement (as per strain gauge readings: $\varepsilon_s > \varepsilon_y$), with ductile failure mechanisms also observed. RRC-A-50 (1) and RRS-A-50 (2) beams were found to have failed prior to concrete crushing (as per strain gauge readings: $\varepsilon_c = 0.001$ to 0.0015) and without yielding of the reinforcement.
- Forensic examination indicated poor construction quality of the RRC-A-50 (2) and RRS-A-50 (1) beams due to improper stirrup spacing (up to 190 mm) and rotation of the stirrups through the beams. Significant shear cracking (specific to RRC-A-50 (2) and RRS-A-50 (1) only) also indicated insufficient shear strength (V_n) of the beams leading to brittle failure prior to rebar yielding.
- Concerning CSA A23.3-14 predictions, experimental moment resistance values ($M_{n\text{-}exp}$) were found to exceed factored (+53-65%) significantly and nominal strength (+23-35%) M_r predictions for all LCC mixtures. In the case of brittle failure for the RRC-A-50 (2) and RRS-A-50 (1) beams, higher $M_{n\text{-}exp}$ were also observed relative to nominal (+12-26%) and factored (+39-58%) M_r predictions.

- Regardless of mixture design, LCC material content or failure mechanism, all LCC beams demonstrated sufficient flexural strength capacity similar to the control specimens despite differences within compressive strength properties of the various mixtures. As a result, it can be concluded that LCC beams provide sufficient flexural strength capabilities, suitable for use within structural applications.

Serviceability Properties-SLS

- Similar midspan displacements ($\Delta_{mid\text{-}exp}$) were observed for most of the tested beams at peak load, ranging from 17.98 – 12.9 mm regardless of LCC material incorporation, differences within the hardened properties, or stiffness properties of the various concrete mixtures.
- LCC mixtures (except NRS-C-50) were all found to display reduced stiffness properties (i.e., based on P-Δ plots) relative to conventional concrete mixtures, attributed to the reduced MOE of RCA relative to NA [26,112]. The improved stiffness of NRS-C-50 beams was attributed to the various optimization methods that strengthened the hardened concrete microstructure and improved the f'_{ct} properties.
- In terms of Mcr, despite comparable or improved flexural strength characteristics of the LCC beams, lower Mcr-exp values were often observed for the LCC mixtures relative to the control beams, ranging from (3.6-5.3 kNm). RRC-A-50 mixtures were found to present the highest overall $M_{cr\text{-}exp}$ values overall (up to 6.7 kNm). However, significant variability was observed between companion beams (21.8% difference), with similar variability also reported amongst all LCC mixtures (attributed to material variability/quality of the LCC materials).
- Comparison of the cracking moment ($M_{cr\text{-}exp}$) and deflection (Δ_{exp}) values found that an inverse linear relation can accurately be utilized to model the midspan $M_{cr\text{-}exp}$ and Δ_{exp} of the beams, with increased deflections attributed to reduced M_{cr} properties given the reduced stiffness and deformability of mixtures
- With regards to existing CSA A23.3-14 design standards, experimental midspan deflection ($\Delta_{y\text{-}exp}$) were observed to be significantly larger than empirical predictions ($\Delta_{y\text{-}pred}$) for both LCC and control mixtures (+21 - 95%). Inaccuracies within $\Delta_{y\text{-}pred}$ values were attributed to errors within the computed E_c values (derived from CSA A23.3-14 standards) given the effect of LCC materials on member stiffness properties (evident by P-Δ plots). However, computed $\Delta_{y\text{-}pred}$ values considering $0.7E_c$ still produced $\Delta_{y\text{-}pred}$ values that were also found to be 7 - 62 %

lower than $\Delta_{y\text{-}exp}$ values. Such findings indicate that further effects due to errors within I_e, M_{cr}, f_r, f'_c variations may also contribute to the lack of empirical prediction accuracy.

- In terms of Mcr, the empirical values using CSA A23.3-14 standards were able to provide empirical predictions within 6% of the Mcr-exp values (average amongst all mixtures) when no density-modification factor (λ) was applied to the fr values despite the reduced density and use of FRCA within the LCC mixtures

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Conclusions

The effect of CRCA, FRCA and SCM's and the effect on the mechanical performance of LCC mixtures was investigated through a detailed comparison of the mechanical strength properties of LCC and conventional concrete mixtures. Preliminary testing and evaluation of small-scale cylindrical specimens found that LCC materials significantly affect concrete mixtures' fresh and hardened mechanical strength performance. Further analysis concluded that due to differences in LCC aggregate and material properties, conventional mixture design methods such as those presented within CSA A23.1-14 [3] are not suitable for LCC mixture development. Mixture design optimization through water compensation, cement optimization, and material modifications found that LCC could be developed to achieve target strengths of 30 and 50 MPa by effectively considering the failure mechanisms based on LCC material incorporations that govern the resultant strength properties. Flexural testing of 2-metre reinforced concrete beams indicated that conventional concrete and LCC beams exhibited similar flexural strengths, cracking patterns, and cracking moment (M_{cr}) characteristics despite differences in mixture composition, f'_c, f'_{ct} and E_c. Assessment of the deflection characteristics, however, found that LCC and conventional concrete beams presented significant differences within midspan deflections, although experimental values were found to be greater than empirical estimates for all beams regardless of mixture composition. Comparison with existing CSA A23.3-14 empirical design standards found current design standards provided conservative empirical estimates with experimental flexural strengths found to be at least 1.32 higher than factored empirical moment resistance predictions for all LCC mixtures.

The following detailed conclusions are based on the analysis conducted in this study:

Low Carbon Concerte Database

- Extsing LCC research has focused primariliy on LCC made with CRCA, while LCC with FRCA or multiple LCC materials (RCA and SCM's) has been limited.
- The use of CRCA, FRCA or multiple LCC materials (even at 100% RCA replacements) did not impact f'_c properties indicating that contray to many studies increasing CRCA usage does not solely reduce f'c properties, with similar relatiosn between f'c and w/cm ratio observed for mixtrues with NA and RCA.

- CRCA usage led to redcued splitting tensile strength (f'_{ct}) and modulus of elasticity (MOE), properties, attributed to increased porosity [26,33] and deformability of the CRCA relative to NA [26,126].
- Analysis of experimental observations indicates that empirical f_r values often exceed experimetnal f'_{ct} findings. While in terms of E_c, CSA A23.3-14 equations provide an accurate predictions relative with experimental E_c values, although empirical predictions over-estimated approximately 31.4% of all findings, which may result in unconservative stiffness and deflection predictions.

Database Analysis Part 2: Mixture Design Optimization

- EMV/M-EMV proportioning was found to improve the f'_c properties and reduce variability of LCC mixtures relative to LCC developed with conventional mixture proportioning methods due to the effective consideration of residual mortar of the CRCA.
- EMV/M-EMV was also found to reduce cement contents (relative to mixtures proportioned with conventional mixtures proportioning methods) to achieve specified compressive strength values. However, cement efficency improvemernts were only valid for mixtures with f'c up to 45 MPa.
- Assessment of alternative mixing methods found that such methods did not provide any observable benefits in terms of compressive strength improvement. However, due to the lack of studies whcihv have utilized such methods with LCC, further experimental testing is required.

Recycled Concrete Aggregate Properties

- CRCA sources were found to present approximately 14% lower BSG and 15% lower bulk density properties relative to NCA sources, while 210% higher AC_{24} values were observed on average.
- FRCA sources were found to present approximately 21% lower BSG, while 442-846% higher AC_{24} values than those reported relative to NFA sources.
- Differences within the aggregate properties of the RCA can be attributed to the residual mortar (RM) fraction, which was found to range from 21-31% by weight within the CRCA sources. Variability amongst the properties of the RCA source can be attributed to the incorporation of deleterious materials, variability within source concrete and RCA productions methods.
- CRCA sources had abrasion resistances on average 75% lower than NCA. As noted from previous literature, such findings can be attributed to the weak bond between the OVA and RM fraction at the ITZ and the propensity for separation under abrasive action or loading.

- Upon complete submersion in water, NFA's were found to achieve saturated total moisture conditions (i.e., internal and absorbed moisture conditions), while FRCA continually absorbed water throughout the entire testing duration (up to 24 hours), reaching approximately 77-92% of the saturated moisture conditions within 2-hours of submersion.

Mechanical Properties of LCC and Effect of LCC Materials

- For the 30 MPa target strength classes mixtures, CRCA usage resulted in up to 3% higher f'_{c7} and 15 to 25% lower f'_c values. While in the 50 MPa target strength mixtures, CRCA usage resulted in significant f'_{c7} and f'_c reductions ranging from 33 to 41%. Similar conclusions were also observed with regard to f'_{ct} properties
- FRCA usage was found to result within significant f'_{c7}, f'_{ct} and f'c reductions. The higher slump values indicated a lack of water absorption by the FRCA, which was reasoned to have increased the w/cm ratios due to higher free-water content leading to reduced mechanical strength values. Despite mixture deficiencies, higher compressive strength properties were still observed with the 50 MPa target strength class relative to the RNC-A-50 mixtures (CRCA usage).
- Similar mechanical strength reductions were observed for mixtures with CRCA and FRCA, for each strength class as those observed within the NRC-A-30 and RNC-A-50 mixtures despite the complete replacement of NA. Such findings indicate that increasing LCC usage does not equate to progressive reductions within mechanical properties.
- Minor f'_{ct} improvements were observed for mixtures proportioned with the M-EMV method, although limited f'_c improvements were observed relative to mixtures prepared with absolute-volume proportioning, regardless of mixture target strength.
- Assessment of the mechanical strength properties found that within the 30 MPa target strength mixtures, the mortar fraction of the hardened concrete mixture serves as the limiting strength contributor and governs the failure mechanisms. Assessment of the mechanical properties, fracture patterns observed during testing and compressive strength properties of mortar cube specimens found that FRCA negatively impacts the mortar strength properties of the mixture with fractures observed to propagate through the mortar fractions and around the coarse aggregates regardless of coarse aggregate source.
- Assessment of the mechanical strength properties found that within the 50 MPa target strength mixtures, the coarse aggregate fraction of the hardened concrete mixture serves as the limiting strength contributor and governs failure. Assessment of the mortar strength properties found

that regardless of fine aggregate usage, mortar strength properties were of significantly higher magnitude than those of the compressive strength properties observed during concrete testing, indicating the incorporation of aggregates serves as a limiting factor in terms of f'_c of the mixture. Systematic evaluation of the mechanical strength properties of the hardened concrete mixtures found that CRCA usage limits the resulting strength properties, with fractures observed to propagate through the coarse aggregate fractions regardless of the fine aggregate source.

- The use of 50% GGBFS led to minor variations within the 28-day mechanical properties (f'c and f'_{ct}), although significant f'_{c7} reductions were observed, attributed to the slower strength development properties relative to OPC [36,134].

Implications on Mixture Design and Mixture Optimization

- Total absorbed moisture testing of the FRCA indicated that FRCA may only absorb a portion of the reported AC values during typical concrete mixing and setting durations, which may result in higher than assumed free-water contents, and therefore higher w/cm ratios. It was recommended that for mixtures incorporating FRCA, the 2-hour absorption values (AC_2) be used in lieu of the AC values for mixture design calculations to improve consistency in workability while minimizing the potential for undesired w/cm values and reductions in hardened properties.
- M-EMV proportioning provided for up to 66 kg/m^3 lower cement requirements. However, using the absolute volume method (as per CSA A23.1-14) with the partial replacement of cement with GGBFS offers significant cement carbon savings, without any slump or workability concerns observed within M-EMV proportioning.
- Based on the governing failure mechanisms, the omittance of FRCA or CRCA based on the target strength of the mixture, minor modifications to the w/cm ratios, and use of modified water compensation methods considering the 2-hour aggregate absorption values were observed to result in consistent workability and allowed for the strength optimization of the LCC mixtures. Compressive strength values of 29.1 and 49.8 MPa were obtained for low and high target strength mixtures, respectively, while up to 8% higher f'_{ct} values were observed relative to the control mixtures while using 50% GGBFS within the LCC mixtures.

Flexural Performance of Reinforced Beams

- Flexural testing of ten (10) singly-reinforced concrete beams found that both LCC and conventional concrete present similar peak loads (P_n) under 4-point flexural loading. Up to 3% higher moment resistance values were reported for the LCC beams relative to conventional concrete regardless of differences within mixture composition (i.e., materials), mix design method, or 30% lower f'_c properties of the LCC mixtures.
- The similar flexural performance was primarily attributed to the low reinforcement ratio ρ_s (%) constant amongst all beams. The findings indicate that the effective design of reinforced concrete structures can minimize the effect of f'_c reductions (characteristic of LCC mixtures) and result in comparable structural performance between LCC and conventional concrete flexural elements.
- Similar cracking, rebar yielding (i.e., $\varepsilon_s > \varepsilon_y$) and ductility behaviour were observed amongst all beams (LCC and conventional concrete) except for the RRC-A-50 (1) and RRS-A-50 (2) beams. These beams presented reduced peak loads (P_n) values, with brittle failure mechanisms and significant shear cracking observed. Forensic examination indicated that improper stirrup spacing and rotation of the stirrups along the beams limited the shear strength properties with significant shear cracking, indicating a lack of shear strength specific to RRC-A-50 (2) and RRS-A-50 (1) beams leading to brittle failure prior to rebar yielding.
- Despite minor variability within experimental peak loading values, experimental moment resistance values ($M_{n\text{-}exp}$) were found to exceed factored (+53-65%) and nominal strength (+23-35%) M_r predictions for all LCC mixtures as per CSA A23.3-14 predictions even in the case of the RRC-A-50 (2) and RRS-A-50 (1) beams (i.e., +6-12% higher than nominal M_r predictions and +32-39% higher than factored M_r predictions). Note that similar findings were also observed for conventional concrete beams in terms of comparison of experimental and empirical moment resistance predictions.

Serviceability Properties of Reinforced Beams

- Significant differences within peak load midspan displacements ($\Delta_{mid\text{-}exp}$) were observed for the majority of the tested beams, ranging from 12.89-17.98 mm. Although at the onset of steel yielding (i.e., elastic deformations only- $\Delta_{y\text{-}exp}$), similar midspan deflections ranging from 11.58 – 14.82 mm were observed.

- Assessment of the P-Δ plots found that except for the NRS-C-50 mixture, all LCC beams had reduced stiffness properties relative to conventional concrete mixtures, which was reasoned to be attributed to the increased deformability due to the anticipated lower elastic modulus of RCA relative to NA. The improved stiffness of NRS-C-50 beams was concluded to be a result of the various optimization methods, which strengthened the hardened concrete micro-structure, improving f'_c, f'_{ct} and E_c properties.
- LCC beams presented lower $M_{cr\text{-}exp}$ values than the control beams, with up to 27.1% lower values reported on average. The RRC-A-50 mixtures presented the highest overall $M_{cr\text{-}exp}$ values overall (average of 6.1 kNm), although significant variability was observed between companion beams (21.8% difference) with similar variability also reported amongst all LCC mixtures, attributed to material variability/quality of the LCC materials.
- CSA A23.3-14 standards were able to provide M_{cr} predictions within 6% of the experimental values when no density-modification factor (λ) was applied to the fr properties regardless of the effect of aggregates on the density properties of the LCC mixtures.
- Assessment of $M_{cr\text{-}exp}$ and $\Delta_{ult\text{-}exp}$ properties found that increased deflections were linearly attributed to reduced M_{cr} given the reduced stiffness leading to increased deformability of the beams under flexural loading.
- Comparison with CSA A23.3-14 design standards found that regardless of the concrete type (LCC or conventional concrete), experimental midspan deflections at the yield limit ($\Delta_{y\text{-}exp}$) were significantly larger than empirical predictions ($\Delta_{y\text{-}pred}$) by 21 - 95%. Such differences were reasoned to be attributed to errors within the computed Ec values (based on empirical predictions from CSA A23.3-14 standards). However, despite the reduced E_c of the LCC mixtures, consideration of $0.7E_c$ still presented deflection predictions that were 7 - 62 % lower than experimental values, indicating that further effects due to errors within I_e, M_{cr}, f_r and f'_c variations may significantly contribute to the limited accuracy within empirical and experimental deflection predictions.

9.2. Recommendations and Areas of future research

While the future of LCC and the construction industry appears promising, it is not without the continued research and time investment that can drive innovation and further application. The current research program stands on the foundation provided by previous studies and will serve as a stepping point for those that come after. To build upon the experimental conclusions, proposed theories, and most importantly, unfinished research areas, a natural and logical follow-up to the completed research program would be the further structural assessment of various other structural elements and the long-term durability testing of the LCC mixtures developed within this research program.

In terms of the structural assessment, the observed experimental findings indicate that LCC can demonstrate suitable ultimate and serviceability performance. As a result, it is concluded that small-scale applications and preliminary trials be conducted in terms of industrial applications. However, further research is required to assess the effects of LCC reinforced concrete beams containing higher reinforcement ratios and larger cross-sectional dimensions to ensure that large members increasingly used within modern construction present sufficient structural characteristics. Further research investment can also be directed towards other structural elements such as columns and slabs, as well as shear walls in terms of seismic performance. It can be reasoned that the further experimental testing of LCC structural members and sufficient research findings can aid in the wide-scale implementation of dedicated design-based standards for LCC, thereby paving the way forward for sustainability within the global construction industry.

Another research avenue worth considerable investment would be the comprehensive durability of testing of LCC mixtures. Given the variability within LCC materials, specifically RCA, extensive testing of ample RCA sources and LCC mixtures would need to be completed to understand and ensure the satisfactory durability performance required for numerous exposure conditions within a wide array of applications. Even in the case of limited structural usage in building construction applications, adequate durability experimental results would allow LCC to be utilized as an eco-friendly concrete alternative within roadway, mass concrete or marine environments providing extensive environmental savings given the billions of tons of concrete required annually for global construction applications.

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APPENDICES

Appendix A: Testing Standards

Table 35-Aggregate Properties Tested and Corresponding Testing Standards

Material Property	Primary CSA Standard	Secondary Assessment Standard ***
Coarse Aggregates		
Bulk Specific Gravity (BSG)	CSA A23.2-12A [3]	ASTM C127 [165]
Absorption (AC_{24})	CSA A23.2-12A [3]	ASTM C127 [165]
Bulk Density	CSA A23.2-10A [3]	ASTM C29 [166]
Gradation/Sieve Analysis	CSA A23.2-2A [3]	OPSS MTO LS-602 [167,168]
Micro-Deval Abrasion Resistance	-	ASTM D6928 [169], OPSS MTO LS-618 [170]
Residual Mortar (RM) Content		*, **
Fine Aggregates		
Bulk Specific Gravity (BSG)	CSA A23.2-6A [3]	ASTM C128 [171]
Absorption	CSA A23.2-6A [3]	ASTM C128 [171]
Gradation/Sieve Analysis	CSA A23.2-2A [3]	OPSS MTO LS-602 [167,168]
Total absorbed moisture/absorption rate		*

**No Existing Standard or testing procedures developed*
***Testing standards used from existing studies*
****Use of additional assessment standard, if applicable. Used for further reference*

Table 36-General aggregate handling and concrete testing and preparation standards

Design Step	Primary CSA Standard	Secondary Assessment Standard*
Handling of aggregate sources		
Standard Practice for Sampling Aggregates	CSA A23.2-1A [3]	ASTM D75/D75M-14 [178]
Reducing Samples of Aggregate to Testing Size	CSA A23.2-1A [3]	ASTM C702-03 [179]
Concrete Testing and Preparation		
Mechanical Mixing of Concrete/Mortar	CSA A23.2-2C [3]	ASTM C 305 – 06 [180]
Casting and Curing of Concrete Specimens	CSA A23.2-3C [3]	ASTM C 192/C 192M – 06 [163]
Slump Measurement	CSA A23.2-5C [3]	ASTM C 143/C 143M – 03 [181]
Compressive Strength Testing of Cylindrical Specimens	CSA A23.2-9C [3]	ASTM C 39/C 39M – 03 [182]
Splitting Tensile Strength Testing of Cylindrical Specimens	CSA A23.2-13C [3]	ASTM C 496/C 496M – 04 [183]

**Use of additional assessment standards, if applicable. Used for further reference*

Appendix B: Aggregate Properties from Literature

Table 37-CRCA Properties from Literature Review

	Aggregate Info		Aggregate Properties					Residual Mortar Content (RMC) Properties	
	Type	Nominal Size (mm)	BSG	Absorption Capacity (%)	Bulk Density (kg/m3)	ACV (%)	LA Abrasion (%)	RMC (%)	Testing Method
1	CRCA	25	2.67	0.89	-	-	-	20.0	-
7	CRCA	20	2.31	6.00	1311	-	-	39.0	Thermal
7	CRCA	20	2.33	4.70	1329	-	-	32.0	Thermal
15	CRCA	19	2.31	5.40	-	-	-	-	DIC
15	CRCA	19	2.42	3.30	-	-	-	-	DIC
63	CRCA	20	2.54	3.63	1374	-	-	-	-
38	CRCA	20	2.66	2.71	1348	-	-	-	-
16	CRCA	20	2.23	5.33	-	-	-	26.0	Chemical
16	CRCA	20	2.28	5.95	-	-	-	36.2	Chemical
16	CRCA	20	2.29	5.52	-	-	-	34.7	Chemical
16	CRCA	20	2.31	5.13	-	-	-	24.4	Chemical
16	CRCA	20	2.3	5.42	-	-	-	33.1	Chemical
16	CRCA	20	2.48	2.38	-	-	-	18.5	Chemical
16	CRCA	20	2.33	5.01	-	-	-	26.9	Chemical
16	CRCA	20	2.33	5.02	-	-	-	26.7	Chemical
16	CRCA	20	2.21	7.24	-	-	-	44.0	Chemical
16	CRCA	20	2.30	5.61	-	-	-	30.1	Chemical
16	CRCA	20	1.94	9.68	-	-	-	48.1	Chemical
16	CRCA	20	2.2	6.23	-	-	-	40.9	Chemical
16	CRCA	20	2.31	5.41	-	-	-	32.2	Chemical
35	CRCA	20	2.57	3.52	-	-	-	-	-
23	CRCA	20	2.45	3.47	-	22.5	-	24.3	Chemical
23	CRCA	20	2.37	5.66	-	23.4	-	34.0	Chemical
23	CRCA	20	2.36	5.77	-	23.9	-	61.1	Chemical
81	CRCA	-	2.62	5.59	-	-	-	-	-
81	CRCA	-	2.00	6.13	-	-	-	-	-
81	CRCA	-	2.57	6.43	-	-	-	-	-
81	CRCA	-	2.58	6.18	-	-	-	-	-
81	CRCA	-	2.55	7.02	-	-	-	-	-
81	CRCA	-	2.53	8.60	-	-	-	-	-
81	CRCA	-	2.55	7.95	-	-	-	-	-
81	CRCA	-	2.52	7.78	-	-	-	-	-
81	CRCA	-	2.51	8.98	-	-	-	-	-
81	CRCA	-	2.48	9.65	-	-	-	-	-
81	CRCA	-	2.50	9.52	-	-	-	-	-
42	CRCA	20	2.50	4.4	1360	-	-	-	-
45	CRCA	-	2.42	5.37	-	-	-	-	-
45	CRCA	-	2.37	5.39	-	-	-	-	-
45	CRCA	-	2.54	1.98	-	-	-	11.6	Chemical
45	CRCA	-	2.35	4.45	-	-	-	35.5	Chemical
70	CRCA	-	2.32	8.00	-	-	-	-	-
104	CRCA	20	2.54	2.33	1220	31.3	-	-	-
109	CRCA	20	1.98	5.30	1090	-	-	-	-
22	CRCA	-	2.47	3.98	1539	23.1	15.1	46.0	-
22	CRCA	-	2.45	5.72	1458	26.0	22.1	56.0	-
56	CRCA	20	2.52	3.65	1568	26.0	38	-	-
56	CRCA	20	2.51	4.10	1536	25.0	35	-	-
56	CRCA	20	2.48	4.86	1498	23.0	33	-	-

39	CRCA	25	2.59	3.20	1462	25.4	-	-	-
39	CRCA	25	2.60	3.40	1433	25.3	-	-	-
39	CRCA	25	2.55	3.30	1433	24.3	-	-	-
108	CRCA	25	2.48	4.53	-	-	32.2	40.1	Empirical
138	CRCA	20	2.55	1.97	-	-	-	11.9	Various
55	CRCA	20	2.61	4.54	1325	12.6	-	-	-
55	CRCA	20	3.11	0.35	1521	11.4	-	-	-
152	CRCA	20	2.59	11.3	-	-	-	-	-
130	CRCA	20	2.45	5.63	-	-	-	-	-
52	CRCA	-	2.52	3.82	-	-	-	25.0	Thermal
52	CRCA	-	2.34	6.61	-	-	-	46.8	Thermal
52	CRCA	-	2.48	4.53	-	-	32.2	39.9	Thermal
46	CRCA	20	2.34	4.12	-	-	38.33	-	-
176	CRCA	-	2.53	4.00	-	17.6	-	-	-
25	CRCA	-	2.31	5.30	1420	-	42.0	-	-
116	CRCA	20	2.41	5.56	-	-	32.8	-	-
110	CRCA	20	2.37	6.28	-	-	-	-	-
101	CRCA	20	2.57	3.52	-	-	-	-	-
184	CRCA	20	2.32	5.30	1420	-	42	-	-
102	CRCA	20	2.40	4.81	-	-	-	-	-
102	CRCA	20	2.35	6.75	-	-	-	-	-
102	CRCA	20	2.33	5.30	-	-	-	-	-
Average Value		-	2.44	5.71	1434	23.45	32.47	33.05	-

Table 38-FRCA Properties from Literature Review

	Aggregate Type	Aggregate Properties			
		BSG	Absorption Capacity (%)	Bulk Density (kg/m3)	Fineness Modulus (FM)
64	FRCA	2.43	5.91	-	3.01
35	FRCA	2.3	11.86	-	-
133	FRCA	2.01	12.50	-	-
34	FRCA	2.05	6.20	-	-
33	FRCA	1.91	13.1	1234	2.38
32	FRCA	2.08	11.9	1466	2.90
70	FRCA	2.15	10.0	-	-
39	FRCA	2.23	11.2	1324	-
39	FRCA	2.25	11.4	1342	-
39	FRCA	2.23	12.7	1321	-
138	FRCA	2.45	5.03	-	3.01
152	FRCA	2.28	10.4	-	-
152	FRCA	2.39	6.59	-	2.89
46	FRCA	2.03	5.92	-	-
116	FRCA	2.37	8.78	-	-
Average Value		2.21	9.56	1337	2.84

Table 39-NCA Properties from Literature Review

	Aggregate Info		Aggregate Properties				
	Type	Nominal Size (mm)	BSG	Absorption Capacity (%)	Bulk Density (kg/m^3)	ACV (%)	LA Abrasion (%)
[7]	NCA	20	2.671	0.6	1510	-	-
[15]	NCA	19	2.7	0.34	-	-	-
[15]	NCA	19	2.72	0.89	-	-	-
[63]	NCA	20	2.93	1.59	1647.7	-	-
[64]	NCA	-	2.67	0.93	-	-	-
[38]	NCA	20	2.79	0.2	1422.5	-	-
[16]	NCA	20	2.64	0.26	-	-	-
[16]	NCA	20	2.55	1.83	-	-	-
[16]	NCA	20	2.62	1	-	-	-
[23]	NCA	20	2.6	0.9	-	21.7	-
[81]	NCA	16	2.67	2.08	-	-	-
[42]	NCA	20	2.63	1.06	1600	-	-
[32]	NCA	20	2.68	1.45	1471	23.13	18.83
[45]	NCA	-	2.64	0.77	-	-	-
[70]	NCA	-	2.68	2	-	-	-
[104]	NCA	20	2.9	0.45	1350	28.65	-
[109]	NCA	20	2.54	2.4	1400	-	-
[22]	NCA	-	2.7	1.54	1733	18.2	11.9
[157]	NCA	-	2.64	0.92	-	-	24.6
[56]	NCA	20	2.8	0.3	1625	22	26
[108]	NCA	25	2.65	0.7	-	-	18.8
[138]	NCA	20	2.7	0.93	-	-	-
[152]	NCA	20	2.66	1.73	-	-	40.99
[130]	NCA	20	2.62	1.11	-	-	-
[52]	NCA	-	2.71	0.37	-	-	-
[46]	NCA	20	2.59	0.75	-	-	-
[176]	NCA	-	2.721	0.49	-	9.5	-
[25]	NCA	-	2.525	1.7	1530	-	31
[116]	NCA	20	2.77	0.47	-	-	16.7
[110]	NCA	20	2.62	1.24	-	-	-
[101]	NCA	20	2.62	1.11	-	-	-
[184]	NCA	20	2.54	1.6	1530	-	-
[40]	NCA	19	2.69	0.4	-	-	-
[124]	NCA	-	2.71	-	-	19	24
Average Value		-	2.67	1.03	1529	20.31	23.65

Table 40-NFA Properties from Literature Review

	Aggregate Info	Aggregate Properties			
	Type	BSG	Absorption Capacity (%)	Bulk Density (kg/m^3)	Fineness Modulus (FM)
7	NFA	2.65	0.7	-	-
7	NFA	2.665	1.6	-	-
63	NFA	2.66	0.24	1578.2	-
64	NFA	2.63	1.05	-	2.71
35	NFA	2.6	0.88	-	-
133	NFA	2.62	1.2	-	-
34	NFA	2.65	0.8	-	-
33	NFA	2.54	0.8	1517	2.38
42	NFA	2.6	2.1	1580	-
32	NFA	2.67	0.44	1607	2.51
70	NFA	2.62	3	-	-
104	NFA	2.6	0.8	1600	-
109	NFA	2.56	-	1040	1.27
108	NFA	2.56	1.1	-	-
138	NFA	2.63	1.05	-	2.71
152	NFA	2.6	0.8	-	2.8
46	NFA	2.62	0.67	-	-
46	NFA	2.64	1.2	-	-
176	NFA	2.69	-	-	2.45
116	NFA	2.64	0.87	-	2.4
Average Value		2.62	1.07	1487	2.40

Appendix C: Absolute Volume Proportioning Sample Calculation

1. Mix Specifications/requirements
   - *Exposure Class: N
   - *Air Entrainment: No
   - Strength Target: 50 MPa
   - Cement type: GU Ordinary Portland cement (GU-OPC) (BSG = 3.15)
   - Where applicable, refer to existing CSA A23.3-14 standards for minimum requirements for various exposure classes or applications

2. Aggregate Properties:
   - Coarse Aggregate- Natural Coarse Aggregate (NCA)
     - Nominal Size (mm) → 19
     - BSG_{OD} → 2.606
     - Absorption Capacity (AC_{24}) (%) → 2.090
     - Bulk Density (kg/m^3) → 1606.532
     - Moisture Content (%) → 0.289
   - Fine recycled concrete aggregate (FRCA)
     - BSG_{OD} → 1.927
     - Absorption Capacity (AC_{24}) (%) → 14.404
     - Fineness Modulus (FM) → 2.7
     - Moisture Content (%) → 2.591

3. Water-to-cement ratio*
   - To achieve strength requirements: w/cm = 0.42 (based on previous testing)
   - *Where applicable, refer to existing CSA A23.3-14 standards for minimum requirements for various exposure classes

4. Slump Requirements
   - Target Slump range: 75-100 mm

5. Water/ Air Content
   - Based on target slump, air entrainment and nominal aggregate size,
     - Free-water content: 205 kg/m^3
     - Air Content: 2% (non-air entrained concrete)

6. Cementitious Material Content
   - Supplementary cementitious materials to be added: n/a
   - Cement Content Requirements
     - Based on w/cm ratio: 488.09524 kg/m^3 ***(Governs)***
     - Minimum Requirements for coarse aggregate size: 320 kg/m^3

7. Coarse Aggregate Content
   - Based on fine aggregate FM and nominal size of coarse aggregate, bulk volume of dry rodded coarse aggregate per unit volume of concrete (bulk volume): 0.63
   - NCA Content: Bulk Volume * Bulk Density = 0.63 *1606.532 = 1012.1149 kg/m^3

8. Fine Aggregate Content
    - $V_{NCA=}$ = 1012.1149 / (2.606 * 1000) = 0.3883845
    - V_{cement} = 488.09524 / (3.15 * 1000)) = 0.1549509
    - V_{water} = 205 / 1000 = 0.205
    - V_{air} = 2% = 0.02
    - 0.7683354
    - $V_{fine\text{-}agg\ (FRCA)}$ = 1 - 0.7683354 = 0.2316646
    - $W_{Fine\text{-}agg\ (FRCA)}$ =0.2316646 * (1000 * 1.927) = 446.43125 kg/m^3
    -
9. Mix Proportions Summary
    - $W_{Fine\text{-}agg\ (FRCA)}$ 446.43125 kg/m^3
    - W_{water} 205 kg/m^3
    - W_{Cement} 488.09524 kg/m^3
    - W_{NCA} 1012.1149 kg/m^3

10. Moisture Adjustment

- Adjust aggregate volumes and water content to account for moisture content and absorption capacity values of the coarse and fine aggregates. Same method as with conventional mixture proportioning. Calculations not shown for conciseness

Appendix D: EMV Proportioning Sample Calculation

1. Mixture Proportioned based on CSA proportioning guidelines (Natural Aggregate Concrete-NAC)- Oven-dried values shown
   - Cement: 507.14 kg/m^3
   - Natural Coarse Aggregate: 1012.11 kg/m^3
   - Natural Fine Aggregate: 487.78 kg/m^3
   - Water: 177.5 kg/m^3

2. Checking maximum replacement ratio of CRCA
   - RMC (%) of CRCA-(RMC_{CRCA}): 27.5 %
   - BSG^{NCA}_{OD} *: 2.606
   - BSG^{RCA}_{OD} *: 2.288
   - $V^{NAC}_{Dry\ Rodded\ NCA}$ **: 0.63

*Oven-Dried BSG values shown,**Based on fineness modulus (FM) of NFA and aggregate size of NCA. NCA nominal size: 19 mm, FM: 2.532

- $RMC_{max} = 1 - V_{NAC-dry\ rodded} \times \frac{BSG_{NCA-OD}}{BSG_{CRCA-OD}} \rightarrow 1 - 0.63 \times \frac{2.606}{2.288} = 28.236\ \%$
- Therefore 100% CRCA is possible as $RMC_{max} > RMC_{CRCA}$

3. (If $RMC_{max} < RMC_{CRCA}$) Minimum NCA content (R_{NCA}) within the mixture; otherwise, skip
   - $R_{NCA} = 1 - \frac{RMC_{CRCA}}{V_{NAC-dry\ rodded}} \times \frac{BSG_{CRCA-OD}}{BSG_{NCA-OD}}$
   - In sample calc $RMC_{max} > RMC_{CRCA}$, therefore, skip this calculation (i.e., $R_{NCA} = 0$)

4. Ensure $V^{NAC}_{NCA} = V^{LCC}_{CRCA-OVA}$
   - $V^{LCC}_{CRCA-OVA} = V^{NAC}_{NCA} = 1012.11/ (2.606*1000) = 0.3883845$

5. Calculate V^{LCC}_{CRCA} ($V^{LCC}_{CRCA} = V^{LCC}_{CRCA-OVA} + V^{LCC}_{CRCA-RM}$)
   - $V^{LCC}_{CRCA-OVA} = 0.3883845$
   - $V^{LCC}_{CRCA} = \frac{V^{NAC}_{NCA} \times (1 - R_{NCA})}{(1 - RMC_{CRCA/100}) * BSG_{CRCA-OD}/BSG_{NCA-OD}} = \frac{0.3883845*(1-0)}{(1-0.275)*(2.288/2.606)} = 0.6102197$
   - $V^{LCC}_{CRCA-RM} = 0.6102197 - 0.3883845 = 0.2218352$

6. Ensure equivalent mortar fractions within NAC and LCC (i.e., $V^{LCC}_{M} = V^{NAC}_{M}$)
   - $V^{LCC}_{M} = V^{NAC}_{M} = 1 - V^{NAC}_{NCA} = 1 - 0.3883845 = 0.6116155$
   - $V^{LCC}_{M} = V^{LCC}_{CRCA-RM} + V^{LCC}_{NM} \rightarrow V^{ANC}_{E} = V^{LCC}_{M} - V^{LCC}_{CRCA-RM} = 0.6116155 – 0.2218352 = 0.3897803$

7. Calculate weight proportions of all materials (W^{LCC}_{X})
   - $W^{LCC}_{CRCA} = 0.6102197*2.288*1000 = 1396.0164\ kg/m^3$
   - $W^{LCC}_{NCA} = 0$ kg/m^3
   - $W^{LCC}_{water} = W^{NAC}_{water} * \frac{V^{LCC}_{NM}}{V^{LCC}_{M}} = 177.499 \times \frac{0.3897803}{0.6116155} = 113.11946\ kg/m^3$

- $W^{LCC}{}_{Cement} = W^{NAC}{}_{cement} * \frac{V^{LCC}{}_{NM}}{V^{LCC}{}_{M}} = 507.14 \times \frac{0.3897803}{0.6116155} = 323.19846\ kg/m^3$
- $W^{LCC}{}_{NFA} = W^{NAC}{}_{NFA} * \frac{V^{LCC}{}_{NM}}{V^{LCC}{}_{M}} = 487.77637 \times \frac{0.3897803}{0.6116155} = 310.85808\ kg/m^3$

8. Summary-LCC Mixture Proportions
   - W^{LCC}_{CRCA}: 1396.02 kg/m^3
   - W^{LCC}_{NCA}: 0 kg/m^3
   - W^{LCC}_{Water}: 113.12 kg/m^3
   - W^{LCC}_{Cement}: 323.2 kg/m^3
   - W^{LCC}_{NFA}: 310.86 kg/m^3

9. Moisture Adjustment
   - Adjust aggregate volumes and water content to account for moisture content and absorption capacity values of the coarse and fine aggregates. Same method as with conventional mixture proportioning. Calculations not shown for conciseness

Appendix E: M-EMV (S=5) Proportioning Sample Calculation

1. Mixture Proportioned based on CSA proportioning (Natural aggregate concrete-NAC)
   - Cement 507.14 kg/m^3
   - Natural Coarse Aggregate (NCA)* 1012.11 kg/m^3
   - Natural Fine Aggregate (NFA)* 487.78 kg/m^3
   - Water 177.50 kg/m^3

   *Oven-dried values shown, water values shown without any moisture adjustments

2. Checking maximum replacement ratio of CRCA
   - The same method as EMV proportioning, however, shown again for completeness
   - RMC (%) of CRCA-(RMC_{CRCA}) 27.5
   - BSG^{NCA}_{OD} * 2.606
   - BSG^{RCA}_{OD} * 2.288
   - $V^{NAC}_{Dry\ Rodded\ NCA}$ ** 0.63

   - *Oven-Dried BSG values shown
   - **Based on fineness modulus (FM) of NFA and aggregate size of NCA. NCA nominal size: 19 mm, FM: 2.532

   - $RMC_{max} = 1 - V_{NAC-dry\ rodded} \times \frac{BSG_{NCA-OD}}{BSG_{CRCA-OD}} \rightarrow 1 - 0.63 \times \frac{2.606}{2.288} = 28.236\ \%$
   - Therefore 100% CRCA is possible as $RMC_{max} > RMC_{CRCA}$

3. (If $RMC_{max} < RMC_{CRCA}$) Minimum NCA content (R_{NCA}) within the mixture; otherwise, skip
   - $R_{NCA} = 1 - \frac{RMC_{CRCA}}{V_{NAC-dry\ rodded}} \times \frac{BSG_{CRCA-OD}}{BSG_{NCA-OD}}$
   - In sample calc $RMC_{max} > RMC_{CRCA}$, therefore, skip this calculation (i.e., $R_{NCA} = 0$)

4. Coarse Aggregate Content
   - V^{NAC}_{NCA} = 1012.11/ (2.606*1000) = 0.3883845
   - $V^{LCC}_{NCA} = R * V^{NAC}_{NCA} = 0$
   - $V^{LCC}_{CRCA} = \frac{V^{NAC}_{NCA} \times (1 - R_{NCA})}{\left(1 - RMC_{CRCA}/100 \times \frac{1}{S}\right) * BSG_{CRCA-OD}/BSG_{NCA-OD}} = \frac{0.3883845*(1-0)}{(1-0.275*1/5)*(2.288/2.606)} = 0.4681591$

5. New Mortar Content
   - $V^{LCC}_{NM} = V^{NAC}_{M} - V^{LCC}_{RMa}$
   - $V^{NAC}_{M} = 1 - V^{NAC}_{NCA}$ = 1- 0.3883845 = 0.6116155
   - $V^{LCC}_{RMa} = V^{LCC}_{CRCA} \times \left(1 - \left(1 - \frac{\frac{RMC}{100}}{S}\right) \times \frac{BSG_{CRCA-OD}}{BSG_{NCA-OD}}\right) = 0.4681591 \times \left(1 - \left(1 - \frac{0.275}{5}\right) \times \frac{2.288}{2.606}\right)$
   - $= 0.0797746$
   - $V^{LCC}_{NM} = V^{NAC}_{M} - V^{LCC}_{RMa}$ → 0.6116155 -0.0797746 = 0.5318409

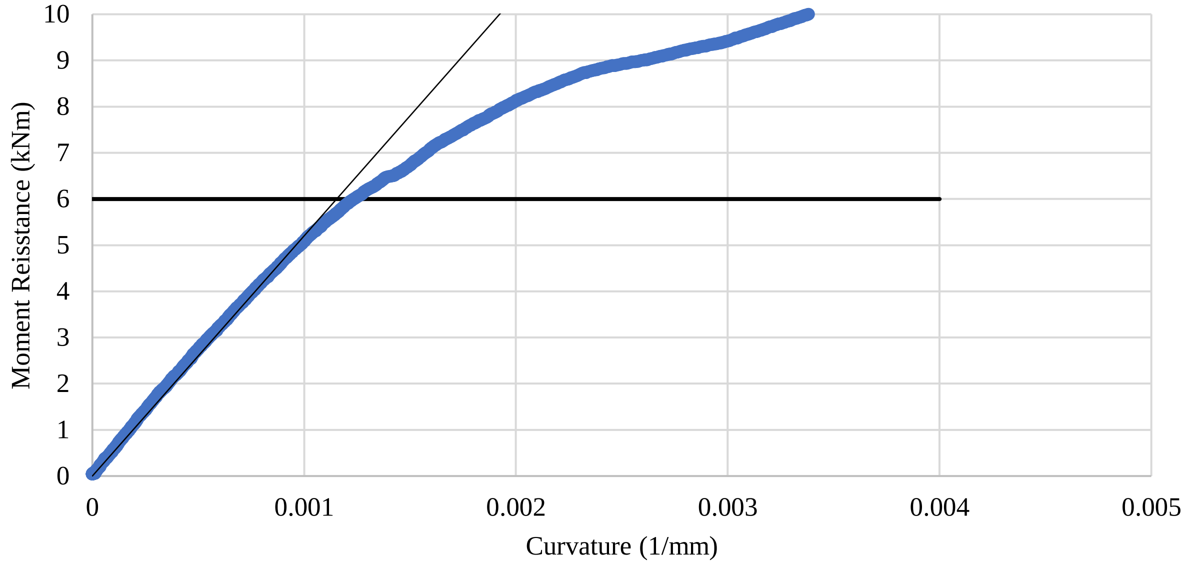
6. Calculate weight proportions of all materials (W^{LCC}_{X})
   - W^{LCC}_{CRCA} = 0.4681591*2.288*1000 = 1071.0206 kg/m^3
   - W^{LCC}_{NCA} = 0 kg/m^3

- $W^{LCC}{}_{water} = W^{NAC}{}_{water} * \frac{V^{LCC}{}_{NM}}{V^{LCC}{}_{M}} = 177.499 \times \frac{0.5318409}{0.6116155} = 154.35\ kg/m^3$
- $W^{LCC}{}_{Cement} = W^{NAC}{}_{cement} * \frac{V^{LCC}{}_{NM}}{V^{LCC}{}_{M}} = 507.14 \times \frac{0.5318409}{0.6116155} = 440.99\ kg/m^3$
- $W^{LCC}{}_{NFA} = W^{NAC}{}_{NFA} * \frac{V^{LCC}{}_{NM}}{V^{LCC}{}_{M}} = 487.77637 \times \frac{0.5318409}{0.6116155} = 435.99\ kg/m^3$

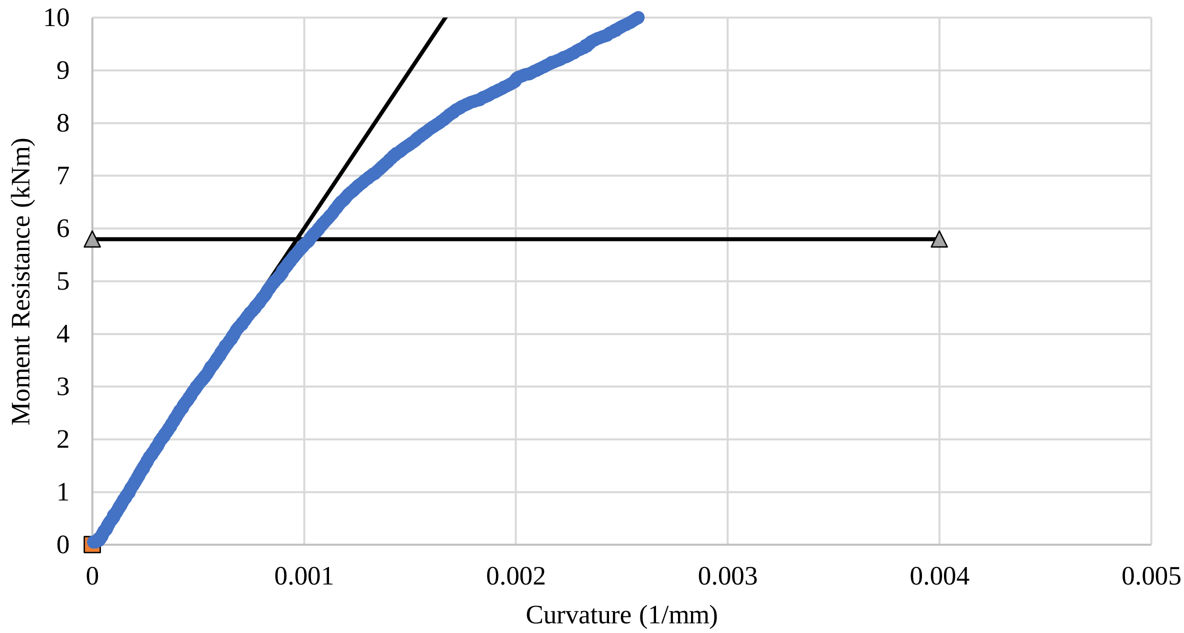
7. Summary-LCC Mixture Proportions
   - $W^{LCC}{}_{CRCA}$ 1071.0206 kg/m^3
   - $W^{LCC}{}_{NCA}$ 0 kg/m^3
   - $W^{LCC}{}_{Water}$ 154.34733 kg/m^3
   - $W^{LCC}{}_{Cement}$ 440.99238 kg/m^3
   - $W^{LCC}{}_{NFA}$ 435.14556 kg/m^3

8. Moisture Adjustment
   - Adjust aggregate volumes and water content to account for moisture content and absorption capacity values of the coarse and fine aggregates—same method as with conventional mixture proportioning. Calculations are not shown for conciseness.

Appendix F: Moment Curvature Plots

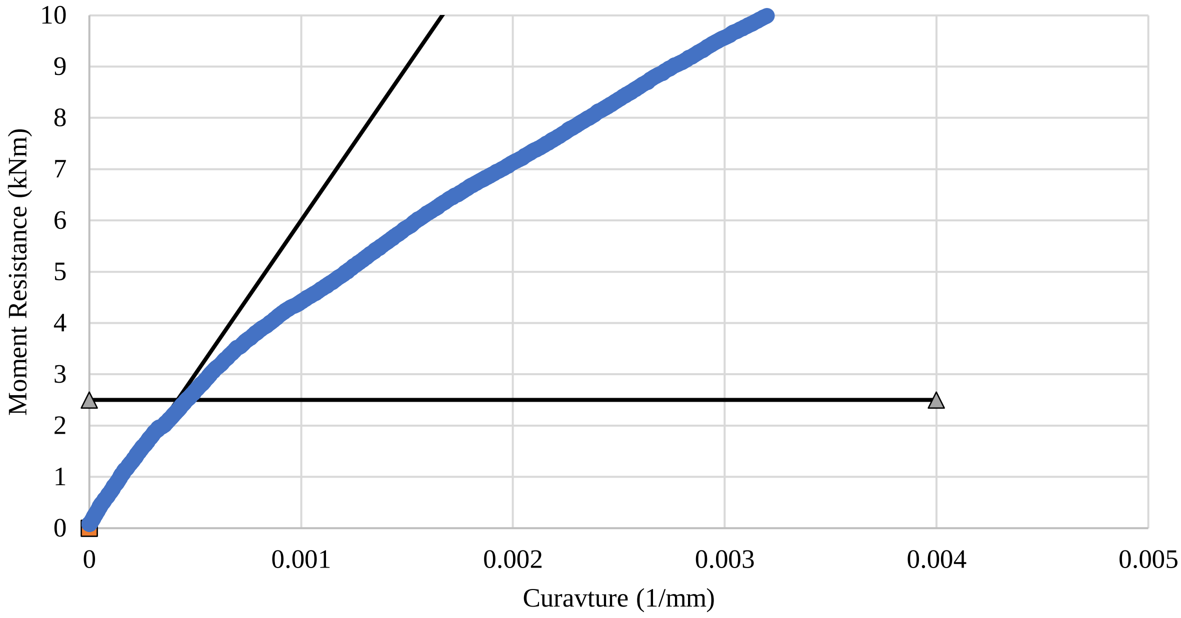


(a)

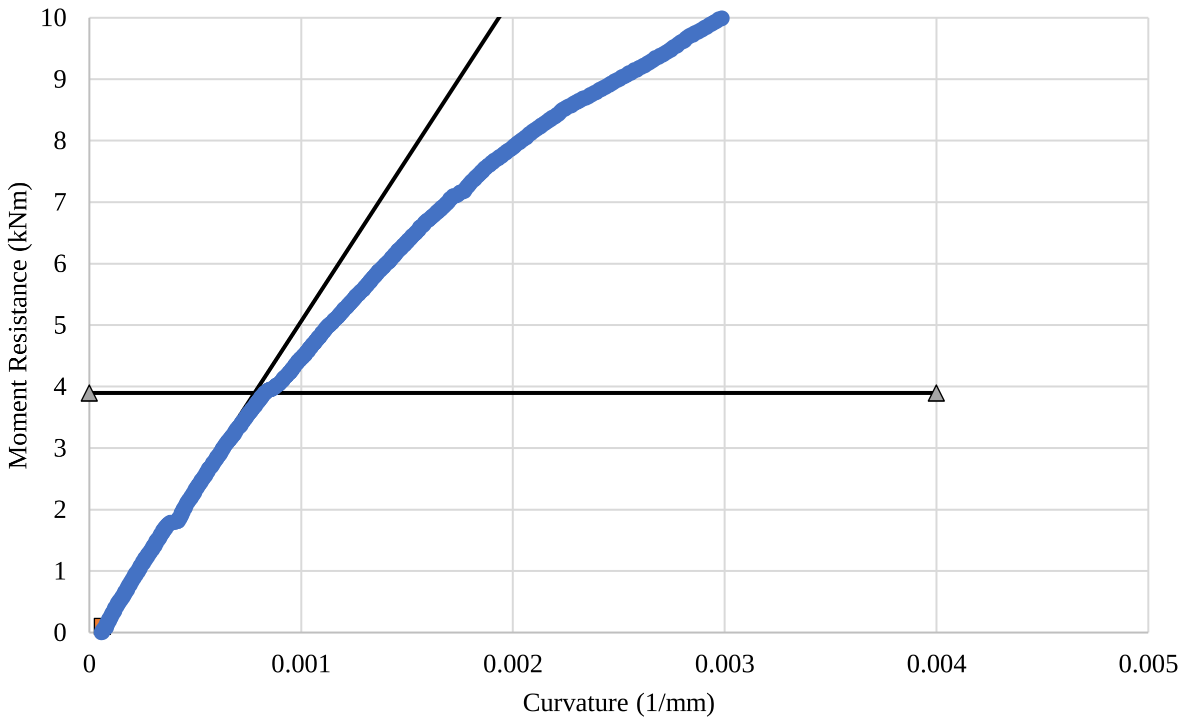


(b)

Figure 79-Moment Curvature plots- (a) NNC-A-50 (1), (b) NNC-A-50 (2)

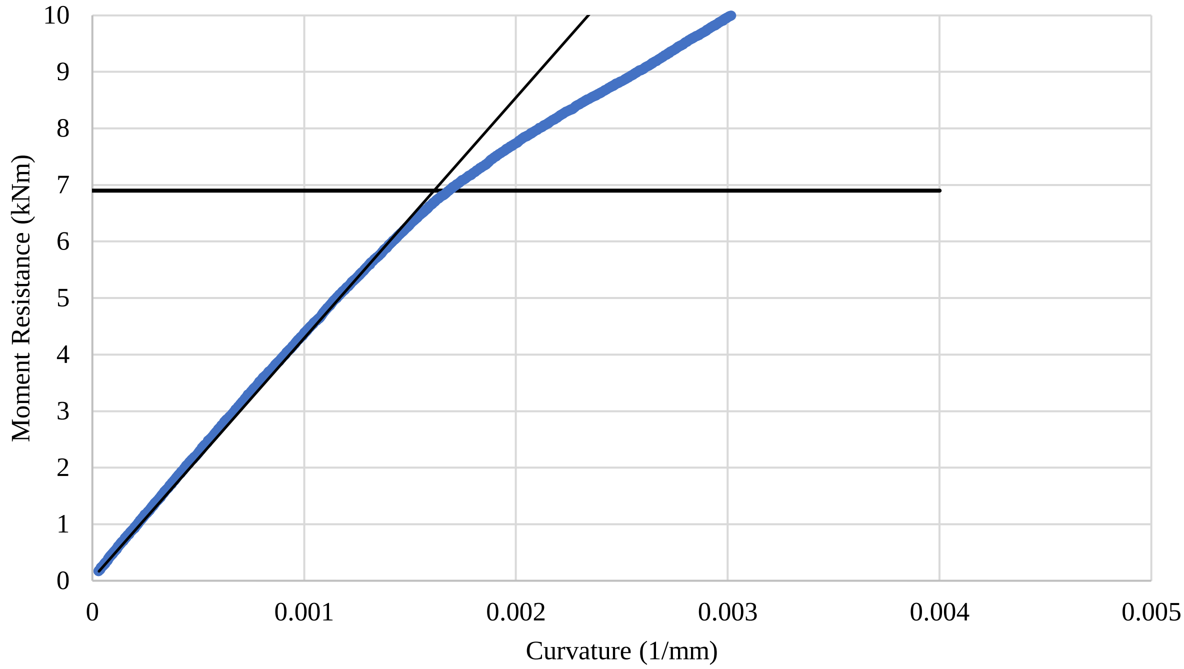


(a)

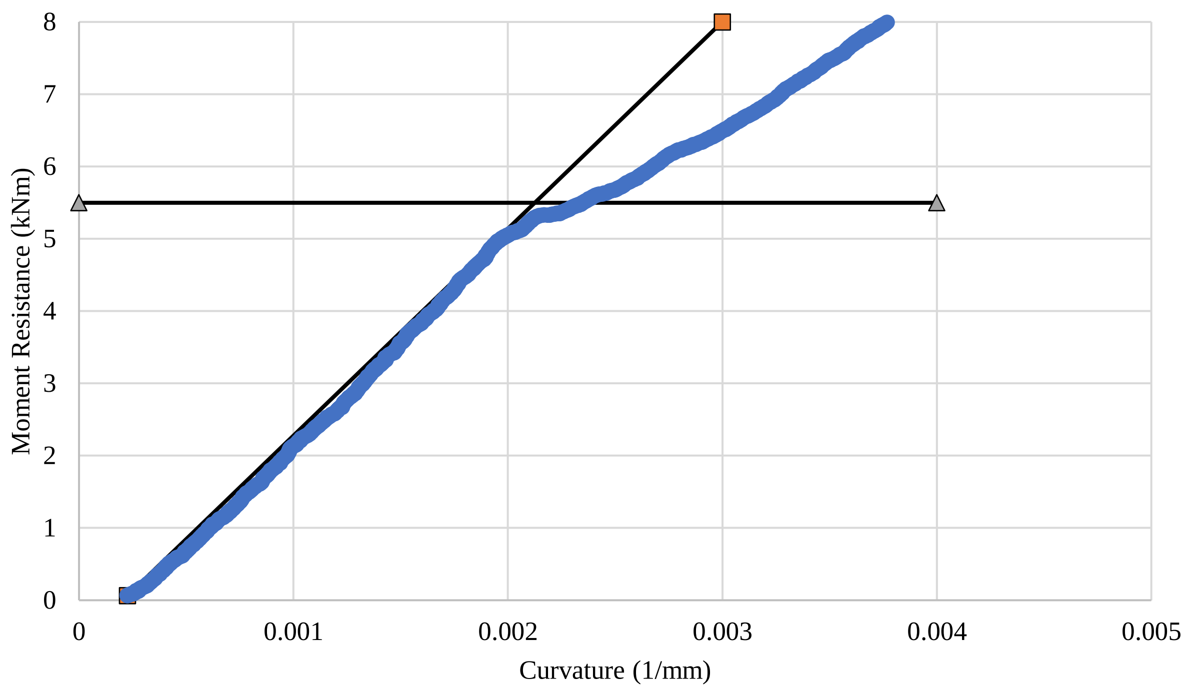


(b)

Figure 80-Moment Curvature plots- NNC-A-30 (2)
(Note: No distinct M_{cr} observed for NNC-A-30 (1))

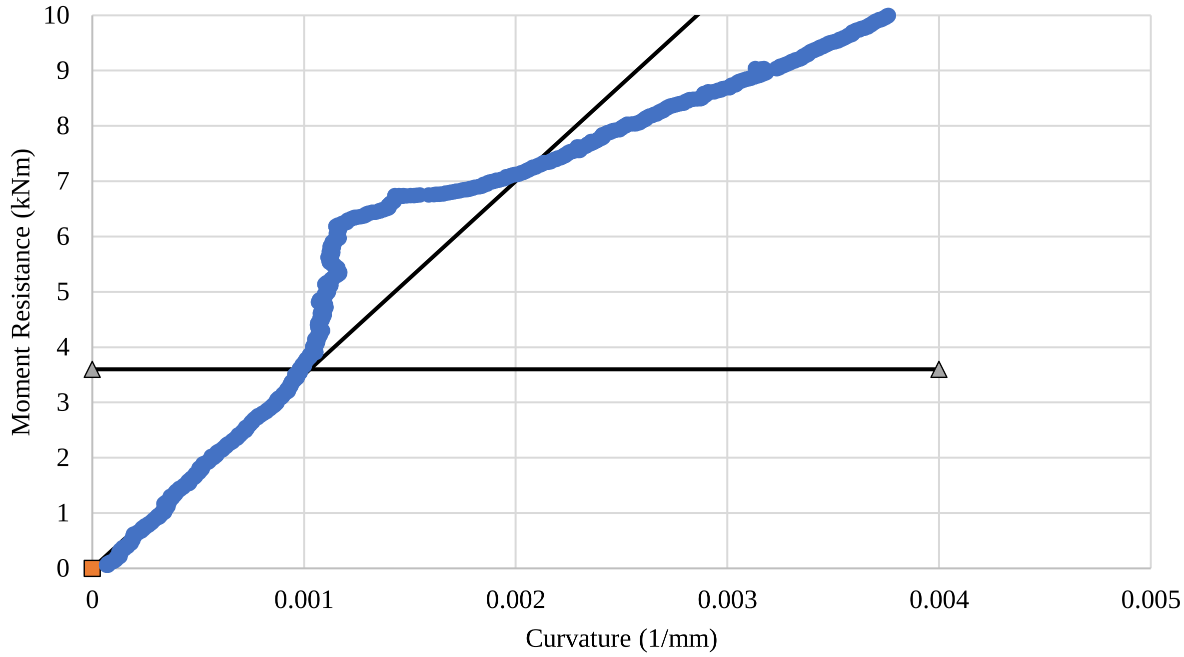


(a)

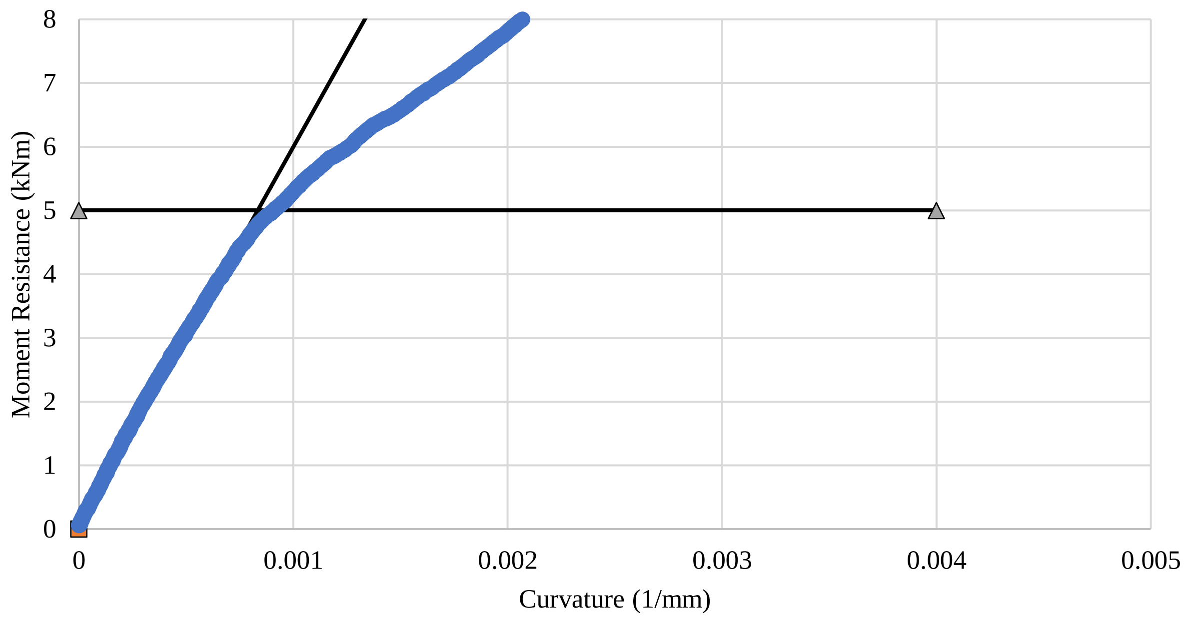


(b)

Figure 81-Moment Curvature plots- (a) RRC-A-50 (1), (b) RRC-A-50 (2)

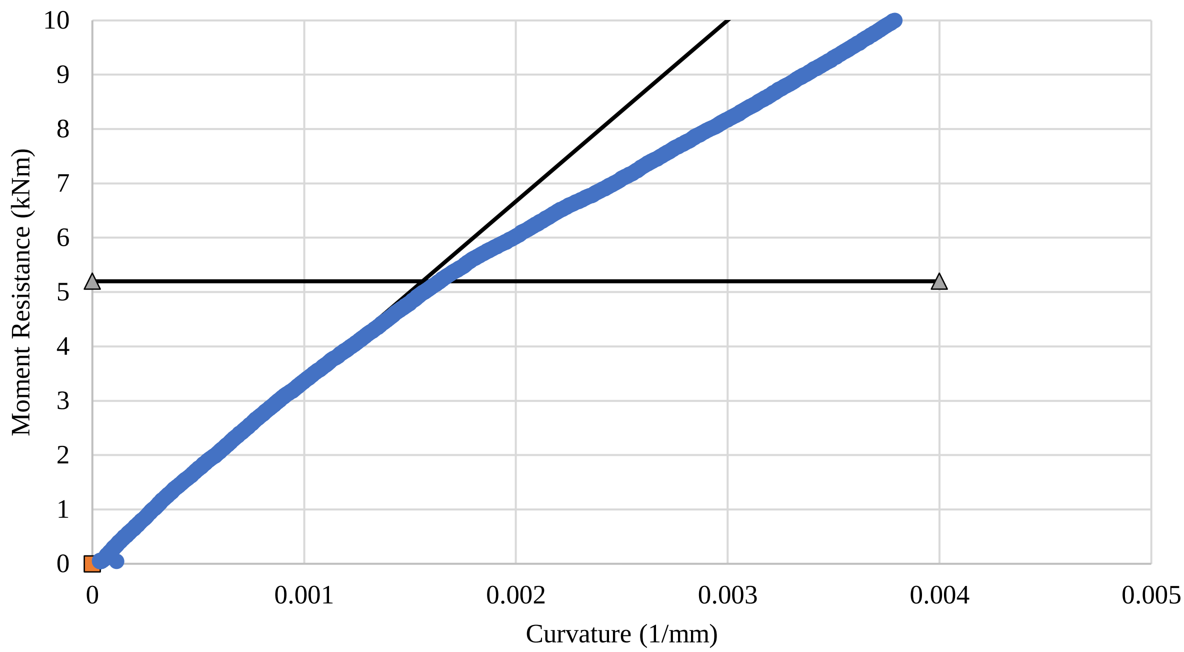


(a)

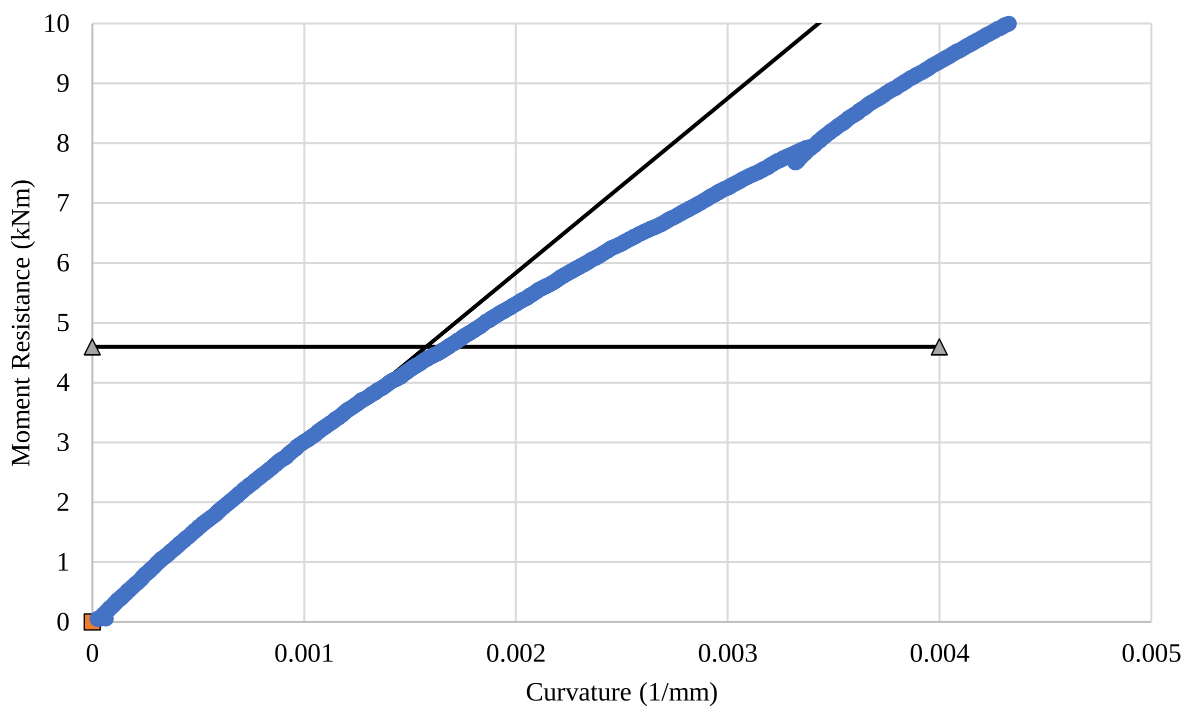


(b)

Figure 82-Moment Curvature plots- (a) RRS-A-50 (1), (b) RRS-A-50 (2)

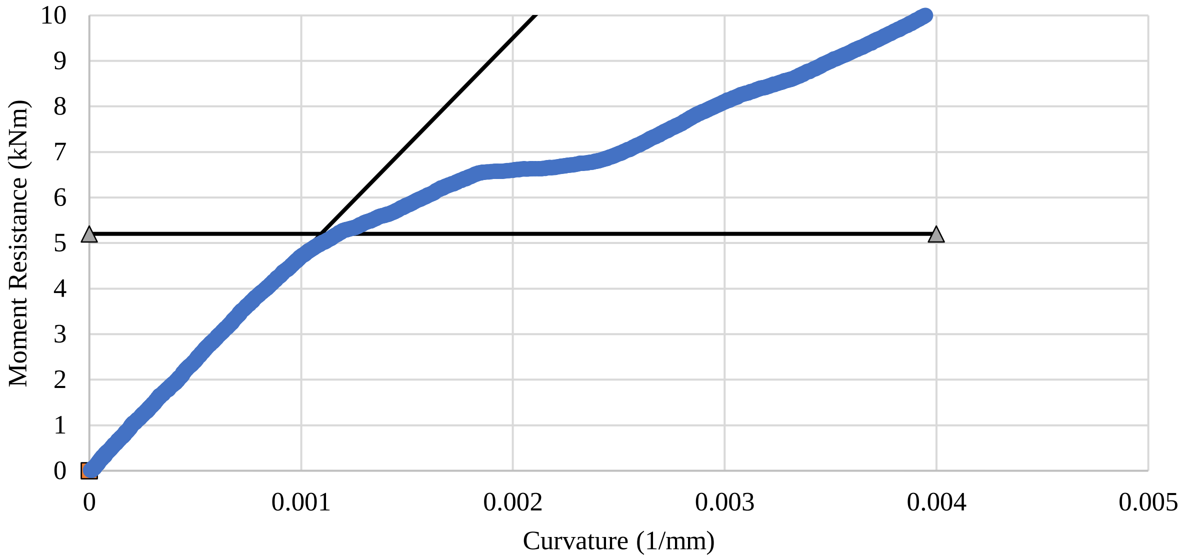


(a)

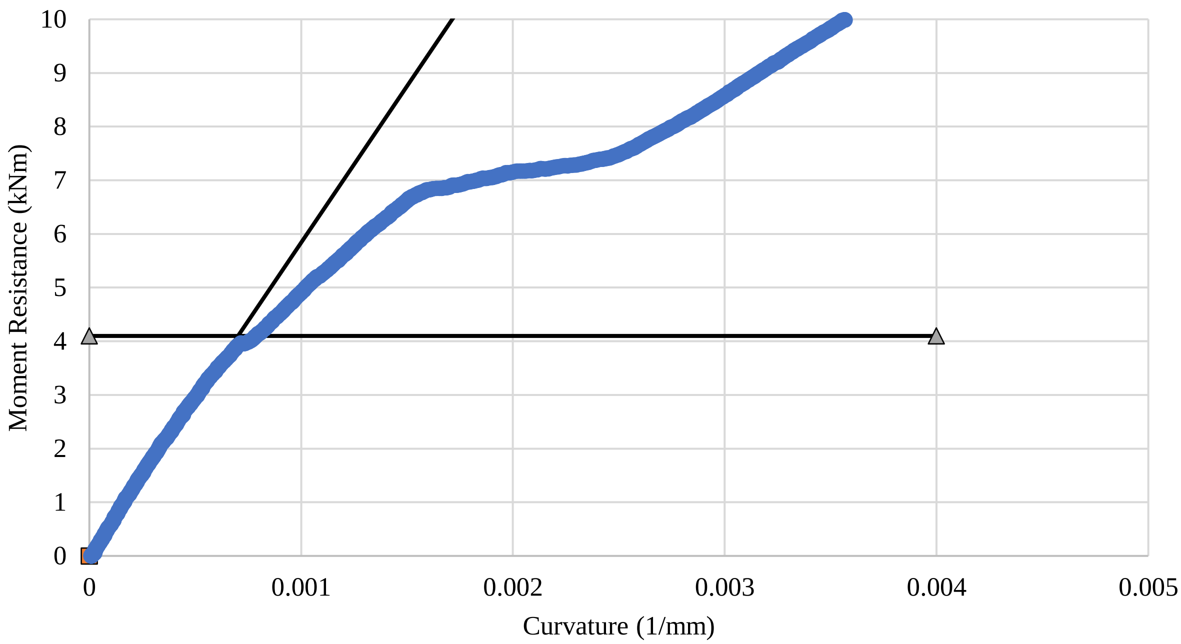


(b)

Figure 83-Moment Curvature plots- (a) RRS-B-M5-50 (1), (b) RRS-B-M5-50 (2)



(a)



(b)

Figure 84-Moment Curvature plots- (a) NRS-C-50 (1), (b) NRS-C-50 (2)

Appendix G: Trial Mixture Data

Mix ID	Mixture Characteristics		Mixture Proportions (kg/m^3)									Slump (mm)
	Mix Prop Method	Mixing Method	w/cm**	Water***	Water****	Cement	GGBFS	NCA	NFA	CRCA	FRCA	
Trial 1	Volume Replacement*	CSA Standards*	0.58	177	79	305	0	0	0	929	578	>250
Trial 2	Absolute Volume*	CSA Standards*	0.63	205	23	380	0	1023	652	0	0	>250
Trial 3	Absolute Volume*	CSA Standards*	0.61	208	34	342	0	1023	683	0	0	235
Trial 4	Absolute Volume*	CSA Standards*	0.40	245	21	617	0	1035	476	0	0	110
Trial 5	Absolute Volume*	CSA Standards*	0.51	205	23	471	0	1046	555	0	0	90
Trial 6	Absolute Volume*	CSA Standards*	0.46	205	23	513	0	1023	545	0	0	85
Trial 7	Absolute Volume*	CSA Standards*	0.51	170	23	380	0	1023	652	0	0	85
Trial 8	Absolute Volume*	CSA Standards*	0.40	205	22	513	0	1035	521	0	0	60
Trial 9	Absolute Volume*	CSA Standards*	0.54	207	34	380	0	1023	652	0	0	210
Trial 10	Absolute Volume*	CSA Standards*	0.58	205	23	353	0	1015	732	0	0	230

*As per CSA A23.1-14 design standards (absolute volume proportioning and normal mixing approach)
**Effective water-to-cementitious materials ratio,
***Free-water content
****Additional water added to compensate for aggregate absorption

Appendix H: Low Carbon Concrete Database

Click to access low-carbon concrete database.

It is recommended to download the file as an excel worksheet (.xlsx) for the best user experience.