

Concrete Made with Fine Recycled Concrete Aggregate (FRCA): A Feasibility Study

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Abstract

In the process of crushing concrete waste, significant amounts of fine by-products, the so called fine recycled concrete aggregates (FRCA), are generated and excluded from potential use. Limited research has thoroughly investigated the performance of concrete mixes with FRCA, very likely due to the complexity in analysing non-negligible amounts of adhered residual cement paste (RCP). Although some studies have proposed promising sustainable mix-design procedures accounting for the different microstructure when using coarse recycled concrete aggregates (CRCA), no similar approach exists for FRCA concrete. In this work, two promising procedures for mix-designing eco-efficient concrete with 100% FRCA are proposed accounting for the presence of RCP to reduce cement content in new mixtures. First, built on top of the existing procedure for CRCA mix-design, modifications to the Equivalent Volume (EV) method were introduced to consider full replacement of fine natural sand by FRCA. Second, based on the concept of continuous Particle Packing Models (PPM), an optimized procedure was proposed to allow maximum packing density of FRCA mix linked to a given level of measured RCP content. Results verified the feasibility of producing eco-efficient concrete mixes with 100% FRCA, emphasising the PPM mixes to report superior rheological and mechanical performance along with suitable durability-related properties. Yet, results also indicated the influence of simple or multistage crushed FRCA on the overall performance of mixes.

Keywords: Fine recycled concrete aggregates (FRCA); low-cement concrete; eco-friendly concrete, rheological behaviour, sustainable mix-design, particle packing model.

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Table of Contents

List of Figures	viii
List of Tables.....	x
List of Symbols/Acronyms	xi
1. Chapter One: Introduction	1
1.1. Background	1
1.1.1. Research on sustainable concrete	2
1.2. Research Objectives and Scope of Work	3
1.3. Thesis Overview	4
1.4. References	5
2. Chapter Two: Literature Review.....	9
2.1. Recycled Concrete Aggregates	9
2.1.1. Process production and physical properties	9
2.1.2. Residual cement paste (RCP)	10
2.1.3. Microstructure and concrete performance	11
2.2. Available Methods of Mix-Design	11
2.2.1. Direct replacement methods (DRM).....	12
2.2.2. Equivalent mortar volume (EMV)	13
2.2.3. Modified EMV (EMV-mod).....	13
2.2.4. Equivalent volume (EV).....	14
2.2.5. Particle packing models (PPM)	15
2.3. Durability Performance.....	16
2.3.1. Non-destructive tests (NDT)	16
2.3.2. Stress-strain behaviour	17
2.3.3. Resistance to accelerated freezing and thawing cycles	18
2.4. Concrete Eco-Efficiency	19
2.5. References	21
3. Chapter Three: Evaluation of the Overall Behaviour of Fine Recycled Concrete Aggregate (FRCA) Mixtures Proportioned by Different Techniques	30
3.1. Abstract.....	30
3.2. Introduction	31

3.3.	Background	32
3.3.1.	Microstructure and performance of RCA concrete	32
3.3.2.	Techniques to mix-proportion RCA concrete.....	33
3.3.2.1.	Direct replacement method (DRM)	34
3.3.2.2.	Equivalent mortar volume (EMV)	35
3.3.2.3.	Modified equivalent mortar volume (EMV-mod)	36
3.3.2.4.	Equivalent volume (EV).....	36
3.3.2.5.	Particle packing models (PPM)	37
3.4.	Scope of work	38
3.5.	Experimental program	39
3.5.1.	FRCA production process.....	39
3.5.2.	Assessment of residual cement paste (RCP)	40
3.5.3.	Raw materials characterization.....	41
3.5.4.	Mix-design approaches.....	45
3.5.5.	Mix proportions	46
3.5.6.	Specimens preparation and testing procedures	49
3.5.7.	Fresh state assessment.....	49
3.5.8.	Hardened state assessment.....	50
3.6.	Experimental Results	50
3.6.1.	Rheology of fresh state mixtures	50
3.6.2.	Compressive strength and modulus of elasticity	53
3.7.	Analysis and Discussion.....	54
3.7.1.	Influence of jaw crusher's gap opening size on the PSD of FRCA	54
3.7.2.	Evaluation mix-design methods to proportion FRCA mixtures	56
3.7.3.	Fresh state behaviour	57
3.7.4.	Hardened state behaviour	60
3.7.5.	Binder efficiency	62
3.8.	Conclusions.....	64
3.9.	Acknowledgments	66
3.10.	References	66
4.	Chapter Four: Durability Appraisal of Fine Recycled Concrete Aggregate (FRCA) Mixtures Designed with Distinct Techniques	73
4.1.	Abstract.....	73

4.2.	Introduction	74
4.3.	Background	74
4.3.1.	Microstructure and performance of FRCA concrete.....	76
4.3.2.	Available techniques for RCA concrete mix-design.....	77
4.3.2.1.	Direct replacement method (DRM)	77
4.3.2.2.	Equivalent Mortar Volume (EMV) and Modified EMV (EMV-mod)	77
4.3.2.3.	Equivalent Volume (EV)	78
4.3.2.4.	Particle Packing Models (PPM)	79
4.3.3.	Durability and long-term performance of FRCA concrete	79
4.3.3.1.	Non-destructive tests (NDT)	80
4.3.3.2.	Stress-strain relationship	80
4.3.3.3.	Freeze-thaw resistance	81
4.4.	Scope of Work.....	82
4.5.	Materials and Methods.....	83
4.5.1.	FRCA production and raw materials characterization	83
4.5.2.	Mix-design procedures and proportions	86
4.5.3.	Methods.....	88
4.5.3.1.	Sample preparation	88
4.5.3.2.	Hardened properties.....	88
4.5.3.3.	Resistance to freeze-thaw cycles	89
4.6.	Experimental Results	91
4.6.1.	Surface electrical resistivity	91
4.6.2.	Effect of FRCA on concrete mechanical properties	92
4.6.3.	Stress-strain parameters.....	93
4.6.4.	Freeze-thaw (FT) resistance	94
4.6.4.1.	Mass losses	94
4.6.4.2.	Length changes	96
4.6.4.3.	Residual dynamic modulus of elasticity	97
4.7.	Analysis and discussion	99
4.7.1.	Microscopic analysis	99
4.7.2.	Mechanical properties	100
4.7.3.	Durability factor (DF) for freeze-thaw resistance	103

4.7.4.	Efficiency of FRCA concrete mixtures	104
4.8.	Conclusions.....	105
4.9.	Acknowledgments	106
4.10.	References	107
5.	Chapter Five: Summary and Conclusions	113
6.	Chapter Six: Recommendations for Future Work.....	117

List of Figures

Figure 2.1: Qualitative comparison between volumetric components of materials from EV, CC and EMV [50].....	15
Figure 2.2: SDI and PDI parameters as proposed by [70,71].	18
Figure 3.1: Composition of CRCA (a) and FRCA (b) particles.	33
Figure 3.2: Summary of first method of production where both coarse and fine fractions are produced.	40
Figure 3.3: Summary of second method of production where only the fine fraction is produced.	40
Figure 3.4: Particle size distribution curves for FRCA derived from natural (a) and manufactured sand (b) companion conventional concrete.	43
Figure 3.5: PSD of PC and limestone filler used in the PPM FRCA mixtures.	44
Figure 3.6: EV method proportions of FRCA concrete based on a CC mix-design.....	46
Figure 3.7: Test programme used for analyzing rheology cycle.	50
Figure 3.8: Rheological profiles of the mixtures from NS (a) and MS (b) concrete sources.	52
Figure 3.9: Compressive strength over time for all mixtures.	53
Figure 3.10: Modulus of elasticity (ME) for all the mixtures having FRCA crusher's fine (CF).	54
Figure 3.11: Particle size distribution curves for different aperture sizes in the jaw crusher.	55
Figure 3.12: Volumetric components of each material for mixtures with FRCA from NS source (a) and MS source (b).	57
Figure 3.13: Rheological profiles of a)EV and b)PPM mixes compared to Herschel-Bukley's model.	59
Figure 3.14: Stress-strain analysis for DRM-NS-CF and EV-NS-CF mixtures.	61
Figure 3.15: Difference in ME regarding the type of FRCA used (CF and FG).	62
Figure 3.16: Portland cement (PC) content levels for the mixtures in analysis.	63
Figure 3.17: Relationship between binder intensity with compressive strength at 28 days (adapted from Damineli et al. [80]).	64
Figure 4.1: Composition of CRCA (a) and FRCA (b) particles.	77
Figure 4.2: Summary of the two methods of FRCA production adopted in this experimental work.	84
Figure 4.3: PSD curves for FRCA derived from natural (a) and manufactured sand (b) companion conventional concrete.....	85
Figure 4.4: PSD of PC and limestone filler used in the PPM FRCA mixtures.	86

Figure 4.5: Freeze-thaw chamber used for the test as per ASTM C 666.	89
Figure 4.6: Illustration of specimen measurements as per ASTM C 490 [71].	90
Figure 4.7: Surface electrical resistivity measurements for all FRCA mixtures.	92
Figure 4.8: Mass loss over 300 freeze-thaw cycles for all FRCA mixes.	95
Figure 4.9: Degradation of FRCA mixes at the end of 300 freezing and thawing cycles.	96
Figure 4.10: Length change over 300 cycles for PPM (a) and EV (b) in comparison to DRM mixes.	97
Figure 4.11: Residual dynamic ME over 300 cycles or PPM (a) and EV (b) in comparison to DRM mixes.	98
Figure 4.12: Composition of FRCA particle.	99
Figure 4.13: Microscopic observation of FRCA crusher's fine (a) and FRCA fully ground (b) types.	100
Figure 4.14: Phenolphthalein application on FRCA crusher's fine (a) and FRCA fully ground (b).	100
Figure 4.15: Stress-strain curves comparing a)FRCA-CF and CC mixes from NS source, and b)PPM with FRCA CF and FG types.	102
Figure 4.16: Summary of the DF of concrete mixes subjected to accelerated freezing and thawing cycles.	103
Figure 4.17: Comparison between mechanic and durability-related properties with cement content for the three FRCA mix-design methods studied in this work.	Error! Bookmark not defined.

List of Tables

Table 3.1: Acronyms used for describing RCA mix-proportion methods	34
Table 3.2: Properties of FRCA and natural aggregates.	43
Table 3.3: Physical properties characterization.....	45
Table 3.4: Companion conventional concrete mix-design proportions.	47
Table 3.5: FRCA and control concrete mix-design proportions.	49
Table 3.6: Concrete mixtures rheological properties.	52
Table 3.7: Influence of gap aperture size on the PSD of crushed FRCA (500 g samples).	55
Table 3.8: Parameters of Herschel-Bulkley' equation and experimental initial torque required for the all mixes investigated.	60
Table 4.1: List of acronyms used and their following definitions.	75
Table 4.2: Properties of FRCA and natural aggregates.	85
Table 4.3: Physical properties characterization.....	86
Table 4.4: FRCA and control concrete mix-design proportions.....	87
Table 4.5: Mechanical properties of FRCA CC mixes over time.....	93
Table 4.6: SDT test parameters for FRCA and CC mixes made with NS.	94

List of Symbols/Acronyms

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
AEA	Air Entraining Agent
AV	Apparent Viscosity
BC	Binder Content
bi	Binder Intensity
CA	Coarse Natural Aggregate
CC	Conventional Mix
CF	Crusher's Fine
CRCA	Coarse Recycled Concrete Aggregate
CSA	Canadian Standards Association
CO ₂	Carbon Dioxide
CPFT	Cumulative (Volume) Percent Finer Than D _p
CWD	Construction Demolition Waste
DF	Durability Factor
D _L	Larger Particle Diameter
D _{max}	Maximum Aggregate Size
D _{min}	Minimum Aggregate Size
D _p	Particle Diameter
DRM	Direct Replacement Method
DWR	Direct Weight Replacement
DVR	Direct Volume Replacement
D _s	Smallest Particle Diameter
ER	Electrical Resistivity
EV	Equivalent Volume
EMV	Equivalent Mortar Volume
EMV-mod	Modified Equivalent Mortar Volume
f'_c	Concrete Compressive Strength
FA	Fine Natural Aggregate
FG	Fully Ground
FRCA	Fine Recycled Concrete Aggregate
FT	Freeze and Thaw
HA	Hysteresis Area
He	Helium Gas

HRWRA	High-Range Water-Reducing Admixtures
ITZ	Interfacial Transition Zone
k_B	Viscosity Constant of Bingham
k_{HB}	Viscosity Constant of Herschel-Bulkley
m_{FRCA}	Weight of FRCA
ME	Modulus of Elasticity
MS	Manufactured Sand
n	Flow Behaviour Factor
NA	Natural Aggregate
NS	Natural Sand
OD	Oven-Dry
OVA	Original Virgin Aggregate
PC	Portland Cement
PDI	Plastic Deformation Index
PF	Packing Factor
PPMs	Particle Packing Models
PSD	Particle Size Distribution
q	Distribution Coefficient
RCA	Recycled Concrete Aggregate
RCP	Residual Cement Paste
RP	Residual Paste
RM	Residua Mortar
SCMs	Supplementary Cementitious Materials
SDT	Stiffness Damage Test
SDI	Stiffness Damage Index
SSA	Specific Surface Area
SSD	Saturated Surface Dry
TM	Total Mortar
w/c	Water to Cement Ratio
γ	Rotation
ρ	Fluid Density
τ	Torque
τ_0	Yield Torque

1.1. Background

Concrete is by far one of the most important construction materials widely used as a result of its availability, economic benefits, and outstanding mechanical and durability-related properties. Although the concrete industry is recognized by several benefits, it is also known due to its non-sustainable characteristics. The production of Portland Cement (PC) along with the extraction and manufacturing of natural aggregates are the main factors responsible for the overall energy demand in concrete production and other environmental impacts [1,2]. The production of new concrete is linked to approximately 7% of the carbon dioxide (CO₂) emissions, being PC accounting for as much as 6.5% annually [3–5]. Moreover, the wide use of concrete in the construction industry is larger than all other building materials (i.e. wood, steel, plastic and aluminum) together. Besides concrete production, studies have also demonstrated significant concerns related to the construction waste material that is produced (i.e. discarded/returned concrete and/or construction/demolition waste), which occupies significant amounts of landfills leading to soil and water contamination [6].

One alternative to minimize the carbon footprint and improve concrete eco-efficiency is by manufacturing aggregates from construction demolition waste (CDW) [7,8]. The so-called recycled concrete aggregate (RCA) seems to provide alternative ways of producing new concrete aggregate material yet reducing the impact caused by waste generated from returning concrete or demolition of existing infrastructure [9–11]. Hence, the latter demonstrates that combining RCA with other methods for improving eco-efficiency of new concrete (i.e. reducing cement content) is a promising technique to offer an overall balance between mechanical performance and environmental impacts.

1.1.1. Research on sustainable concrete

Numerous studies investigating the use of RCA from either returned or demolition waste concrete were conducted in the past [12–18]. RCA is commonly seemed as a low-quality material and inappropriate for structural applications, yet used at restricted levels in non-structural grade concrete (i.e. sidewalks and paving) [19,20]. Mechanical performance along with durability-related properties are observed to be a major concern in RCA concrete mixtures since RCA often presents inferior quality when compared to natural aggregates (NA) [13,21,22]. Hence, RCA concrete mix-design standards usually require that this type of concrete be limited to low-risk applications and having very strict levels of NA replacement by RCA material [13,23,24].

However, recent research has proved that RCA may be suitable for both conventional and structural concrete applications when considering its distinct microstructure, caused by the amount of adhered mortar to the RCA particles [13–15,25–27]. One of the first methods to account for the RCA residual mortar (RM) was introduced by Fathifazl et al. [28], the so-called Equivalent Mortar Volume (EMV). The method demonstrated to be a promising procedure in mix-designing concrete with RCA material, yet EMV-proportioned mixtures present undesirable fresh state behaviour [14,15,29]. In order to overcome this issue, some studies [14,30–32] recommended to raise the amount of cementitious materials (i.e. PC content) and/or chemical admixtures in the mixture resulting in a less eco-friendly concrete. Based on the EMV method Hayles et al. [13] proposed a modified version (i.e. EMV-mod) which enhances the fresh state properties of RCA mixtures. However, this method presented a disadvantage regarding eco-efficiency since the PC content is normally increased when compared to CC and EMV-designed mixes with similar compressive strength [11]. Another optimized version of the EMV method called *Equivalent Volume method* (EV). The EV addresses the issues faced by both EMV and EMV-mod techniques, that is, improves the fresh state behaviour while keeping low/moderate levels of PC content [10]. Although various authors have investigated/developed new methods using of coarse RCA, there is a lack of studies that present methods to produce concrete with 100% fine recycled concrete aggregates (FRCA) as well as appraise its fresh, mechanical, and durability-related properties.

1.2. Research Objectives and Scope of Work

The main goals of this experimental research are to evaluate the impact of fully replacing fine NA by FRCA on the fresh, hardened, and durability-related properties of concrete mixtures. This work can be divided into three phases: a) production and characterization of FRCA, b) evaluation of the fresh and hardened state properties of FRCA concrete mixtures, and c) investigation of the durability-related properties of FRCA concrete mixtures.

First, the impact of the FRCA manufacturing process (i.e. crushing stages) on the material physical properties is investigated. Two distinct crushing processes were used to produce FRCA: crusher's fine (i.e. two series of crushing and sieving - CF) and fully ground (i.e. multiple series of crushing and sieving - FG). Moreover, the original conventional concrete (CC) mixtures were fabricated with natural (NS) and manufactured sand (MS) resulting in a total of four types of FRCA: NS-CF, NS-FG, MS-CF, and MS-FG. Then, FRCA is characterized and the residual cement paste (RCP) quantified.

From the aforementioned concepts, in the second phase, three mix-design methods (i.e. EV, direct replacement, and particle packing model - PPM) are used to produce concrete mixtures with 100% of NA replacement by four types of FRCA. Evaluations on numerous fresh and hardened state properties of twelve FRCA mixtures were performed and comparison with CC mixes (0% FRCA) was conducted.

Lastly, prior to validating such remarks, it is understood that FRCA concrete must also satisfy certain durability requirements before being set for large scale application. Hence, the conditions imposed on concrete structures by harsh environmental conditions such as the ones found in Canada (i.e. freezing and thawing damage) were appraised.

1.3. Thesis Overview

This thesis is divided into five chapters. Chapter 1 consists of an overview of the concrete industry impacts on the environment, followed by a background section emphasizing the benefits of using recycled concrete aggregates.

Chapter 2 presents a detailed literature review on the use of RCA as an alternative sustainable material for the construction industry. This section discusses on the following topics: process production and physical properties, RCP content, microstructure and concrete performance, available methods of mix-design, durability performance and concrete eco-efficiency.

Chapter 3 presents, in a journal paper format, the evaluation of the fresh and hardened state behaviour of FRCA mixes proportioned by distinct techniques.

Likewise, in a journal paper format, chapter 4 presents the durability appraisal of FRCA mixtures designed with three distinct techniques.

Finally, chapter 5 and 6 bring a summary of conclusions assessed throughout the experimental programs and propose suggestions for further work, respectively.

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Chapter Two: Literature Review

2.1. Recycled Concrete Aggregates

Two types of RCA are usually referred to in the literature: coarse (CRCA) and fine (FRCA) recycled concrete aggregates. In general, CRCA can be described as a multiphase material composed of NA with substantial amounts of adhered RM to particles surface [1,2]. Therefore, CRCA is comprised of original virgin aggregate (OVA) and RM, which provides the material with a rough and porous microstructure comprised of micro-cracks. The amount of RM, which may be up to 60% of the total volume of CRCA, is linked to the type and physical quality of the OVA and the RM inner characteristic [3]. On the other hand, the FRCA is characterized by a fine granular material with considerable amounts of residual cement paste (RCP) and original particles of fine aggregate. In comparison to CRCA, FRCA is considered a material of worse quality due to its supposedly high amount of residual cement paste (RCP) adhered to the fine particles. The presence of RCP affects several physical characteristics of the FRCA; for instance, reducing the specific gravity, increasing the porosity and water absorption. Similarly to CRCA, the FRCA fabrication may vary significantly depending on factors such as crusher type and crushing series, which leads to important variability to the final product [4,5].

2.1.1. Process production and physical properties

Recently investigations have been carried out verifying the impact of the original concrete source and crushing process on the FRCA overall quality aiming the production of optimized FRCA concrete mixtures [6,7]. Advanced recycling techniques such as water floatation, air blowing, and washing stages have been applied to the production process of FRCA [8] enhancing the physical properties of the resulting material. Ulsen *et al.* [6] have studied distinct crushing techniques using a combination of jaw crusher and vertical shaft impactor at various rotational speeds to produce FRCA with physical characteristics (i.e. particle shape, particle size distribution, etc.)

similar to those of fine natural aggregates. However, it was observed that parameters such as particle size distribution (PSD) and particle shape are not affected by the variable rotational speed of the crusher. Furthermore, Fan et al. [9,10] have studied the effect on FRCA due to the number of crushing stages in which it is subjected. As a result, it was observed that physical properties such as specific gravity and water absorption were significantly affected whether the FRCA was produced by single or multiple crushing stages. These findings are also complemented with the analysis performed by Florea and Brouwers [11] which analyzed the influence of the crushing method on the PSD and specific gravity of RCA. Likewise, it was observed the need for an optimized or even standardized crushing method in order to produce RCA with superior quality. Moreover, further studies need to be done in order to investigate/quantify the RCP content adhered to the FRCA particles, since it is one of the key factors responsible for changes in FRCA's microstructure; hence, affecting several FRCA physical properties.

2.1.2. Residual cement paste (RCP)

In the past years, several studies [12–17] have focused on different methods to quantify or even to remove the RCP adhered to FRCA particles, which is considered the governing factor of its microstructure. After crushing CRCA into FRCA, the material is constituted of two main components which are the RCP and residual amounts of NA (e.g. natural sand or smaller crushed particles of coarse aggregate). Due to the smaller PSD, the RCP present in FRCA is comprised of deleterious amounts of cement paste that remained attached to the crushed NA during the manufacturing process. As a result, the porosity of RCP yields undesirable FRCA properties such as lower particle density, much higher water absorption and lower aggregate mechanical strength than NA [18]. On the other hand, if the RCP would be properly taken into consideration and characterized within the FRCA system, its presence distributed throughout the NA particles could contribute to the optimization of new-mixtures with reduced cement content [19].

2.1.3. Microstructure and concrete performance

Given the high variability of FRCA physical properties (i.e. water absorption, specific gravity and granulometry) resultant from the distinct volume of residual cement paste, it is generally challenging to accurately predict fresh and hardened state performance of recycled concrete mixtures. Recycled concrete mixtures partially or fully replaced by FRCA were observed to yield lower performance in the fresh (i.e. high consistency and low flowability) and hardened states (i.e. low compressive strength and stiffness) when compared to conventional concrete mixes [12,20–26]. The latter was deemed, among others, to the supplementary amount of interfacial transitional zones (ITZ) that is brought to the system with the use of FRCA. In order to overcome these issues, advanced mix-design techniques such as the methods that account for RCA microstructure such as the *Equivalent Volume Method (EV)* or even *Particle Packing Models (PPMs)* might be used. Although, there is currently a lack of literature data illustrating the short- and long-term performance of FRCA mixes proportioned with the above techniques.

2.2. Available Methods of Mix Design

This section comprises the discussion of available methods of concrete mix-design with RCA. It is important to notice that the procedures discussed hereafter comprise the use of only the coarse fraction of RCA (i.e. CRCA). Apart from direct replacement methods (DRM), which does not account for the RCP, a procedure to account for the different microstructure of FRCA in mix-design FRCA concrete is currently lacking in the literature.

Although distinct methods accounting for the RM were developed to enhance CRCA concrete mixtures, they are usually mix designed with outdated techniques such as direct replacement methods (DRM) with limited levels of RCA replacement and increased amounts of cement (i.e. > 400 kg/m³) [27,28]. Regarding FRCA mix-design proportioning, the few studies available in the literature adopt conventional methods of mix design (adding the FRCA based on DRM) resulting in mixes with worse performance in the fresh (i.e. high consistency and low flowability) and hardened states (i.e. low compressive strength and stiffness) when compared to RCA and CC mixes [12,20–26]. The latter is deemed, similar to CRCA, to the supplementary amount of weaker

and more porous interfacial transitional zones (ITZ) that is brought to the system when incorporating FRCA material without accounting for the different microstructure.

2.2.1. Direct replacement methods (DRM)

Direct Replacement Methods (DRM, either by weight or volume of material) are considered as one of the earliest attempts to mix-proportion concrete using RCA. The DRM treats RCA as an homogeneous material and certain amounts of NA are partially replaced without accounting for the difference in microstructure such as the presence of RM [29–32]. Though, important parameters of RCA particles such as specific gravity, water absorption, texture, and angularity are seen to be significantly affected by the RM [2,19]. Consequently, RCA concrete mixtures proportioned through DRM techniques usually yield inferior fresh and hardened state behaviours in comparison to CC mixes made with natural aggregates [33]. Yet, recent studies demonstrate to achieve acceptable fresh and hardened state performance in DRM-mix-designed concrete when increased amounts of binder (i.e. PC), supplementary cementing materials (SCMs), and chemical admixtures are incorporated into the system [34,35].

RCA material is combined with NA (coarse fraction) in the concrete mix and the amount of PC, water and fine aggregates is kept constant for any RCA replacement for both DRM approaches, direct weight replacement (DWR) and direct volume replacement (DVR) [36,37]. Considerable improvement in consistency (i.e. slump measurement) is observed to occur when using DWR [35,38], whereas DVR does not seem to directly impact the RCA mix consistency. Since variable results are observed, low to moderate replacement levels (i.e. 10-30%) of NA by RCA are usually adopted [39]. Furthermore, RCA is treated as a single-phase material in both DWR and DRV methods and thus, the RM within the recycled particles is not accounted for. Then, the total amount of coarse aggregates (i.e. OVA and new added NA) in the system is lower than NA when compared to a CC mix. Lastly, DRM methods tend to offset the potential environmental benefits, since quite often high amounts of cement (i.e. $> 400 \text{ kg/m}^3$) are required in order to obtain similar mechanical and durability-related properties as CC mixes [40].

2.2.2. Equivalent mortar volume (EMV)

The Equivalent Volume Method (EMV) is one of the first promising mix-design procedures that accounts for the distinct microstructure of the RCA, as proposed by Fathifazl et al. [41]. The RCA is treated in this method as a multi-phase material constituted of RM and OVA. In addition, the volume of cementitious material added to the mix is reduced depending on the already existing RM content attached to the RCA particles. Concrete mixtures proportioned with the EMV method are always based on a companion CC mixture, with the same total content of mortar (TM, summation of RM and the fresh mortar) and coarse aggregates than the reference CC mix [12,41].

Although using the EMV method to design RCA concrete provides suitable performance in the hardened state, the mixtures present undesirable fresh state behaviour (i.e. high consistency, low flowability and unreliable rheological behaviour). The latter is explained by the amount of coarse aggregates added in EMV mixes, which is much higher than usual for CC mixes, since RM behaves as an aggregate in the fresh state whereas is a mortar in the hardened state. The former is deemed to be the main factor decreasing the fresh state performance of EMV-designed materials [13,42,43]. Lastly, although the presence of RM considerably affects the flowability of recycled mixes, previous research [44–47] suggests to address such outcomes by increasing the amount of cement and chemical admixtures in the mixture, though, offsetting the environmental benefits of RCA concrete.

2.2.3. Modified EMV (EMV-mod)

A modification to the previous EMV method was proposed by Hayles et al. [48], in order to address common issues faced in the fresh state EMV mixes, especially with reduced amounts of binder (i.e. PC content). The EMV-mod method is comprised of an additional factor to optimize the “cement to sand mass ratio” of the RM, thus allowing the appropriate proportioning of cement to be accounted for in the new EMV-mod mix. Therefore, mixtures proportioned through this method present improved fresh state performance (i.e. lower consistency and higher flowability) when compared to EMV mixtures. Nevertheless, the EMV-mod demonstrated a

shortcoming as the PC content would normally increase for a given targeted strength when compared to both CC and EMV-designed mixes [48].

2.2.4. Equivalent volume (EV)

The promising *Equivalent Volume method* (EV) of mix-design was developed by Ahimoghdam et al. [49]. Built on top of the main concepts of previous EMV and EMV-mod methods, the EV aims to solve the issues faced by both EMV and EMV-mod mix-proportioned mixtures in the fresh state yet providing RCA mixes with an eco-friendly character (i.e. low PC content) while keeping desirable mechanical performance [49].

The novelty of the EV method is that the RCA mix is based on a reference CC mix presenting the same volumetric amount of cement paste (CP) and aggregates (Ag). The RM is considered to be the summation of residual paste (RP) and residual fine aggregates. Thus, the total volumetric CP content for a given EV mixture is described as the sum of RP and fresh paste (FP) volumes. Hence, in order to approach an appropriate mix-design with the EV method, the proportions of OVA and RM must be quantified within the RCA and the following condition is met:

$$V_{CP}^{RCA-concrete} = V_{CP}^{CC} \quad \text{Equation 2.1}$$

$$V_{Ag}^{RCA-concrete} = V_{Ag}^{CC} \quad \text{Equation 2.2}$$

Where: $V_{CP}^{RCA-concrete}$ is the total volume of paste in the mix; V_{CP}^{CC} and V_{Ag}^{CC} are the cement paste and aggregate volumes (both fine and coarse), respectively, in the reference CC mixture; $V_{Ag}^{RCA-concrete}$ is the total volume of both coarse and fine aggregates in the RCA mix, being the volumetric summation of new aggregate (NA: coarse and fine) and the original virgin aggregate (OVA: coarse and fine) in the RCA mix [49]. A summary comparing the volumetric material proportions of RCA mixes designed with three distinct methods (EMV, EV and CC) is shown in **(Error! Reference source not found. 2.1)**. Unlike EMV and EMV-mod methods, EV mixes usually demonstrate suitable fresh state behaviour and cement efficiency (PC contents ≈ 300 kg/m³), since there is a significant increase of fine aggregates and decrease of coarse particles in the system [40,49].

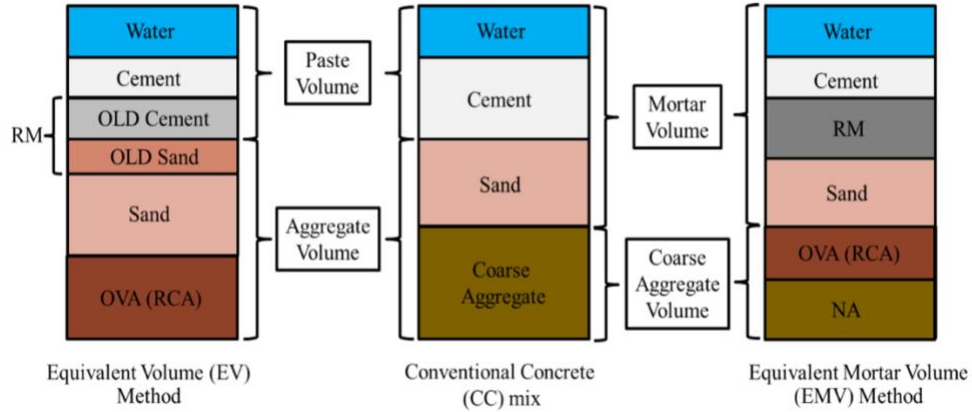


Figure 2.1: Qualitative comparison between volumetric components of materials from EV, CC and EMV [50].

2.2.5. Particle packing models (PPM)

Particle packing models (PPMs) are advanced mix-design techniques used to improve performance of concrete mixes in both fresh and hardened states. PPMs are divided into discrete and continuous models. The first one assumes the existence of a given number of discrete particle sizes that are rearranged to reach the maximum packing density [37,51,52], whereas the second one assumes a continued distribution of particles within the system [52,53]. Either discrete or continuous, PPMs aim to optimize the granular system, resulting in an improved packing density and reduced porosity [52–56]. Hence, concrete mix-proportioned through PPMs often present lower PC amounts when compared to conventionally designed concrete.

The modified-Andreasen or Alfred model, which was initially created by Funk and Dinger in 1980 [57], is one of the most interesting and recognized continuous PPM model. It calculates the optimal particle size distribution based on a coefficient of distribution (q) along with the largest (D_L) and smallest (D_S) particle sizes (i.e. diameter) which are present in the system (Equation 2.3). The q -factor is selected given the fresh state requirements of the mix. For instance, q value ranges between 0.20-0.23 are often selected for self-consolidating mixtures, whereas 0.26-0.28 are normally aimed for vibrated and or pumped concrete. It is worth noting that 0.37 is the q value that yields the highest packing density and thus lowest porosity to the granular system as per [57].

$$CPFT = 100 * \left(\frac{D_P^q - D_S^q}{D_L^q - D_S^q} \right) \quad \text{Equation 2.3}$$

Where: CPFT is the cumulative (volume) percent finer than D_P and D_P is the particle size.

PPMs have been widely used to improve fresh and hardened states performance in eco-efficient [31,58,59], conventional [53,55,60], and high-performance concrete [61,62]. Yet, very few research is performed on using PPMs to optimize recycled concrete, especially FRCA mixtures [31,63].

2.3. Durability Performance

It is known that the fresh and hardened state properties of concrete mixtures must be adequate according to its design in order to allow a correct placing and consolidating in the fresh state and desirable mechanical properties based on the project. However, the durability-related properties are also critical factors that must be accounted during the concrete mix-design, especially for concrete subjected to severe environmental conditions such as freezing-thawing cycles and exposure to de-icing salts [30]. Standards always correct acceptable durability performance of CC mixtures with the w/c, concrete compressive strength, and cement type. In order to mix-design durable FRCA mixtures, the material proportion should be even more important than the other factors since the recycled material presents higher amount of microcracks/inner flaws; hence greater porosity within the RCP. Therefore, a proper FRCA quantification is crucial to have mix-design recycled concrete with desirable long-term performance. A number of non-destructive, mechanical, and accelerated procedures might be used to evaluate the FRCA microstructure and durability performance and are presented hereafter.

2.3.1. Non-destructive tests (NDT)

A fast evaluation of the inner quality of concrete mixtures may be performed through the use of non-destructive techniques (NDT), such as ultrasonic pulse velocity (UPV) and surface electrical resistivity (ER). Such techniques have been verified to be suitable to appraise the overall quality of conventional concrete mixtures subjected to aggressive/harsh environments [64] along with

the effects of RCA replacement on the inner quality of CRCA [13,50,65,66]. Literature results show that the higher the RCA replacement, the lower the UPV and ER results gathered over the test for CRCA mixtures [9,17].

2.3.2. Stress-strain behaviour

It is usually found in the literature that regardless of the mix-design technique used to proportion RCA concrete mixtures, the overall stiffness of concrete tends to be lower than the ones of conventional concrete mixes (CC) [18,35,67,68]. This is very likely due to the presence of residual paste (RP) or residual cement paste (RCP) which is found within coarse or fine aggregate particles, respectively. RCA concrete is comprised of multiple interfacial transition zones (ITZ), brought by the presence of residual mortar present in RCA material. When used to mix-design concrete, RCA mixtures are usually deemed of inferior mechanical performance (i.e. low compressive strength and stiffness) when compared to conventional concrete mixes [12,20–26]. In some cases, even when the RCA concrete achieves compressive strength similar to CC mixes, it tends to present higher deformation due to the lower inner quality of the RCA particles [67,69]. Hence, the stress-strain relationship tends to present a smoother increase and lower values of modulus of elasticity (ME). Besides the ME, the stress-strain curve is a key parameter to evaluate a previously damaged concrete because it measures the ability of the material to respond to compressive load applied. Although RCA concrete is not considered deteriorated concrete due to internal distress mechanism, the appraisal of using a stress-strain relationship may be similar due to the high porosity added to the system caused by multiple ITZ linked to RM or RCP content. In order to better evaluate the stress-strain relationship, using a cyclic set of compression loads, the stiffness damage test (SDT) procedure seems to be a promising and reliable technique.

The Stiffness Damage Test (SDT), as proposed in a revised procedure by Sanchez et al. [70], has proved to be a reliable tool for quantifying physical damage in concrete, yet has never been used to analyse FRCA concrete, although it seems as a promising method to appraise inner quality and long-term performance. The SDT comprises a series of five uniaxial unloading/loading cycles at a controlled rate of 0.10 MPa/s, in which the concrete specimen in analysis is loaded up to 40% of its 28-day compressive strength [71–73]. At this loading level, no deleterious effects are

generated into the concrete since similar loading is recommended for testing modulus of elasticity, as per ASTM C 469 [74]. Therefore, the cracks present in the microstructure are closed as the load increases and remain at this state, without generating additional damage by the stress applied [70,75].

The first output parameter from the SDT is known as the stiffness damage index (SDI; S_I/S_I+S_{II} - Figure 2.2), which evaluates the energy required to close the internal cracks. Likewise, the crack opening leads to a permanent deformation of the material, which compared to the total deformation imposed to the system results in the second output parameter known as the Plastic deformation index (PDI; $DI/DI+DII$ - Figure 2.2). Finally, an additional feature of the SDT is the ability to measure the stiffness (i.e. modulus of elasticity) of the material when considering the average slope of the curve for the second and third loading cycles [70,71].

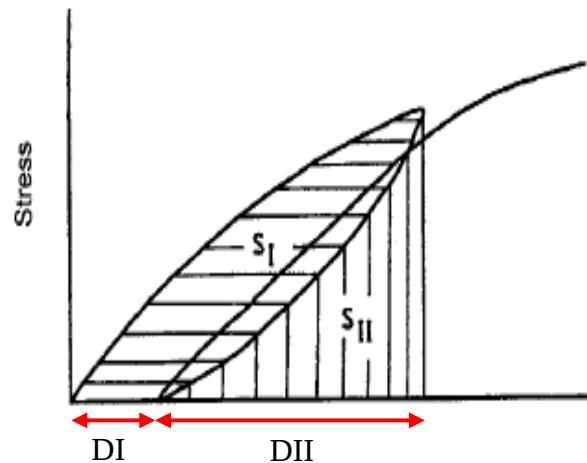


Figure 2.2: SDI and PDI parameters as proposed by [70,71].

2.3.3. Resistance to accelerated freezing and thawing cycles

As mentioned before, one of the main harsh environmental conditions occur in the cold weather countries, for instance, freeze-thaw (FT) cycles and exposure to de-icing salts. The FT resistance of CC is frequently correlated with distinct factors such as the aggregate features, cement paste porosity, and free water within the system. These parameters are more crucial for RCA concrete since the material's higher porosity and absorption leads to further FT damage [76,77]. Although

permeability is also a key parameter in terms of transport mechanisms, the role of permeability of highly porous aggregates such as RCA is not fully understood yet [78].

Although previous studies have investigated the freeze-thaw (FT) resistance of RCA concrete [66,79,80], there is a lack of studies presenting an appropriate way to mix-design durable concrete mixtures with high percentage (or even with 100%) of RCA. It is concluded that the higher the RCA replacement, the lower its resistance to FT cycles, especially for RCA mixtures designed through DRM in which the RCA microstructure is not accounted for. However, EMV-designed mixtures showed to have interesting FT results yielding comparable outcomes when compared to similar CC mixes [80].

Bogas et al. [81] investigated a 35 MPa and 66.5 MPa concrete mixture with 100% replacement FRCA and incorporating moderate to high cement contents of 350 kg/m³ and 420 kg/m³, respectively. The authors observed that normal strength concrete (e.g. 35 MPa) were not freeze-thaw resistant regardless of the replacement ratio of FRCA. Although air entraining agent is usually used to improve FT resistance of CC mixtures, it was observed to be not as effective for FRCA. It may be explained due to the different FRCA microstructure which increases the system porosity. The voids introduced in the system are not completely rounded and equidistant to each other resulting in a decrease of the freeze-thaw performance. Nevertheless, it is worth noting that these mixes were mix-proportioned with moderate to high binder content (> 400 kg/m³) offsetting the eco-friendly concrete concept. Therefore, further research is needed to develop appropriate FRCA concrete mixtures with better freeze-thaw performance, while maintaining the cement content as low as possible.

2.4. Concrete Eco-Efficiency

The concrete industry presents misconception regarding the compressive strength and cement content until now. Although concrete strength is linked to the hydration of PC that forms calcium silicate hydrate (C-S-H), CC compressive strength is governed by the water-to-cement (w/c) ratio rather than the cement content. In order to better evaluate concrete eco-efficiency, the binder

intensity index (Equation 2.4) was created to correlate the amount of binder required to develop one unit of concrete property [82]

$$bi = \frac{BC}{P} \quad \text{Equation 2.4}$$

Where BC is the binder content (kg/m³), and P is the performance requirement (e.g. compressive strength – MPa).

Even though this index was never used to evaluate RCA concrete mixtures, which normally contains a higher amount of PC content, this calculation may be used to compare the binder efficiency of RCA mixtures to CC mixtures.

2.5. Research Contributions and Expected Results

Amongst the key factors associated to provide suitability for using FRCA in concrete is the proper quantification and characterization of the residual cement paste content which clearly states the difference in microstructure between natural and FRCA aggregates. Furthermore, there is also a significant lack of guidelines to develop a framework in order to achieve predictable properties in both fresh and hardened states of concrete made of FRCA. One feasible way to overcome such obstacles is the use and optimization of advanced mix-design techniques (e.g. Equivalent Volume Method – EV and Particle Packing Models - PPMs) which account for the distinct microstructure of FRCA material. In this experimental work, advanced mix-design techniques are selected to produce concrete incorporating significant proportions of fine recycled materials and reduced amount of cement content, yet maintaining short and long-term performance within acceptable range. It is anticipated that the results coming out from this research will provide the Canadian civil industry with immense benefits such as the reduction of the carbon footprint of concrete construction, reuse of waste materials with low-embodied energy and the creation of new market opportunities for Canadian industry related to the increased value of demolition “waste”.

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Chapter Three: Evaluation of the Overall Behaviour of Fine Recycled Concrete Aggregate (FRCA) Mixtures Proportioned by Different Techniques

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3.1. Abstract

Most of the research on the use of recycled concrete aggregates (RCA) disregard its distinct microstructure when compared to natural aggregates (NA) and thus inferior performance of the recycled concrete is often obtained in the fresh and hardened states. In order to improve the overall performance of RCA concrete, advanced mix-design techniques such as the Equivalent Volume Method (EV) or Particle Packing Models (PPMs) might be used. Yet, these techniques have never been applied to mix-proportion fine recycled concrete aggregates (FRCA). This work evaluates the fresh and hardened state behaviours of twelve recycled concrete mixtures containing 100% replacement of fine aggregates by FRCA. Three mix-design methods (i.e. direct replacement, EV and PPMs), two types of aggregate (natural vs manufactured) and two FRCA manufacturing processes (crusher's fine vs fully ground) were selected for this research. Results demonstrate that the aggregate's type and crushing process play an essential role on the inner quality of FRCA. Moreover, EV and PPM-mix-designed FRCA concrete yielded suitable performance in both fresh and hardened states along with an eco-efficient character. Conversely, DRM-mix proportioned mixtures displayed inadequate fresh and hardened state properties.

Keywords: Fine recycled concrete aggregates; residual cement paste; eco-friendly concrete; rheological behaviour; mix-design; particle packing model.

3.2. Introduction

Concrete is one of the most important construction materials used worldwide due to its large availability, reasonably low price and quite interesting mechanical properties and durability. Yet, the concrete industry is currently facing major challenges when it comes to alternative strategies to reduce CO₂ emissions related to the manufacturing of Portland Cement (PC), by far the most important concrete ingredient [1]. Twice as much of concrete is used in the construction industry when compared to all other building materials (i.e. wood, steel, plastic and aluminum) combined. Despite many benefits related to its use for distinct purposes, the concrete manufacturing process requires large amounts of non-renewable materials (e.g. natural aggregates) which accounts for about 5% of the total global emissions [2]. Besides the environmental impacts caused by concrete production, previous studies have also highlighted important concerns regarding the construction waste materials generated [3,4]. Issues in concrete production or delivery results in a huge amount of discarded material, which occupies significant amounts of landfills increasing the risk of soil and water contamination [4–6].

One of the possible ways to decrease the carbon footprint and thus improve eco-efficiency in the concrete industry is by using construction demolition waste (CDW), such as demolished or returned concrete. The so-called recycled concrete aggregate (RCA) may be manufactured and used as a full or partial replacement of natural aggregates in concrete [7,8]. Numerous experimental programs have been performed over the past decades to understand the behaviour of RCA concrete in the material and structural scales [9]. The conventional use of RCA in concrete has been mostly verified to be linked to inferior mechanical [10–14] and durability-related properties [12,15–17], since RCA often displays inferior quality when compared to natural aggregates (NA). Yet, it has been found that whenever the distinct RCA microstructure is accounted for in the design of the recycled material, interesting properties in the hardened state, similar to those of conventional concrete, may be obtained [5,18–26].

3.3. Background

3.3.1. Microstructure and performance of RCA concrete

A number of studies regarding the use of recycled concrete aggregate (RCA) were conducted in the past from either returned or demolition waste concrete [10–16]. During RCA production, two types of materials are normally generated: coarse (CRCA) and fine (FRCA) aggregates (about 30% generation of fine material). Past research investigating the use of CRCA in concrete demonstrated that concrete made of CRCA particles often displays an inferior behaviour in both fresh and hardened states when compared to conventional concrete (CC) made of natural aggregates (NA) [17]. Yet, it has been found that the amount of adhered mortar to the CRCA particles, the so-called residual mortar (RM), is the key factor that changes its microstructure and thus determines the performance of CRCA concrete [1,7,18–20].

The intrinsic difference between CRCA and NA is the fact that CRCA is a two-phase material comprised of the original virgin aggregate (OVA) and RM (Figure 3.1a). The amount of RM may vary and depends upon the type and quality of the OVA (i.e. lithotype, texture, shape, etc.) and the RM inner quality (i.e. mechanical properties). The RM may constitute up to 60% of the total volume of CRCA [21]. Microcracks are also regularly found within the RM likely due to past damage, weathering and/or RCA processing (i.e. crushing, sieving, etc.).

Although various authors have investigated the use of CRCA, very few research and developments [14,22–26] were made on FRCA concrete, especially for high replacement levels (> 20%). FRCA is considered to be a very low-quality material due to its supposedly high amount of residual cement paste (RCP) adhered to the fine particles which results in low specific gravity, high porosity and absorption of the FRCA along with high water demand of the FRCA concrete (Figure 3.1b). Moreover, FRCA fabrication may vary significantly (i.e. crusher type, crushing series, etc.) which leads to important variability to the final product [27,28].

Recycled concrete mixtures partially or fully replaced by FRCA were observed to yield lower performance in the fresh (i.e. high consistency and low flowability) and hardened states (i.e. low compressive strength and stiffness) when compared to conventional concrete mixes [29–36]. The

latter was deemed, among others, to the supplementary amount of interfacial transitional zones (ITZ) that is brought to the system while using FRCA. In order to overcome these issues, advanced mix-design techniques such as the methods that account for RCA microstructure (e.g. *Equivalent Volume Method- EV* or even *Particle Packing Models- PPMs*) might be used. However, there is currently a lack of literature data illustrating the overall performance of FRCA mixes proportioned with the above techniques.

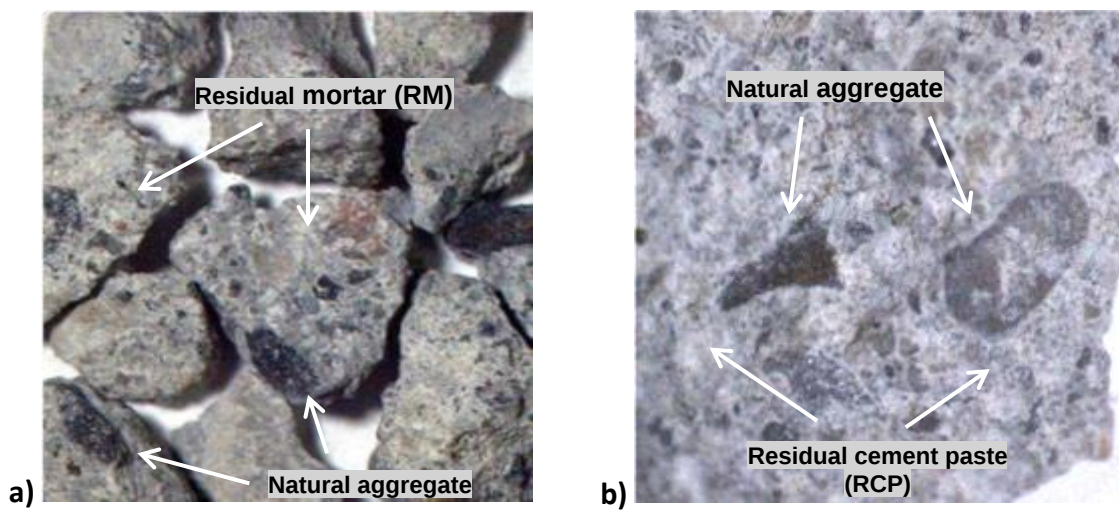


Figure 3.1: Composition of CRCA (a) and FRCA (b) particles.

3.3.2. Techniques to mix-proportion RCA concrete

Table 3.1 presents a summary and description of the acronyms cited throughout this work to describe distinct types of mix-designing RCA concrete mixtures.

Table 3.1: Acronyms used for describing RCA mix-proportion methods

Acronyms	Stands for	Description
RCA	Recycled Concrete Aggregate	Aggregate obtained by crushing concrete waste. It will usually be used to refer the coarse aggregate fraction only (i.e. >5 mm particle size).
FRCA	Fine Recycled Concrete Aggregate	Sub-product of RCA crushing with smaller particle size diameter (i.e. <5 mm).
NA	Natural Aggregate	Natural aggregate obtained from crushed stone or gravel.
RM	Residual Mortar	The portion of mortar comprised of natural sand and hydrated cement attached to the surface of RCA particles.
RCP	Residual Cement Paste	The portion of hydrated and unhydrated cement attached to residual fine material within FRCA material.
ITZ	Interfacial Transition Zone	Interface between aggregate particles and mortar in concrete.
CC	Conventional Concrete	Concrete comprised of natural aggregates only, designed with the ACI method.
FRCA Concrete	Fine Recycled Aggregate Concrete (FRAC)	Concrete proportioned with replacement of the natural aggregate fraction by FRCA.
DRM	Direct Replacement Methods	Design methods for concrete with RCA and FRCA partially replacing (by weight or volume) a portion of natural aggregates not accounting for the residual mortar or residual cement paste.
EV	Equivalent Volume	Mix-design method for concrete with RCA accounting for the difference in microstructure.
PPM	Particle Packing Models	Method for mix-design low-binder concrete with optimization of the particle size distribution and use of a q-factor

3.3.2.1. Direct replacement method (DRM)

One of the earliest attempts to mix-proportion concrete using RCA was performed through the use of *Direct Replacement Methods* (DRM, either by weight or volume of material). In the DRM, RCA is treated as a homogeneous material and partially replaces certain amounts of NA without accounting for its distinct microstructure such as the presence of RM [2,37–39]. However, it has been found that important properties of RCA particles such as specific gravity, water absorption,

texture, and angularity are significantly affected by the RM [25,40]. As a result, RCA concrete mixtures proportioned through DRM techniques are usually linked to inferior fresh and hardened state behaviours when compared to conventional mixes made with natural aggregates [41]. Nevertheless, recent studies showed that suitable fresh and hardened state performance may be achieved by DRM-mix-designed concrete incorporating high amounts of binder (i.e. PC), supplementary cementing materials (SCMs), and chemical admixtures [42,43].

In both DRM approaches, direct weight replacement (DWR) and direct volume replacement (DVR), RCA is combined with NA (coarse fraction) in the mix and the amount of PC, water and fine aggregates is kept constant for any RCA replacement ratio selected [44,45]. It has been found that significant improvement in consistency (i.e. slump measurement) occurs while the use of DWR [43,46], whereas DVR does not seem to directly impact on RCA mix consistency. Due to the higher variability of results, replacements of NA by RCA are usually kept at low to moderate levels (e.g. 10 to 30%) [47]. Furthermore, both DWR and DRV treat RCA as a single-phase material and thus do not account for the RM within the recycled particles; hence, the total amount of coarse aggregates (e.g. OVA and new added NA) in the system is lower than NA when compared to a CC mix. Finally, potential environmental benefits are usually neglected while using DRM methods, since quite often high amounts of PC (e.g. $> 400 \text{ kg/m}^3$) are selected to obtain similar mechanical and durability-related properties than CC [48].

3.3.2.2. Equivalent mortar volume (EMV)

The Equivalent Volume Method (EMV), proposed by Fathifazl et al. [49] is a very promising mix-design procedure that accounts for the distinct microstructure of the RCA; the method treats RCA as a multi-phase material comprised of RM and OVA. In this method, the volume of cementitious material added to the recycled mix is reduced according to the existing RM content adhered to the RCA particles. EMV-proportioned recycled mixes are always based upon a companion CC mixture, presenting the same total mortar (TM, summation of RM and the fresh mortar) and coarse aggregates contents as the reference CC [33,49].

Despite the promising use of the EMV method to provide RCA concrete with desirable performance in the hardened state, quite often EMV-proportioned mixtures present undesirable fresh state behaviour (e.g. high consistency, low flowability and unsuitable rheological profile). It has been found that the amount of coarse aggregates of recycled mixtures proportioned through the EMV method is much higher than usual CC mixes since RM behaves as an aggregate in the fresh state as opposed to a mortar in the hardened state. The latter is deemed to be the main factor decreasing the fresh state performance of EMV-designed materials [50–52]. Finally, although the flowability of recycled mixes is significantly affected by the presence of RM, some works [8,12,53,54] have suggested to overcome this by increasing the amount of cementitious materials (i.e. PC content) and chemical admixtures in the mixture, which offsets the environmental benefits of using RCA concrete.

3.3.2.3. Modified equivalent mortar volume (EMV-mod)

In order to address the issues often faced in the fresh state by EMV-proportioned RCA mixes, especially with reduced amounts of binder (i.e. PC content), a modification to the preliminary method was proposed by Hayles et al. [11]. The EMV-mod method adds a supplementary factor to optimize the “cement to sand mass ratio” of the RM and thus allows the proper selection of the amount of cement to be accounted for in the new RCA mix. As a result, EMV-mod proportioned mixtures present improved fresh state performance (i.e. lower consistency and higher flowability) than EMV mixes. However, this approach was verified to present a drawback as the PC content is normally increased for a given targeted strength when compared to both CC and EMV-designed mixes [11].

3.3.2.4. Equivalent volume (EV)

Based on the main concepts of the previous EMV and EMV-mod methods, an optimized mix-design procedure, the so-called *Equivalent Volume method* (EV) was developed by Ahimoghdam et al. [10]. The EV aims to solve the issues faced by both EMV and EMV-mod mix-proportioned mixtures in the fresh state along with providing recycled mixtures with an eco-friendly character (i.e. low PC content) while keeping suitable performance in the hardened state [10].

Unlike the EMV where the same amount of coarse aggregates and RM are considered for calculations, the novelty of this method is that the RCA mix is based on a reference CC mix presenting the same volumetric amount of cement paste (CP) and aggregates (Ag). Moreover, RM is considered in this method as the summation of residual paste (RP) and residual fine aggregates. Therefore, the total volumetric CP content in a given EV mixture is defined as the summation of RP and fresh paste (FP) volumes. It is worth noting that in order to approach a proper mix-design through the EV method, the amounts of OVA and RM must be quantified within the RCA and meet the following condition:

$$V_{CP}^{RCA-concrete} = V_{CP}^{CC} \quad \text{Equation 3.1}$$

$$V_{Ag}^{RCA-concrete} = V_{Ag}^{CC} \quad \text{Equation 3.2}$$

Where: $V_{CP}^{RCA-concrete}$ is the total volume of paste in the mix; V_{CP}^{CC} and V_{Ag}^{CC} are the cement paste and aggregate volumes (both fine and coarse), respectively, in the reference CC mixture; $V_{Ag}^{RCA-concrete}$ is the total volume of both coarse and fine aggregates in the RCA mix, being the volumetric summation of new aggregate (NA: coarse and fine) and the original virgin aggregate (OVA: coarse and fine) in the RCA mix [10].

As opposed to EMV and EMV-mod methods, EV-proportioned mixes were found to often yield suitable fresh state behaviour and cement efficiency (PC contents $\approx 300 \text{ kg/m}^3$) due to the significant increase of fine aggregates and decrease of coarse particles in the system [10,48].

3.3.2.5. Particle packing models (PPM)

Particle packing models (PPMs) are advanced mix-design techniques used to improve the performance of concrete mixtures in the fresh and hardened states. PPMs may be divided in discrete and continuous; discrete models assume the existence of a given number of discrete particle sizes that are rearranged to reach the maximum packing [45,55,56] whereas continuous approaches assume a continued distribution of particles within the system [56,57]. Either discrete or continuous, PPMs aim to optimize the system PSD, resulting in an improved packing

density and reduced porosity [56–60]. Therefore, PPM-mix-proportioned mixes often present lower PC amounts when compared to conventionally designed concrete.

One of the most interesting and recognized continuous PPM is the so-called modified-Andreasen or Alfred model, which was initially created by Funk and Dinger in 1980 [61]. This model calculates the optimum PSD based on a coefficient of distribution (q) along with the largest (D_L) and smallest (D_S) particle sizes (i.e. diameter) present in the system (Equation 3.3). The coefficient of distribution (q) is adopted based on the fresh state requirements of the mix; q value ranges of 0.20-0.23 are often selected for self-consolidating mixtures, while 0.26-0.28 are normally targeted for vibrated and or pumped concrete. It is worth noting that 0.37 is the q value that yields the highest packing density and thus lowest porosity to the granular system as per [61].

$$CPFT = 100 * \left(\frac{D_P^q - D_S^q}{D_L^q - D_S^q} \right) \quad \text{Equation 3.3}$$

Where: CPFT is the cumulative (volume) percent finer than D_P , and D_P is the particle size.

PPMs have been widely used to improve fresh and hardened states performance in eco-efficient [38,62,63], conventional [57,59,64], and high-performance concrete [65,66]. Yet, very few research is performed on using PPMs to optimize recycled concrete, especially FRCA mixtures [38,67].

3.4. Scope of work

Most of the previous research on RCA has focused on using CRCA in concrete and thus a number of characterization techniques and mix-proportioning procedures are available in the literature for this type of recycled material. Yet, there is currently a lack of literature available on the performance of concrete mixtures incorporating fine recycled concrete aggregates (FRCA), especially with high amounts of replacement. This work aims to evaluate the impact of using FRCA (100% replacement) on the overall behaviour of concrete mixtures. It can be divided into two main phases: a) production and characterization of FRCA and b) appraisal of the fresh and hardened state properties of FRCA concrete mixtures.

The first phase evaluates the impact of the manufacturing process (i.e. crushing process) on the physical properties of FRCA. First, two types of 35 MPa conventional concrete (CC) mixtures are fabricated according to ACI standards with natural and manufactured sand and crushed afterwards to produce FRCA. Two distinct crushing processes were used to produce FRCA: crusher's fine (i.e. two series of crushing and sieving) and fully ground (i.e. multiple series of crushing and sieving). Then, FRCA is characterized and the residual cement paste (RCP) quantified. In the second phase, two promising mix-design procedures (i.e. EV and PPM methods) are used to mix-proportion FRCA mixtures made of natural and manufactured sand accounting for the RCP. Evaluations on numerous fresh and hardened state properties are conducted and comparisons with recycled mixtures designed through direct replacement techniques along with control conventional mixes (0% FRCA) are performed.

3.5. Experimental program

3.5.1. FRCA production process

Two-hundred conventional concrete (CC) cylinders (100 mm x 200 mm) were fabricated for each of the concrete families used in this research incorporating natural (NA) and manufactured sand (MS), according to ASTM C 39 [68]. The specimens were cast, demolded after 24h, and moist cured over 28 days. In order to appraise the influence of the crushing process on the final FRCA inner-quality, two manufacturing methods (i.e. crusher's fine - CF and fully ground - FG) were employed to produce FRCA. Figure 3.2 presents the former method, where coarse and fine RCA are produced simultaneously. The CF process has a total of two series of crushing and three stages. First, concrete specimens are crushed with a 19 mm maximum gap opening in the jaw crusher. Then, the produced material follows a second crushing stage with a 5 mm gap opening still in the jaw crusher. Finally, the material is divided into FRCA and CRCA; only the fine fraction was sieved and used in this work as per CSA A23.2-14 [69].



Figure 3.2: Summary of first method of production (CF) where both coarse and fine fractions are produced.

The second method (FG - Figure 3.3) only produces FRCA by multiples (and continuous) series of crushing (5 mm gap opening in the jaw crusher) and sieving as per CSA A23.2-14 [69]. It is worth noting that in both manufacturing methods, the particle size distribution (PSD) of the final FRCA materials ranged from 150 µm to 5 mm.

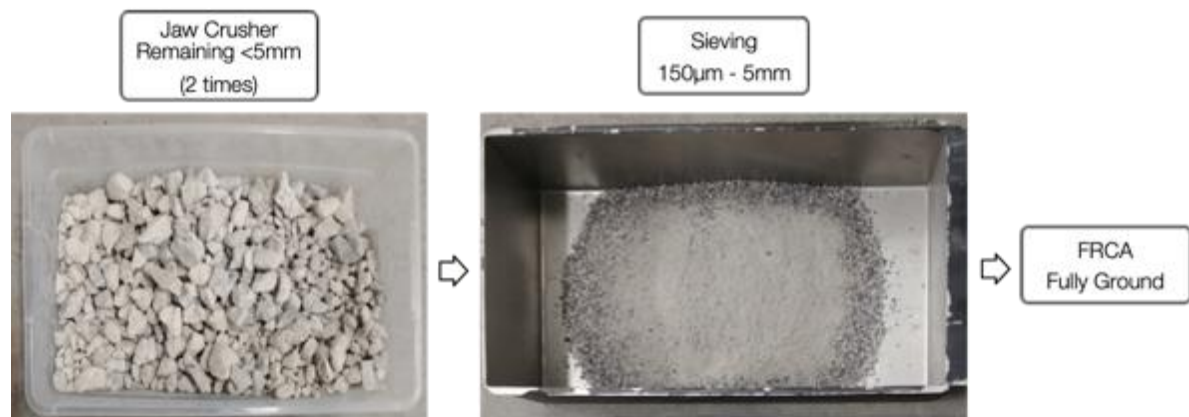


Figure 3.3: Summary of second method of production (FG) where only the fine fraction is produced.

Regardless of the crushing process, two FRCA families were produced in this work: FRCA from natural (FRCA-NS) and manufactured (FRCA-MS) sand. Both of them were produced with the two processes above presented (CF and FG).

3.5.2. Assessment of residual cement paste (RCP)

The residual cement paste (RCP) was measured in this work on all FRCA materials through the soluble silica sub-procedure according to ASTM C1084-15 [70] and C114-18 [71]. This choice was

made due to the fact of using limestone aggregates in this research, which prevented the use of other chemical procedures such as maleic acid digestion. Samples of 2.5 g of all FRCA materials manufactured in 3.5.1 were used for the RCP analysis.

The test protocol consisted of a selective extraction of silica from PC by cold diluted hydrochloric acid with subsequent analysis of soluble silica by conversion to silicon tetrafluoride with hydrofluoric acid. The procedure is based on the assumption that only silica from PC is soluble in cold diluted hydrochloric acid whereas silica from aggregates is not soluble. The unhydrated PC percentage was then calculated by dividing the percentage of silica obtained in the FRCA by the percentage of silica in the PC (Equation 3.4) and multiplied by 100. Since the silica value within the RCP is unknown, it was assumed to be 21% (within a typical range of approximately 18%-21%) (Equation 3.5) as per ASTM C1084-15 [70].

$$C_{SiO_2, wt. (\%)} = \frac{100 \times m_{SiO_2}}{m_{FRCA}} \quad \text{Equation 3.4}$$

$$C_{cement, wt. (\%)} = \frac{10000 \times m_{SiO_2}}{21 \times m_{FRCA}} \quad \text{Equation 3.5}$$

Where: $C_{SiO_2, wt. (\%)}$ is the weight percent of silica in cement, $C_{cement, wt. (\%)}$ is the weight percent of cement in FRCA, and m_{FRCA} and m_{SiO_2} are the weight of FRCA used for the analysis and weight of silica content in the Portland cement.

3.5.3. Raw materials characterization

The specific gravity and water absorption capacity for all the FRCA samples were evaluated according to the proposed method by Rodrigues *et al.* [72] since the procedures from CSA-A23.2-2A-14 [69] were observed to not be reliable for FRCA material due to its cohesiveness and binding behaviour. First, the samples were saturated in 0.1% of sodium hexametaphosphate, which is a clay dispersant commonly used in soil analysis for clay suspensions. For a given sample, a concentration of 1 g/l of the dispersant is used in order to prevent agglomeration of the particles. Then, the procedure was performed as per CSA-A23.2-2A-14 [69], except for a few steps that

were carried out based on the works proposed by [72]. A summary of the characterization process adopted in this research is presented hereafter:

- FRCA samples were first saturated in a sodium hexametaphosphate solution for 24h, decanted afterwards, and dried down to saturated surface dry (SSD) condition. The SSD mass was then recorded as M1;
- As per CSA-A23.2-2A-14 [69], the sample was placed in a pycnometer, filled to the brim and the weight (material + pycnometer) reported; yet, instead of removing the material and storing it in a ventilated oven, it was left in the pycnometer for further 24h in order to have entrapped air bubbles removed. After that, the material was removed from the pycnometer and dried, and its mass recorded as M2;
- The sample was placed in an oven at 110 ± 5 °C for another 24h and its oven-dry (OD) weight was recorded as M4;
- Finally, the mass M3 was also recorded as being the mass of the pycnometer filled with the sodium hexametaphosphate solution.

The oven-dry (OD) density and water absorption have been thus calculated through Equation 3.6 and Equation 3.7, respectively, where the density of the sodium hexametaphosphate solution (p_w) was assumed to be equal to the water at 20 °C [73].

$$p_{OD} = \frac{M_4}{[M_1 - (M_2 - M_3)/p_w]} \quad \text{Equation 3.6}$$

$$W_{\%} = \frac{100 \times (M_1 - M_4)}{M_4} \quad \text{Equation 3.7}$$

Table 3.2 presents a summary of the FRCA characterization results along with properties of both natural and manufactured sand as per CSA A23.2-14 [69].

Table 3.2: Properties of FRCA and natural aggregates.

Physical Property	FRCA NS-CF	FRCA NS-FG	NS	FRCA MS-CF	FRCA MS-FG	MS
RCP content (wt.%)	15.5	11.5	-	16.8	11.4	-
SSD specific gravity (kg/L)	2.47	2.56	2.70	2.51	2.58	2.76
OD specific gravity (kg/L)	2.32	2.42	2.67	2.36	2.44	2.74
Water absorption (%)	7.87	6.38	0.86	7.76	6.16	0.65

Figure 3.4a shows the particle size distribution (PSD) analysis for the original natural sand, NS-CF, and NS-FG, while Figure 3.4b illustrates the results of the original manufacture sand, MS-CF, and MS-FG. The square-dotted lines represent the PSD thresholds as per CSA A23.2-14 [39].

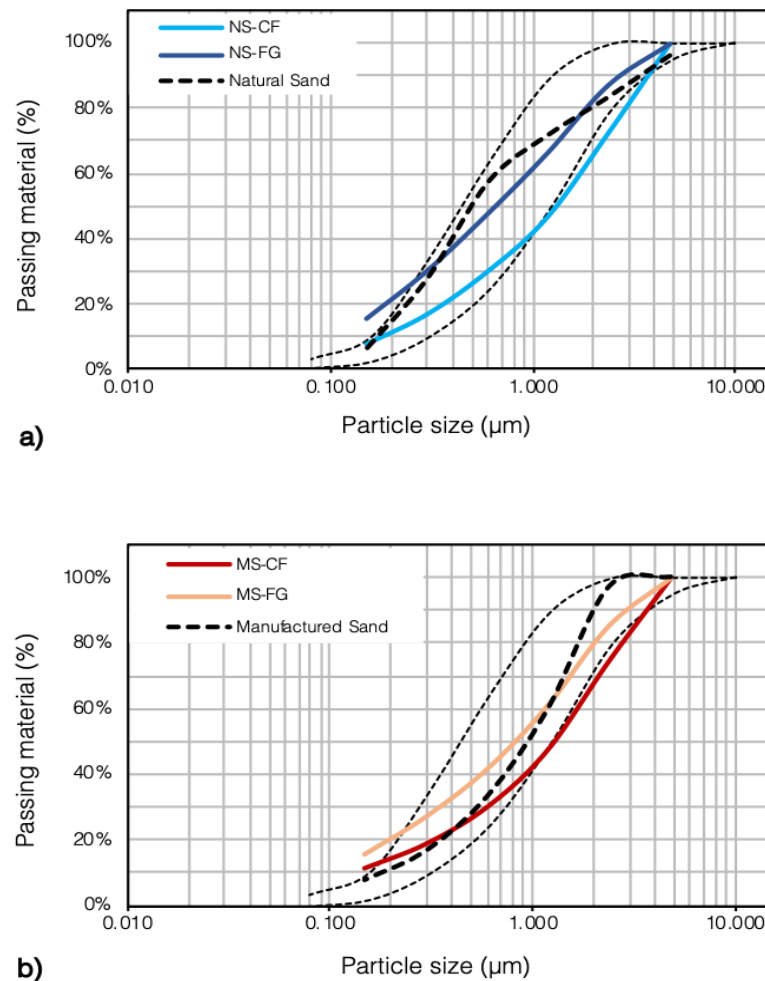


Figure 3.4: Particle size distribution curves for FRCA derived from natural (a) and manufactured sand (b) companion conventional concrete.

From Figure 3.4, it can be observed that the quality of the manufactured and natural FRCA can be significantly affected by the crushing process adopted. For instance, FRCA NS-CF (Figure 3.4a) was observed to be predominantly composed of coarser particles, yielding a fineness modulus of 3.27, whereas the fully ground type (FRCA NS-FG) showed to have a higher amount of fine particles and thus a fineness modulus of 2.53. Moreover, the FRCA NS-FG presents a PSD quite similar to the one of natural sand (i.e. fineness modulus of 2.53). The same trend was also observed for the FRCA-MS of both crusher's fine and fully ground types (Figure 3.4b). The FRCA MS-CF presented a fineness modulus of 3.17, while the FRCA MS-FG and the original manufactured sand displayed 2.70 and 2.85, respectively.

A general use (GU) Portland cement (PC) was used in all mixes along with a limestone coarse aggregate with a nominal maximum size of 19 mm. A limestone filler with particle size distribution smaller than PC (Figure 3.5), known as performance filler, was employed in the mixtures proportioned through PPM methods. For both PC and filler, the specific gravity and surface area (SSA) analyses were performed through the use of a gas pycnometry test and BET, respectively, and the results are summarized below (Table 3.3).

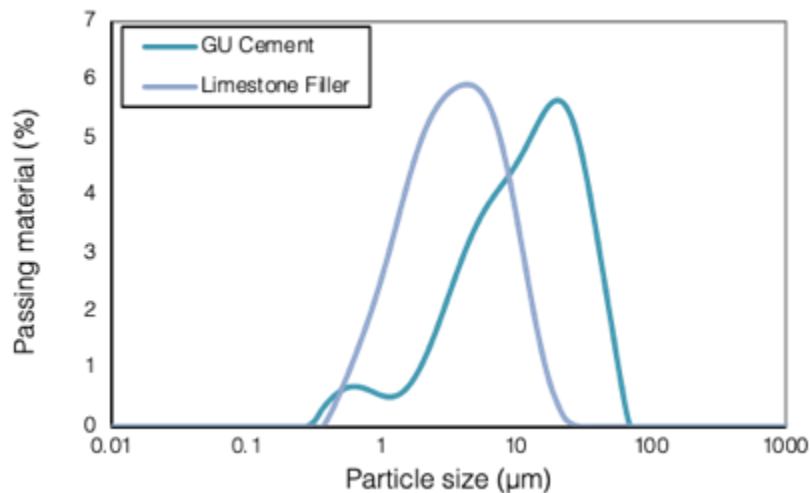


Figure 3.5: PSD of PC and limestone filler used in the PPM FRCA mixtures.

Table 3.3: Physical properties characterization.

Material	Mass (g)	Volume (cm ³)	Specific gravity (g/cm ³)	SSA (m ² /g)
GU cement	31.9	10.49	3.03	1.00
Filler	19.5	7.56	2.60	3.70

A combination of polycarboxylate-based high range and mid-range water reducers was selected to be used in all mixtures to increase concrete flowability. It is worth noting that different amounts of admixtures were used for distinct mixtures in order to achieve a consistency (i.e. slump value) of 100 ± 20 mm.

3.5.4. Mix-design approaches

A total of three distinct concrete mixtures (i.e. DRM, EV method, and PPM) containing 100% replacement of natural fine aggregates by FRCA were designed. Moreover, two control mixes (i.e. ACI method - 0% FRCA) containing natural (NS) and manufactured (MS) sand were also mix-proportioned for comparison purposes.

Concrete mixtures proportioned with the use of the DRM method were mix-designed according to the ACI standard (i.e. absolute volume method), purposely treating FRCA as presenting the same properties of natural fine aggregates; the latter is a common practice adopted in the construction industry as previously discussed in 3.3.2.1.

The Equivalent Volume (EV) method, was initially developed to mix-proportion recycled concrete mixtures made of CRCA as per [10]. This technique accounts for the residual mortar (RM) content adhered to the CRCA and has shown to be promising as presented in 3.3.2.4. In this work, the initial EV method was adapted to mix-design recycled mixtures made with 100% FRCA and accounting for the RCP content attached to the fine particles. Yet, the main concept of the technique was kept the same as follows: the FRCA mix is based on a companion conventional concrete (CC) mixture, having the same amount (in volume) of cement paste (CP) and aggregates. In other words, the total amount of cement paste in the EV mix is considered as the summation of the RCP plus the fresh paste added to the mix, while the total volume of aggregates is the volume of original virgin aggregates (OVA) plus the volume of natural aggregates (NA). To better

visualize the aforementioned description, Figure 3.6 illustrates a comparison between the EV mix-designed concrete and a companion CC mix.

In addition to the above methods, a novel approach using a combination of EV and a continuous PPM technique (i.e. Alfred's model) is also developed in this research. Limestone fillers, presenting a particle size distribution (PSD) smaller than PC (Table 3.3), were used in the PPM mix-designed mixtures to lessen the overall porosity and binder content (e.g. Portland cement - PC) of the system. The q-factor selected in this work was 0.28, to ensure a suitable fresh state behaviour (i.e. targeting a vibrated and/or pumped concrete) with minimum requirement of chemical admixtures.

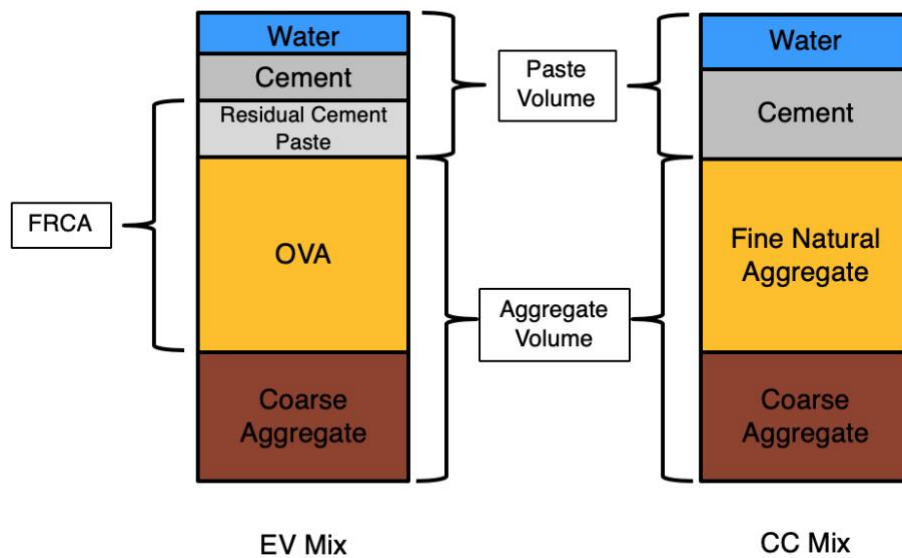


Figure 3.6: EV method proportions of FRCA concrete based on a CC mix-design.

3.5.5. Mix proportions

FRCA fabrication

The FRCA used in this work was derived from a crushed companion CC, which was mix-proportioned through the ACI method (i.e. absolute volume method) and manufactured under laboratory conditions. Two families of FRCA were produced, one containing natural sand (ACI-NS) and the other incorporating limestone manufactured sand (ACI-MS). Both were produced

with targeted 28-day compressive strength of 35 MPa, which was selected as an average value based on the market demand. A limestone coarse aggregate, with a nominal maximum size of 19 mm was used to produce the CC mixes. It is worth noting that no chemical nor mineral admixtures were utilized in the CC mixtures so that a benchmark of the resulted FRCA properties could be determined alongside with practical thresholds.

Table 3.4 summarizes the CC mix-designs employed in this work to make FRCA. It may be noticed that the cement content, coarse aggregate, and water-to-cement ratio (w/c) of both CC mixtures are kept constant equal to 370 kg/m³, 1032 kg/m³, and 0.47, respectively; whereas the fine aggregate contents changed due to the differences in specific gravity of NS and MS.

Table 3.4: Companion conventional concrete mix-design proportions.

ACI - NS	Type	Mass (kg/m³)
Cement	GU	370
Fine aggregate	Natural sand	898
Coarse aggregate	Limestone	1032
Water	-	174
ACI - MS		Mass (kg/m³)
Cement	GU	370
Fine aggregate (MS)	Manufactured sand	934
Coarse aggregate	Limestone	1032
Water	-	174

Concrete mixtures

DRM, EV, and PPM mix-designed recycled mixtures were proportioned with 100% FRCA replacement from the four FRCA sources previously mentioned. The target 28-day compressive strength was selected as 35 MPa. A water-to-cement (w/c) ratio of 0.35 was adopted for all recycled mixes and their consistency (i.e. slump values) was aimed to lie within 100 ± 20 mm. Likewise, control conventional mixes (ACI-NS and ACI-MS) were proportioned for the same target strength and consistency. An air entraining agent (AEA) was used in all mixtures (i.e. control and recycled) so that they incorporate an air content of 7-8% as per CSA A23.1-14 [68], as required for structural concrete exposed to freeze-thaw cycles. A summary of all mixes is presented in Table 3.5.

The mixes proportioned through the DRM method (i.e. absolute volume method) treated the FRCA material as being the same as natural fine aggregates, resulting in mixtures with high amounts of PC (e.g. nearly 500 kg/m³). Otherwise, since the EV and PPM methods account for the RCP attached to the FRCA particles, the mixtures proportioned by these procedures presented much lower PC content. In the case of EV method, it was possible to obtain mixtures with PC contents ($\approx$ 374 kg/m³) very similar to those of ACI method (i.e. 370 kg/m³). Likewise, mixtures designed through continuous PPM techniques (q-factor of 0.28) and with the use of inert fillers yielded final PC contents ranging from 333 to 299 kg/m³ (using a minimum of chemical admixtures).

Considering that the fourteen concrete mixtures were designed to a targeted slump range (100 $\pm$ 20 mm), previous experimental work was conducted to evaluate the optimum amount of the mid-range to high-range water reducer combination to improve performance while avoiding segregation [55]. The admixtures were selected as a percentage of the cement mass for EV-mix-designed mixtures; whereas for the PPM-mix-proportioned mixes, they were adopted based on a percentage mass of fines (i.e. particles < 100 μ m – PC and filler). All mixtures were named according to their mix-design technique, original natural aggregate source, and crushing process. For instance, a concrete mix-proportioned through PPM with FRCA fully ground from a CC made of NS is named PPM-NS-FG.

Table 3.5: FRCA and control concrete mix-design proportions.

Mixture	Cement (kg/m ³)	FRCA (kg/m ³)	Natural FA (kg/m ³)	Natural CA (kg/m ³)	Filler (kg/m ³)	Water (kg/m ³)	AEA (kg/m ³)	Mid-range + HRWR (kg/m ³)
ACI-NS	370	-	685	1032	-	174	2.5	-
ACI-MS	370	-	704	1032	-	174	2.5	-
DRM-NS CF	497	524		1032	-	174	2.4	-
DRM-NS FG	497	546		1032	-	174	2.4	-
DRM-MS CF	497	533		1032	-	174	2.4	-
DRM-MS FG	497	551		1032	-	174	2.4	-
EV-NS CF	373	714	-	1005	-	131	1.9	1.2
EV-NS FG	373	740	-	1014	-	131	1.9	1.2
EV-MS CF	372	732	-	1004	-	130	1.8	1.2
EV-MS FG	373	752	-	1006	-	131	1.8	1.2
PPM-NS CF	308	879	-	806	108	108	1.5	1.0
PPM-NS FG	333	907	-	797	83	117	1.7	1.0
PPM-MS CF	299	898	-	809	118	105	1.5	1.2
PPM-MS FG	332	915	-	798	84	116	1.7	1.2

3.5.6. Specimens preparation and testing procedures

Forty litres of concrete were manufactured for each of the mixtures analyzed in this work in order to appraise their fresh state behaviour. Furthermore, 100x200 mm concrete cylinders from all the fourteen mixes were fabricated according to CSA A23.2-3C [69], demolded after 24h, and moist cured over 28 days prior to testing.

3.5.7. Fresh state assessment

The fresh state behaviour of the fourteen mixes was investigated by slump measurements and rheological characterization through the use of a planetary rheometer (i.e. IBB rheometer). The rheological profile was determined with a two-step process: increase in shear-rate up to approximately 43 rpm, followed by a decrease period at the same stepwise, keeping a constant rotation for roughly 10 seconds as illustrated in Figure 3.7. Furthermore, the impeller rotates for about 180 seconds throughout the test analysis (i.e. increasing and decreasing phases), in which the rotation speed reaches the peak level after 100 seconds approximately from the beginning of the test.

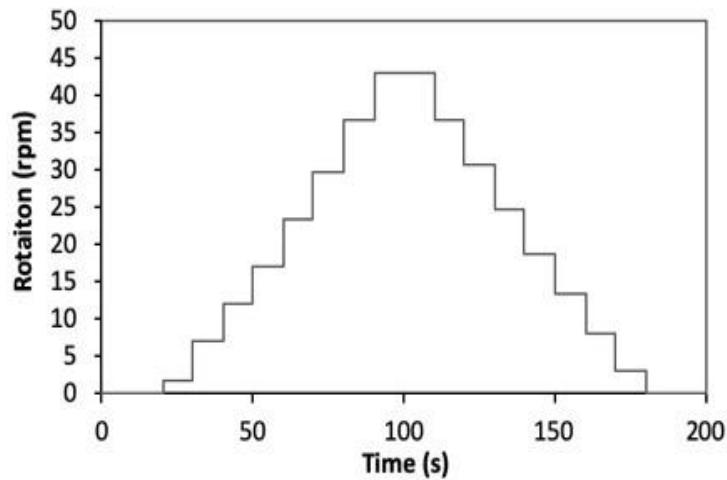


Figure 3.7: Test programme used for analyzing rheology cycle.

3.5.8. Hardened state assessment

The evaluation of hardened state properties was performed through compressive strength and static modulus of elasticity tests. To evaluate the compressive strength, three samples of each mixture were tested over time (i.e. 7, 14 and 28 days) according to CSA-A23.2-9C [69]. Furthermore, the static modulus of elasticity was also conducted on three samples from each mix at 28 days as per ASTM C469-17 [74].

3.6. Experimental Results

3.6.1. Rheology of fresh state mixtures

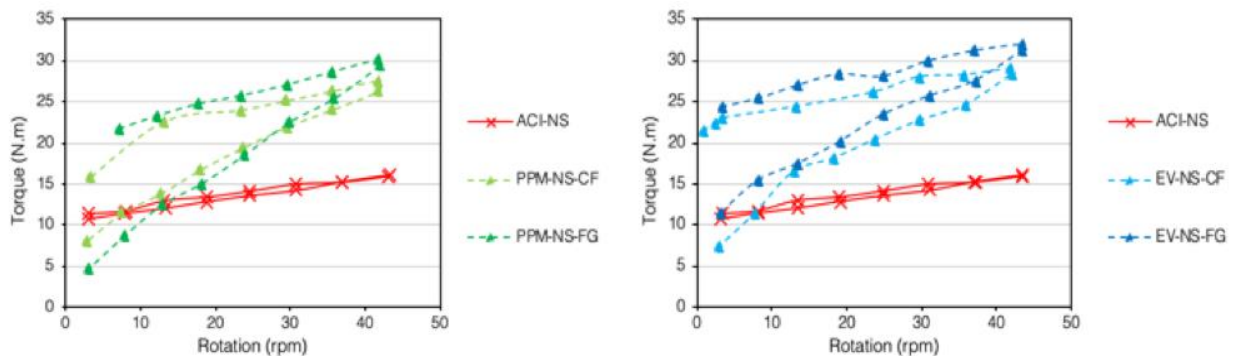
A summary of the rheological profiles for ACI, EV and PPM fresh state mixtures is presented in Figure 3.8. Analyzing the plots below, one may notice that all mixtures present a shear thinning behaviour; i.e. the viscosity decreases as a function of the torque applied regardless of the mix-design procedure adopted. Table 3.6 displays three key rheological parameters (i.e. minimum experimental torque, apparent viscosity and hysteresis area) along with the slump results of ten mixtures (eight FRCA concrete mixtures + two CC). It is worth noting that due to torque

limitations of the IBB rheometer used for the analysis, the DRM mixtures could not be investigated in this section since they presented a high cohesive and low flowable character.

Table 3.6 data clearly shows that a correlation may be established between the slump measurements and the minimum initial torque required for the mixtures; the higher the slump, the lower the minimum torque to enable flow, as expected. All recycled mixtures presented a lower minimum torque (and higher slump value) when compared to CC mixes made of both natural and manufactured sand. EV mixtures presented a minimum initial torque ranging from 7.32 N.m to 11.33 N.m with slump values from 105 mm to 120 mm; whereas PPM mixtures yielded initial torques ranging from 4.74 N.m to 8.17 N.m with slump measurements from 125 mm to 165 mm. The above means that PPM mix-designed mixtures were the ones to present the lowest yield stress values, followed by EV and ACI mix-designed mixtures.

Regarding the apparent viscosity results (i.e. defined as the shear stress to shear rate ratio at the first deceleration point), it is observed that all EV-MS and PPM-MS mixes presented lower values than the ones from NS concrete. Therefore, mixtures proportioned with the manufactured sand yielded lower viscosity values at the peak than the mixes with natural sand.

a)



b)

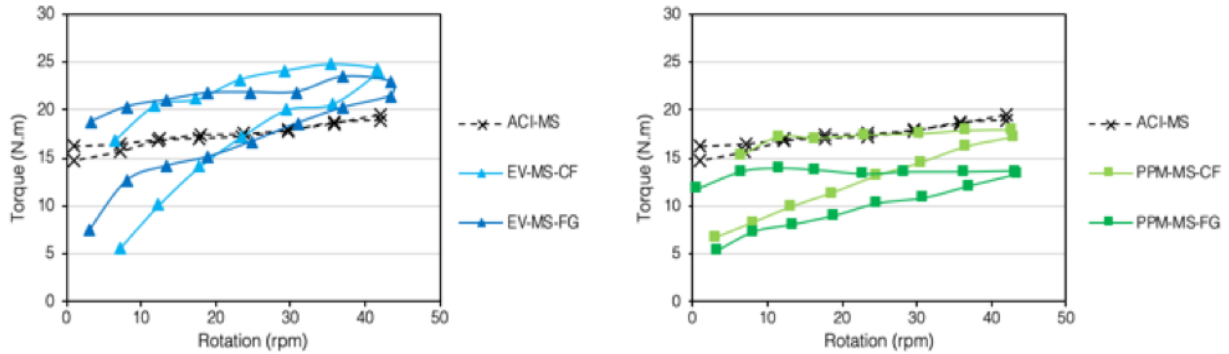


Figure 3.8: Rheological profiles of the mixtures from NS (a) and MS (b) concrete sources.

The time dependency (thixotropic vs rheopexy behaviour) of all mixtures was also evaluated. Thixotropic fluids yield a shear thinning time-dependent behaviour where viscosity decreases over time under constant shear stress or shear rate. Conversely, rheopexy behaviour occurs when viscosity increases over time under a constant torque applied to the system [75,76]. From Table 3.6, it can be initially observed that all mixtures presented positive values of hysteresis area (HA), displaying thus a thixotropic behaviour. ACI mixes presented the lowest HA values, followed by EV and PPM. Furthermore, FG mixes showed higher HA values than CF mixtures, except for the EV-NS-FG mix.

Table 3.6: Concrete mixtures rheological properties.

Mixture	ACI-NS	EV-NS-CF	EV-NS-FG	PPM-NS-CF	PPM-NS-FG
Minimum torque (N.m)	10.70	7.33	11.33	8.17	4.74
Apparent viscosity (N.m/rpm)	0.37	0.69	0.74	0.66	0.72
Hysteresis area (N.m.rpm)	35.43	323.12	298.67	217.75	221.87
Slump (mm)	110	115	120	130	165
Mixture	ACI-MS	EV-MS-CF	EV-MS-FG	PPM-MS-CF	PPM-MS-FG
Minimum torque (N.m)	14.81	10.12	7.48	6.75	5.45
Apparent viscosity (N.m/rpm)	0.46	0.58	0.63	0.42	0.32
Hysteresis area (N.m.rpm)	21.82	225.44	245.49	134.49	191.40
Slump (mm)	95	105	115	125	130

3.6.2. Compressive strength and modulus of elasticity

Figure 3.9 displays the 28-day compressive strength of the fourteen mixtures studied as a function of time. First of all, it can be observed that PPM mixtures presented superior performance, with 28-day compressive strength results varying from 41 MPa (PPM-NS-CF) to 65 MPa (PPM-MS-FG), when compared to CC mixes made of both natural and manufactured sand. On the other hand, the lowest results are seen for DRM mixes varying from 19 MPa (DRM-NS-CF) to 21 MPa (DRM-MS-FG). It is important to note that all mixes were designed for a target strength similar to the CC control mixes made of both natural and manufactured sand (i.e. ACI-NS and ACI-MS), which yielded compressive strength results within the range of 35 - 40 MPa. Regarding the mixes designed with the EV method, the compressive strength ranged from 26 MPa to 31 MPa for EV-NS-CF and EV-MS-FG, respectively.

The results above clearly demonstrate the efficiency of using PPM techniques in mix-designing FRCA concrete, since in this case, it represents an overall gain on average of approximately 24 MPa and 33 MPa in comparison to EV and DRM mixes, respectively. It is worth noting that a higher compressive strength gain was found on the FG mixtures, representing 33 MPa (EV) and 43 MPa (DRM), respectively.

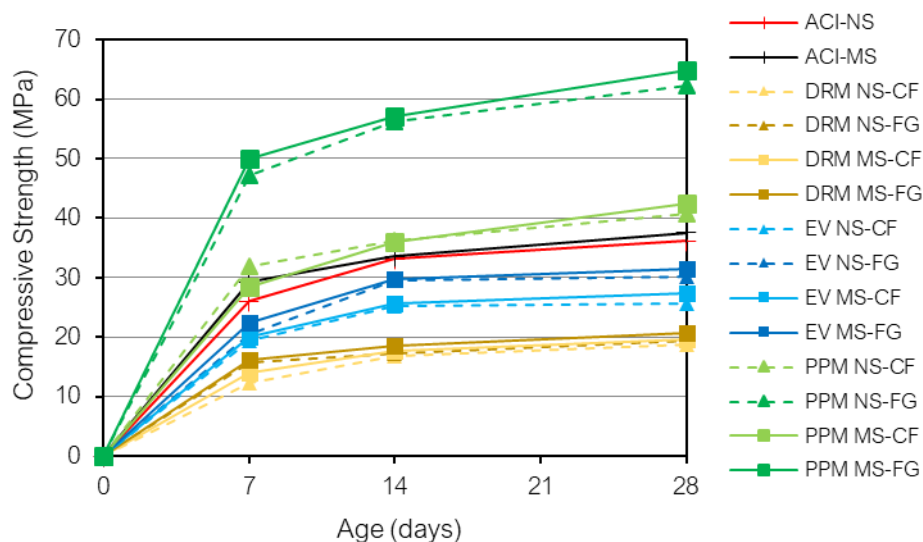


Figure 3.9: Compressive strength over time for all mixtures.

Figure 3.10 illustrates the stiffness (i.e. modulus of elasticity) results for the mixtures proportioned with FRCA-CF along with CC mix from NS source. The stiffness analysis of all mixes was performed through five cycles of loading-unloading up until 40% of the 28-day compressive strength of each mix, at a constant loading rate of 0.10 MPa/s. The modulus of elasticity (ME) was then calculated as being the average secant modulus of the cycles two and three; cycle one was discarded in this process. The ME results obtained were 21 GPa, 26 GPa, and 29 GPa for mixtures designed through EV, DRM and PPM respectively, whereas the CC mix reached approximately 41 GPa. A similar trend was also observed for all the mixtures from MS source.

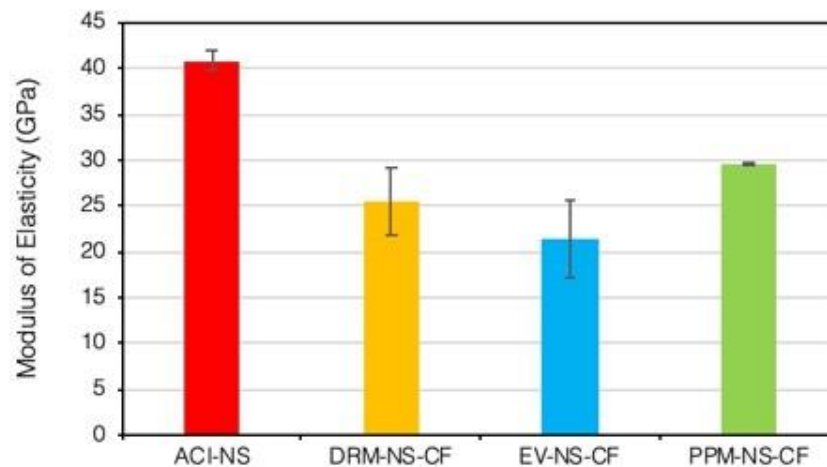


Figure 3.10: Modulus of elasticity (ME) for all the mixtures having FRCA crusher's fine (CF).

3.7. Analysis and Discussion

3.7.1. Influence of jaw crusher's gap opening size on the PSD of FRCA

In addition to the results of particle size distribution analysis presented in section 3.5.3 for a given FRCA production process, the influence of the gap opening size on the FRCA PSD was also appraised. Four representative samples of coarse RCA (500 g) with a maximum particle size of 10 mm were crushed into FRCA with gap openings of 2.0 mm, 1.0 mm, 0.5 mm, and 0 mm. Then, the particle size distribution was appraised against the amount of powder material retained

(<150 μm). Figure 3.11 displays the PSD curves for the four samples produced with distinct gap openings along with the limits of CSA A23.2-14 (dashed lines).

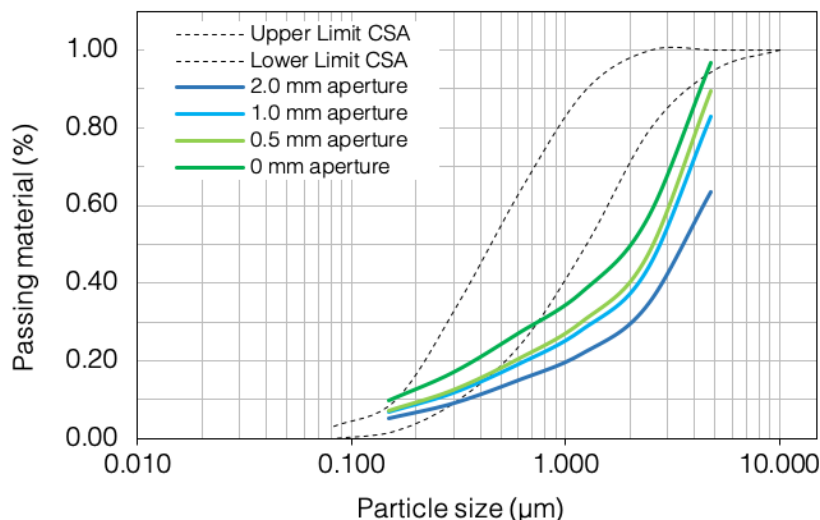


Figure 3.11: Particle size distribution curves for different aperture sizes in the jaw crusher.

From Figure 3.11, one may notice that the gap opening size does not affect significantly the PSD shape of the produced FRCA. However, the opening size has a major influence on the amount of powder material produced (i.e. particles smaller than 150 μm that are often discarded due to lack of inner quality). It has been observed that the lower the gap opening, the higher the fine materials, which also correlates with the fineness modulus obtained. The amount of fine materials retained ranged from 26 g to 48 g for gap opening sizes of 2.0 mm and 0.0 mm, respectively. A summary of the analyses is displayed in Table 3.7.

Table 3.7: Influence of gap aperture size on the PSD of crushed FRCA (500 g samples).

Opening size	Fineness modulus	Material retained (<150 μm)
2.0 mm	4.52	26.50 g
1.0 mm	4.09	34.17 g
0.5 mm	3.94	36.00 g
0.0 mm	3.57	48.33 g

The above results clearly indicate that an appropriate and optimized process is needed to produce FRCA in order to minimize waste generation (i.e. particles lower than 150 μm) along with energy consumption in the manufacturing process.

3.7.2. Evaluation mix-design methods to proportion FRCA mixtures

A summary of the volumetric components of each material used in the FRCA and CC mixes is illustrated in Figure 3.12. Analyzing the results, one observes that normally a decrease in the amount of water and binder (i.e. PC content) takes place for FRCA mixtures, except for DRM-designed mixes which treated FRCA as being the same as natural fine aggregates. The overall amount of binder (i.e. PC content) in both CC mixes made of NS and MS sand represent 11.8% of their total volume; whereas for DRM, EV and PPM-proportioned mixes, the values obtained were 15.9%, 11.9%, and 10.5% (on average), respectively. The latter seems to demonstrate the inefficiency of DRM techniques to proportion eco-efficiency FRCA concrete. Moreover, it is clear the efficiency of PPM methods to design low cement content recycled mixtures, especially with the use of inert fillers.

The type of FRCA material (i.e. CF or FG, which is based on the crushing method adopted) also demonstrates to play a role on the binder demand of the mixtures, except for DRM mixes. Evaluating PPM mixes, one observes that the use of FRCA-CF yields a slight decrease in cement content (i.e. about 10%) when compared to the mixtures incorporating FRCA-FG (i.e. 11%). In fact, such a difference in PC content is linked to the amount of inert fillers (i.e. PSD smaller than cement) used in the system, which is related to the amount of RCP content attached to the FRCA particles. The latter is deemed to be lower in FRCA FG since it is produced through multiple series of crushing. Otherwise, EV mixes did not yield a significant difference in PC content according to the type of FRCA used.

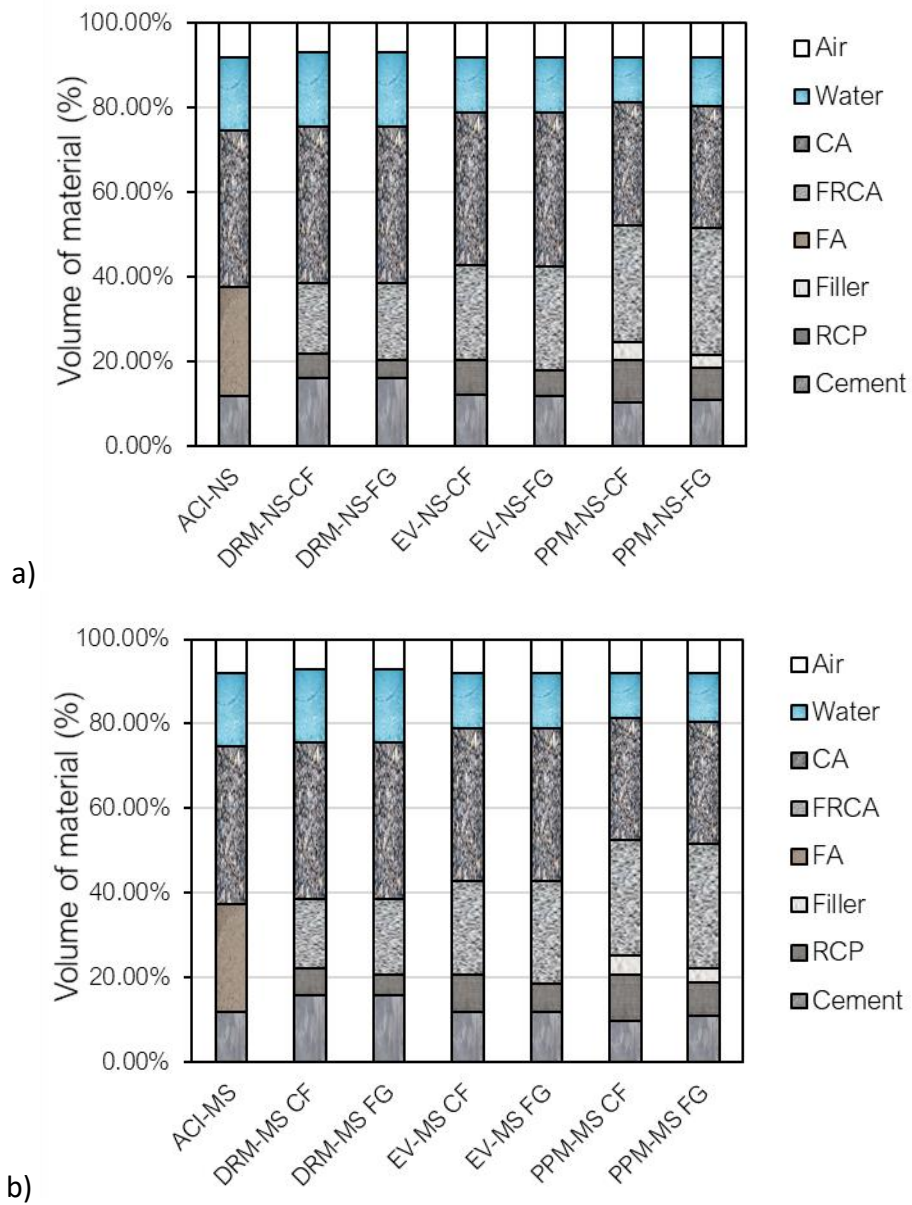


Figure 3.12: Volumetric components of each material for mixtures with FRCA from NS source (a) and MS source (b).

3.7.3. Fresh state behaviour

The rheological behaviour of conventional concrete mixtures is often described according to Bingham's model [76,77], represented by a linear relationship between the shear stress and shear rate. Equation 3.8 express the aforementioned relationship where: τ is the torque, τ_0 is the yield torque, k_B is the viscosity constant of Bingham and γ is the rotation.

$$\tau = \tau_0 + k_B \gamma \quad \text{Equation 3.8}$$

Although the above rheological behaviour has been successfully applied to describe the behaviour of high flowable conventional mixtures, the FRCA concrete mixes evaluated in this research were found to follow a distinct nonlinear trend (i.e. shear thinning behaviour) where the viscosity lessens with the increase of shear rate.

Recent research [57,78] evaluating the rheological profile of concrete with reduced PC content (such as the EV and PPM-mix designed FRCA mixtures) verified that such eco-efficient mixtures might be precisely described in the fresh state through the Herschel-Bulkley model. Equation 3.9 establishes this model, where k_{HB} is the viscosity constant of Herschel-Bulkley and n is flow behaviour factor, which is $n < 1$ for suspensions presenting shear thinning behaviour and $n > 1$ for shear thickening ones [77].

$$\tau = \tau_0 + k_{HB} \gamma^n \quad \text{Equation 3.9}$$

Figure 3.13 illustrates the rheological behaviour profiles measured from all (a) EV and (b) PPM mixes in comparison to CC mixes and Herschel-Bulkley's model. Table 3.8 displays the Herschel-Bulkley's variables obtained for each of the mixtures studied. Evaluating the results, one verifies that both EV and PPM mixes present lower flow behaviour factors (i.e. $n < 1$), while some CC mixes (ACI-NS) present values near and or higher than 1. This correlation with the flow behaviour factor validates the shear thinning behaviour of the FRCA mixes, since they require less torque applied in the system at a higher shear stress regime. The overall experimental initial torque required by each mix-design represents 12.8 N.m, 9.1 N.m and 6.3 N.m on average for CC, EV and PPM mixes, respectively. Furthermore, the k_{HB} constant is also observed to yield the lowest overall values for PPM and CC mixes in comparison to EV. It is worth noting that the higher k_{HB} values, the higher the slope of the rheological profile curve (i.e. higher viscosity). The latter validates the PPM-designs mixes to be mixtures with the most suitable rheological behaviour for vibrated and or pumped concrete. It is worth noting that some results presented in Table 3.8 are also subject to

some test inconsistencies which may explain some unexpected results (e.g. no trend can be explained between the PPM mixes when looking at the k_{HB} factor).

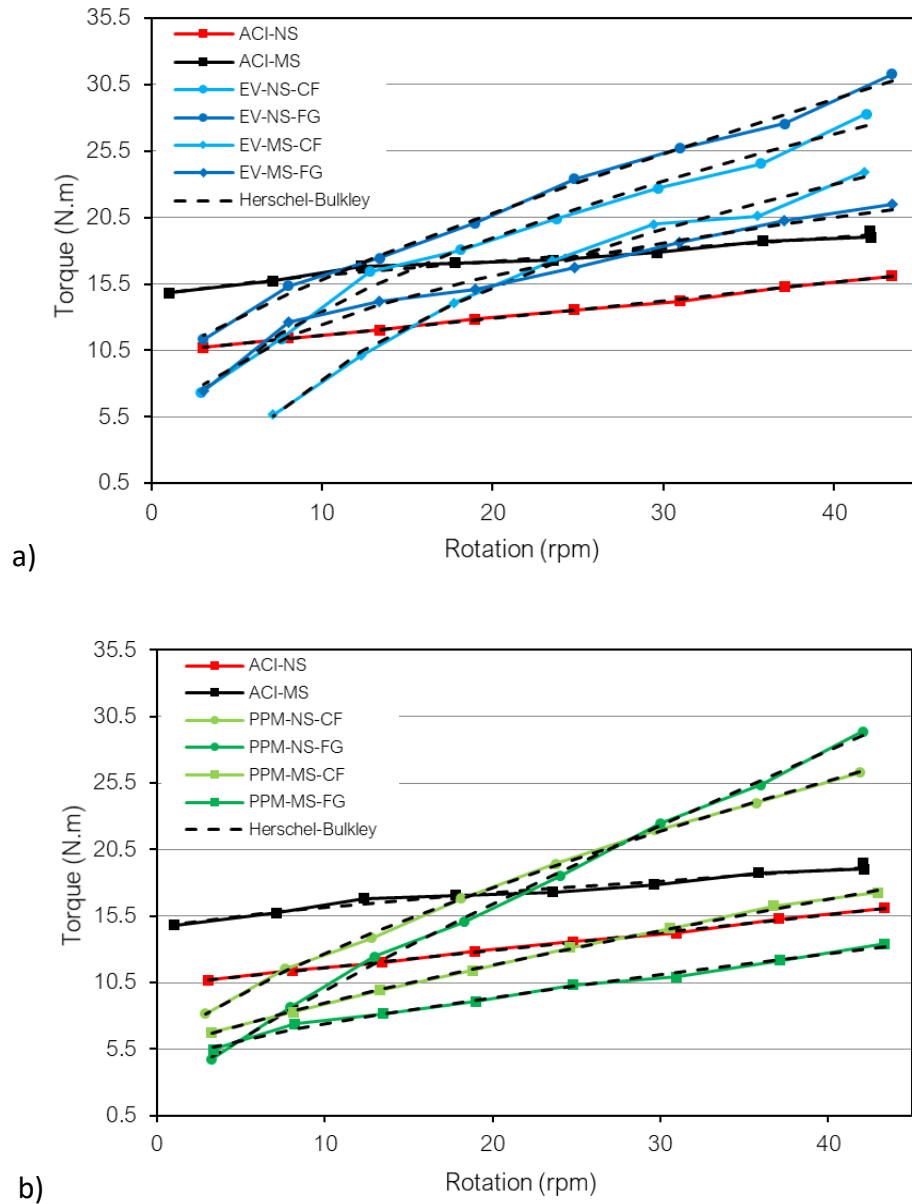


Figure 3.13: Rheological profiles of a)EV and b)PPM mixes compared to Herschel-Bukley's model.

Table 3.8: Parameters of Herschel-Bulkley' equation and experimental initial torque required for the all mixes investigated.

Mixture	Experimental Initial Torque (N.m)	τ_0	K_{HB}	n
ACI-NS	10.7	10.4	0.11	1.05
ACI-MS	14.8	14.5	0.33	0.73
EV-NS-CF	7.3	0.3	4.20	0.50
EV-NS-FG	11.3	8.8	1.18	0.78
EV-MS-CF	10.1	0.2	1.71	0.71
EV-MS-FG	7.5	2.6	7.45	0.31
PPM-NS-CF	8.2	4.9	1.54	0.71
PPM-NS-FG	4.7	1.8	1.17	0.84
PPM-MS-CF	6.7	5.1	0.63	0.79
PPM-MS-FG	5.5	4.2	0.63	0.70

3.7.4. Hardened state behaviour

The type of FRCA (i.e. CF vs FG) was observed to have low impact on the compressive strength of DRM and EV mixes, and a more significant one on the PPM-mix proportioned mixtures. In general, the mixtures proportioned with FRCA-FG aggregates yielded better strength results for the same w/c ratio. The latter is likely due to the fact that FRCA-FG is comprised of less RCP adhered to the surface of the particles besides being more angular in shape and rougher in texture. An increase of nearly 53% in compressive strength was obtained for PPM-designed mixes, whereas a slight increase of about 16% and 4% was observed for EV and DRM mixes, respectively. The latter indicates that the quality and angularity of the FRCA particles are more important in mixtures with better PSD and thus lower amount of porosity.

Another important discussion to be made is on the interesting stiffness results obtained in this research. Surprisingly, the stiffness values did not follow a conventional and expected trend (i.e. the higher the strength, the higher the stiffness, see section 3.6.2). For instance, although EV mixtures yielded higher compressive strength results than DRM mixes due to the consideration of RCP content in the system (Figure 3.9), the modulus of elasticity (ME) obtained was much lower. These findings may be justified by the fact that EV mixes have a much higher FRCA content (735 kg/m^3) when compared to DRM (539 kg/m^3); thus more interfacial transition zones (ITZ) are found in the system, which may govern (and lessen) the overall stiffness of the material. To

further understand the values obtained, the stress-strain relationship of DRM and EV FRCA mixtures was also plotted as shown in Figure 3.14. Analyzing the plot, one verifies that not only the ME is different between DRM and EV mixtures but also the hysteresis area (i.e. area under the stress-strain curve) and plastic deformation are quite distinct. The EV mix demonstrated much higher energy dissipation and plastic deformation over the five cycles of the test. The latter is deemed to be related to the amount of FRCA (and thus ITZ) in the system, which brings more defects/flaws to the material's microstructure and thus increase its energy dissipation and plastic deformation over controlled cyclic loads. It is worth mentioning that PPM-mix-designed recycled mixtures presented a stress-strain relationship similar to DRM; yet a much steeper slope (i.e. higher ME) was found for those mixtures.

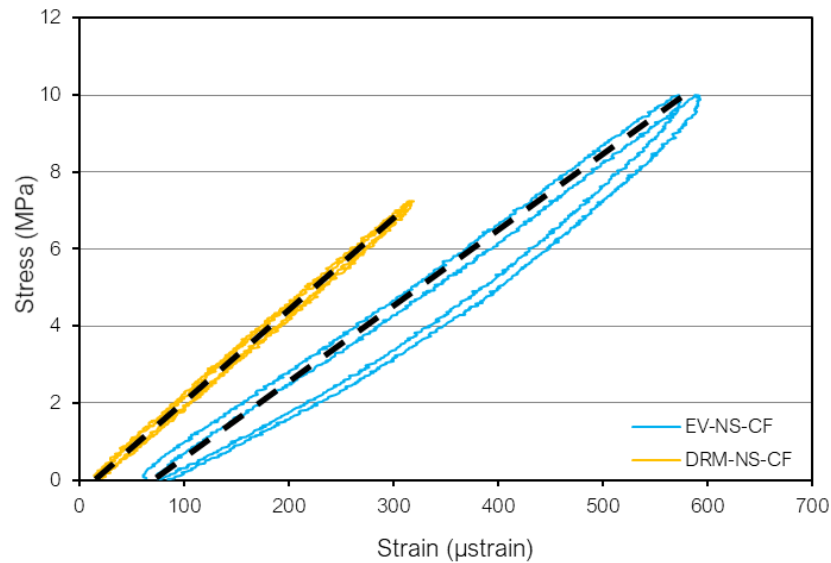


Figure 3.14: Stress-strain analysis for DRM-NS-CF and EV-NS-CF mixtures.

Figure 3.15 analyzes the variation of PPM mixtures ME as a function of the type of recycled aggregate (CF vs FG). Assessing the data, one observes that the PPM-FG mix presents a much higher ME ($\approx 30\%$) when compared to FRCA mixes with CF aggregates (38 and 29 GPa, respectively). This confirms both the influence of the crushing process (i.e. FG displays less RCP and thus ITZ within the particles when compared to CF) and mix-proportioning technique (PPM mixes showed improved behaviour when compared to DRM and EV mixtures) on the stiffness of FRCA concrete. Even though PPMs are deemed to optimize the particle size distribution of the

granular system and thus significantly decrease its porosity, which may raise the overall stiffness of the material, further studies are still needed in order to better understand such findings.

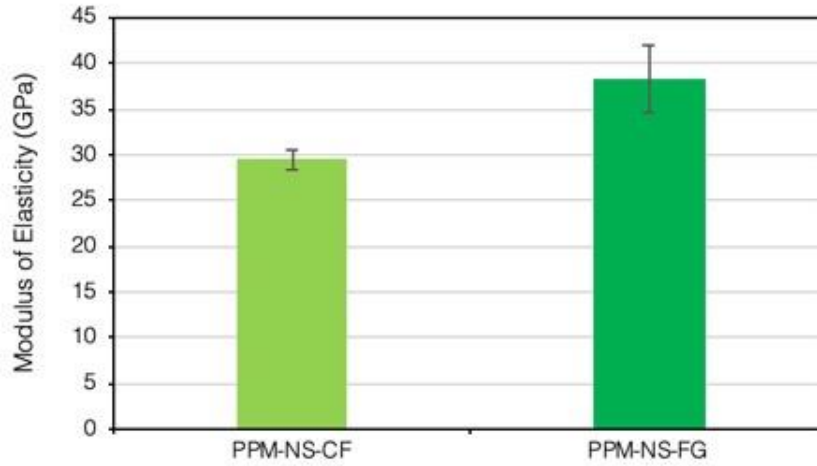


Figure 3.15: Difference in ME regarding the type of FRCA used (CF and FG).

3.7.5. Binder efficiency

Portland Cement (PC) is one of the main contributors to carbon emissions in the construction industry worldwide. In order to appraise the eco-efficiency of concrete mixtures, Damineli *et al.* [80] developed an index, the so-called binder intensity (bi), which accounts for the amount of binder (kg/m^3) required to obtain one unit of a given mechanical property, for example, 1 MPa of compressive strength at 28-days (Equation 3.10).

$$bi = \frac{BC}{f'_c} \quad \text{Equation 3.10}$$

Figure 3.16 displays the amount of PC used to obtain the highest compressive strength results gathered for each of the three mix-design methods utilized in this work. Evaluating the findings, one notices that an increase in binder content does not necessarily reflect on an increase in mechanical properties. Among all FRCA mixes, PPM-MS-FG yielded the highest 28-day compressive strength (i.e. nearly 65 MPa) while presenting a moderate to low binder content (332 kg/m^3). Considering the mixes designed with the EV method, the mixture EV-MS-FG showed the highest compressive strength (i.e. about 31 MPa) and a binder content of 373 kg/m^3 , which

is slightly higher than the ones used for PPM-designed mixes. Lastly, amongst DRM mixes, DRM-MS-FG yielded the highest compressive strength of roughly 21 MPa with a very high binder content of nearly 500 kg/m³. The latter confirms that it is possible to produce eco-friendly FRCA concrete mixtures with interesting mechanical properties, especially using PPM techniques. Moreover, it is clear that the overall performance of recycled mixtures is not directly linked to the amount of PC used but rather to the quality of ingredients and efficiency of the mix-proportioning method.

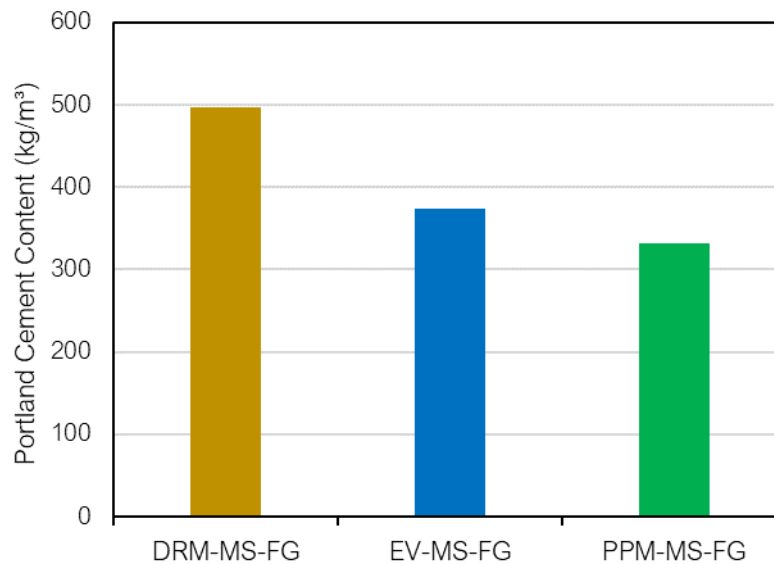


Figure 3.16: Portland cement (PC) content levels for the mixtures in analysis.

In order to evaluate the binder efficiency of all CC and FRCA mixtures studied in this experimental program, the *bi* factor was calculated for all of them and the results are illustrated in Figure 3.17. It can be observed from the plot that PPM-mix-designed mixtures were the most eco-efficient FRCA mixtures designed in this research since they yielded the values closest to the bottom line of the plot (i.e. PC content = 250 kg/m³). The CC mixes presented an averaged *bi* factor of 10 kg.m³.MPa⁻¹ for average 28-day compressive strength of about 37 MPa while PPM mixes reached averaged *bi* values of 8.3 kg.m³.MPa⁻¹ with an approximate average 28-day compressive strength of 53 MPa. DRM and EV mixes presented averaged *bi* factors of approximately 25 and 13.1 kg.m³.MPa⁻¹ for average compressive strength of 20 and 29 MPa, respectively. The results above

demonstrate once more the promising character of PPM techniques to mix-proportion eco-efficient FRCA concrete with suitable fresh and hardened state properties.

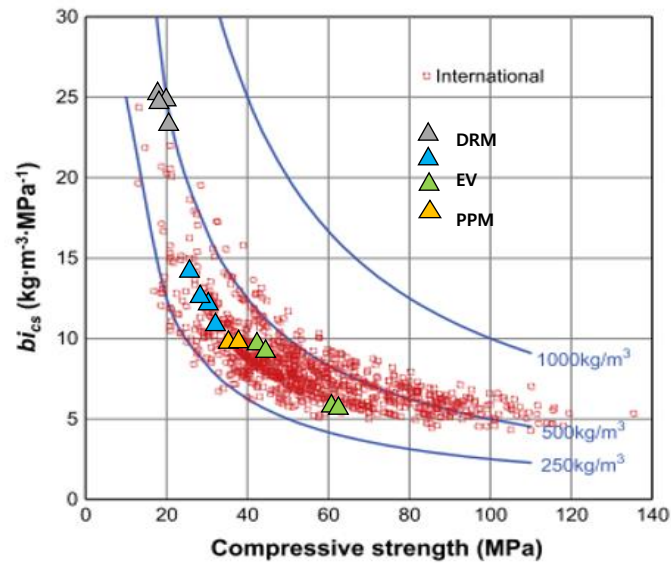


Figure 3.17: Relationship between binder intensity with compressive strength at 28 days (adapted from Damineli et al. [80]).

3.8. Conclusions

The current research aimed to understand the overall behaviour of FRCA concrete presenting different ingredients (i.e. MS vs NS), manufacturing processes (i.e. CF vs FG) and mix-design techniques (DRM, EV and PPMs). The main findings of this research are presented hereafter:

- The overall quality of FRCA material seems to be dependent on the manufacturing (i.e. crushing) method selected. Simple stage crushing produces FRCA (i.e. FRCA crusher's fine) with coarser particle size distribution, and high amounts of residual cement paste adhered. Yet, multiple crushing series were observed to produce FRCA (i.e. FRCA fully ground type) with particle size distribution similar to natural aggregate and presenting less residual cement paste attached to the particles due to further separation of mortar during crushing;

- The quantification of residual cement paste attached to FRCA particles correlates adequately with FRCA's manufacturing method. The higher the crushing stages the higher the RCP detachment from the particles which improves the overall quality of the recycled material;
- The specific gravity and water absorption are also parameters that may define the overall quality of FRCA. Such properties are directly linked to the amount of residual cement paste; the higher the RCP attached to FRCA particles, the lower the specific gravity and the higher the water absorption;
- The gap opening size does not have a significant influence on the particle size distribution of the FRCA, but rather affects the amount of powder material (i.e. $< 150 \mu\text{m}$) produced during crushing;
- The fresh state behaviour of FRCA mixtures proportioned through both EV and PPM methods demonstrated interesting performance, showing a shear thinning profile (i.e. decrease of viscosity as a function of the torque). Yet, PPM-mix-designed FRCA concrete demonstrated the best rheological variables (i.e. minimum torque required and lowest apparent viscosity) among all mixtures; the latter indicates its suitability for vibrated or pumped applications;
- Interesting hardened state properties (i.e. compressive strength and stiffness) were achieved with the use of both EV and PPM techniques. The DRM method yielded, in general, the worst mechanical performance obtained in this work. Yet, PPM-mix-designed FRCA showed to be the most promising mix-design technique to proportion FRCA concrete mixes with suitable mechanical properties and binder efficiency;
- Finally, it seems that both the aggregate's type (NS vs MS) and crushing process (CF vs FG) play an important role on the overall FRCA quality (CRP content, particle's shape, texture, etc.). Yet, the results obtained in this experimental campaign clearly demonstrated that even more important than the recycled material's features and inner quality is the mix-design procedure adopted to produce FRCA concrete.

3.9. Acknowledgments

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Chapter Four: Durability Appraisal of Fine Recycled Concrete Aggregate (FRCA) Mixtures Designed with Distinct Techniques

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4.1. Abstract

In the past decades, several studies have focused on mix-proportioning sustainable concrete mixtures through the use of coarse recycled concrete aggregates (RCA). Besides the economic and environmental benefits, RCA concrete still presents inferior mechanical and durability-related performance when compared to conventional concrete (CC). The latter is related to the residual mortar (RM) attached to aggregate particles leading to multiple interfacial transition zones (ITZ) in the system. Hence, numerous RCA mix-design techniques have been developed to account for its distinct microstructure, which among those, the Equivalent Volume (EV) and Particle Packing Models (PPM) seem to be very promising. Yet, such methods have never been used for mix-designing fine recycled concrete aggregates, the so-called FRCA. This work evaluates the mechanical and durability related performance of twelve recycled concrete mixtures containing 100% replacement of fine aggregates by FRCA. Three mix-design methods (i.e. direct replacement, EV and PPMs), two types of aggregate (natural vs manufactured) and two FRCA manufacturing processes (crusher's fine vs fully ground) were selected for this research. Results demonstrate that the aggregate's type and crushing process play an essential role on the inner quality of FRCA. Moreover, EV and PPM-mix-designed FRCA concrete yielded suitable mechanical and durability-related performance along with an eco-efficient character. Conversely, DRM-mix proportioned mixtures displayed inadequate short and long-term behaviour.

Keywords: Fine recycled concrete aggregates; low cement concrete; eco-friendly concrete, durability of FRCA concrete, mix-design, and particle packing model.

4.2. Introduction

The use of recycled concrete aggregates (RCA) has been progressively considered as a sustainable alternative to decrease the carbon footprint of concrete construction. Yet, the vast majority of RCA's use has been limited to non-structural applications, mostly due to concerns over material quality, fresh and hardened state properties and long-term behaviour [1–4]. In fact, a number of research projects have reported inferior fresh and hardened state properties of RCA concrete. The response of many researchers has been to suggest that RCA should not be permitted for structural purposes, and that additional cement, mineral and/or chemical admixtures should be added to compensate for this lack of performance [5–7]. The latter clearly offsets the key concept of using RCA to produce eco-efficient concrete.

Much of the research performed on RCA implicitly treats the material as being *homogeneous* and directly replaces certain proportions of natural aggregate (NA) in the concrete mix-design by the RCA material, with little to no further consideration on its unique microstructure and multiphase composition [8–11]. Given the high variability of RCA features and properties according to its source, it is generally difficult or even impossible to accurately estimate and/or predict the fresh and hardened state performance of recycled concrete mixtures [12–15]. Yet, it has been found that whenever the distinct RCA microstructure is accounted for in the mix-design of recycled concrete, interesting short and long-term properties, similar to those of conventional mixtures, may be achieved [7,12,16–19].

4.3. Background

Table 4.1 presents a summary and description of the acronyms cited throughout this work to describe distinct types of mix-designing RCA concrete mixtures.

Table 4.1: List of acronyms used and their following definitions.

Acronyms	Stands for	Description
RCA	Recycled Concrete Aggregate	Aggregate obtained by crushing concrete waste. It will usually be used to refer the coarse aggregate fraction only (i.e. >5 mm particle size).
FRCA	Fine Recycled Concrete Aggregate	Sub-product of RCA crushing with smaller particle size diameter (i.e. <5 mm).
NA	Natural Aggregate	Natural aggregate obtained from crushed stone or gravel.
RM	Residual Mortar	The portion of mortar comprised of natural sand and hydrated cement attached to the surface of RCA particles.
RCP	Residual Cement Paste	The portion of hydrated and unhydrated cement attached to residual fine material within FRCA material.
ITZ	Interfacial Transition Zone	Interface between aggregate particles and mortar in concrete.
CC	Conventional Concrete	Concrete comprised of natural aggregates only, designed with the ACI method.
FRCA Concrete	Fine Recycled Aggregate Concrete (FRAC)	Concrete proportioned with replacement of the natural aggregate fraction by FRCA.
DRM	Direct Replacement Methods	Design methods for concrete with RCA and FRCA partially replacing (by weight or volume) a portion of natural aggregates not accounting for the residual mortar or residual cement paste.
EV	Equivalent Volume	Mix-design method for concrete with RCA accounting for the difference in microstructure.
PPM	Particle Packing Models	Method for mix-design low-binder concrete with optimization of the particle size distribution and use of a q-factor.
DF	Durability Factor	Index regarding the performance of concrete exposed to a certain number of freeze-thaw cycles.
FT	Freeze-Thaw	Referred to cycles of freezing and thawing conditions causing external and internal damage in concrete.
BI	Binder Index	Relationship between amount of binder required to obtain one unit of 28-day compressive strength in concrete.

4.3.1. Microstructure and performance of FRCA concrete

Two types of RCA are usually referred to in the literature: coarse (CRCA) and fine (FRCA) recycled concrete aggregates. Although various authors have investigated the use of CRCA in concrete, very few research and developments [13–18] were made on FRCA concrete, especially for high replacement levels (> 20%).

CRCA is defined as a two-phase material comprised of original virgin aggregate (OVA) and RM (Figure 4.1a). The amount of RM may vary and depends upon the type and quality of the OVA (i.e. lithotype, texture, shape, etc.) and the RM inner quality (i.e. mechanical properties). The RM may constitute up to 60% of the total volume of CRCA [19]. Microcracks are also regularly found within the RM likely due to past damage, weathering and/or RCA processing (i.e. crushing, sieving, etc.). On the other hand, FRCA is defined as a fine granular material comprised of residual cement paste (RCP) and residual particles of natural and or manufactured aggregate (Figure 4.1b). FRCA is considered to be a very low-quality material due to its supposedly high amount of residual cement paste (RCP) adhered to the fine particles which results in low specific gravity, high porosity and absorption of the FRCA along with high water demand of the FRCA concrete. Moreover, FRCA fabrication may vary significantly (i.e. crusher type, crushing series, etc.) which leads to important variability to the final product [20,21].

Recycled concrete mixtures partially or fully replaced by FRCA were observed to yield lower performance in the fresh (i.e. high consistency and low flowability) and hardened states (i.e. low compressive strength and stiffness) when compared to conventional concrete mixes [10,22–28]. The latter was deemed, among others, to the supplementary amount of interfacial transitional zones (ITZ) that is brought to the system in FRCA. In order to overcome these issues, advanced mix-design techniques such as the methods that account for RCA microstructure such as the *Equivalent Volume Method (EV)* or even *Particle Packing Models (PPMs)* might be used. However, there is currently a lack of literature data illustrating the short and long-term performance of FRCA mixes proportioned with the above techniques

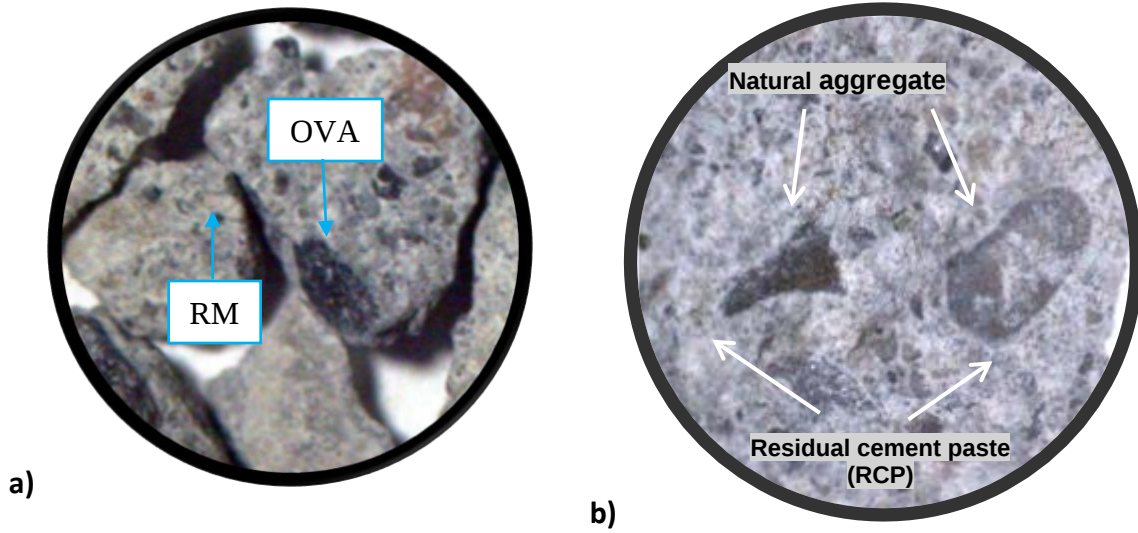


Figure 4.1: Composition of CRCA (a) and FRCA (b) particles.

4.3.2. Available techniques for RCA concrete mix-design

4.3.2.1. Direct replacement method (DRM)

Direct replacement methods, either by weight or volume, may be seen as one of the earliest attempts to mix-proportion concrete using RCA. Regardless of the procedure adopted, by weight (DWR) or volume replacement (DVR), the RCA material is simply combined in the mixture with NA, usually the coarse fraction. Then, the amount of cementitious materials, water and fine aggregates is kept constant for any material replacement ratio, which is usually selected at levels lower than 30% [4,29]. Results of recycled concrete mixes designed through DRM were verified to be extremely variable; yet a similar trend is often observed: the higher the RCA amount, the lower the mechanical performance of the RCA concrete.

4.3.2.2. Equivalent Mortar Volume (EMV) and Modified EMV (EMV-mod)

The Equivalent Volume Method (EMV) is a novel mix-design procedure for RCA concrete proportioning which accounts for the distinct microstructure of the RCA, as proposed by Fathifazl et al. [30]. The method treats RCA as a multiphase material comprised of RM and OVA, yet the volume of cement added to the mix is reduced according to the existing RM content adhered to

the RCA particles. The latter is always based upon a companion CC mixture presenting the same total mortar (TM, summation of RM and the fresh mortar) and coarse aggregates contents than the reference CC [10,30]. Despite the promising features of the EMV method, challenges in the fresh state are often faced by EMV-proportioned mixtures due to the higher presence of coarse aggregates compared to fine fractions, thus reducing the mortar content and flowability of the mix.

In order to overcome the aforementioned fresh state issues, a modification to the conventional EMV method was proposed by Hayles et al. [31]. The EMV-mod method adds a supplementary factor to optimize the “cement to sand mass ratio” of the RM and thus allows a proper selection of the amount of cement to be accounted for in the new RCA mix. As a result, mixtures proportioned through the EMV-mod present improved fresh state performance (i.e. lower consistency and higher flowability) than EMV mixes. Nonetheless, this approach was verified to present a drawback as the PC content is normally increased for a given targeted strength when compared to both CC and EMV-designed mixes [31].

4.3.2.3. Equivalent Volume (EV)

Based on the main concepts of the previous EMV and EMV-mod methods, the so-called *Equivalent Volume method* (EV) was proposed by Ahimoghadam et al. [32]. The EV aims to solve the fresh state challenges faced by mixtures designed through the EMV and EMV-mod methods along with providing recycled mixtures with an eco-friendly character (i.e. low PC content), while keeping suitable performance in the hardened state [32]. Unlike the EMV where the same amount of coarse aggregates and RM are considered for calculations, the novelty of this method is that the RCA mix is based on a reference CC mixture presenting the same volumetric amount of cement paste (CP) and aggregates (Ag). Moreover, RM is considered in this method as the summation of residual paste (RP) and residual fine aggregates. Therefore, the total volumetric CP content in a given EV mixture is defined as the summation of RP and fresh paste (FP) volumes. As a result, EV-proportioned mixes were found to often yield suitable fresh state behaviour (high flowability) and cement efficiency (PC contents $\approx 300 \text{ kg/m}^3$) due to the significant increase of fine aggregates and decrease of coarse particles in the system [32,33].

4.3.2.4. Particle Packing Models (PPM)

Particle packing models (PPMs) are advanced mix-design techniques used to improve performance of concrete mixes in both fresh and hardened states. PPMs are divided into discrete and continuous models. The first one assumes the existence of a given number of discrete particle sizes that are rearranged to reach the maximum packing density [29,34,35], whereas the second one assumes a continued distribution of particles within the system [35,36]. Either discrete or continuous, PPMs aim to optimize the granular system, resulting in an improved packing density and reduced porosity [35–39]. Hence, concrete mix-proportioned through PPMs often present lower PC amounts when compared to conventionally designed concrete.

In the literature, one of the most recognized continuous PPM is the modified-Andreasen or Alfred model, initially created by Funk and Dinger in 1980 [40]. This model calculates the optimum PSD based on a coefficient of distribution (q) along with the largest (D_L) and smallest (D_S) particle sizes (i.e. diameter) present in the system (Equation 4.1). The coefficient of distribution (q) is normally adopted based on the fresh state requirements of the mix. Distribution coefficients (q) ranging between 0.20-0.23 are often selected for self-consolidating mixtures while values between 0.26-0.28 are normally targeted for vibrated and/or pumped concrete. It is worth noting that 0.37 is the q value that yields the highest packing density and thus lowest porosity to the granular system as per [40].

$$CPFT = 100 * \left(\frac{D_P^q - D_S^q}{D_L^q - D_S^q} \right) \quad \text{Equation 4.1}$$

Where: CPFT is the cumulative (volume) percent finer than D_P , and D_P is the particle size.

4.3.3. Durability and long-term performance of FRCA concrete

Durability-related properties are one of the essential factors to be accounted for concrete subjected to harsh environmental conditions such as freezing-thawing cycles and exposure to de-icing salts [41]. It is widely accepted that the durability performance of conventional concrete mixtures is related to the quality of the ingredients and mix-proportion of the material. The latter should be even more important in FRCA mixtures since recycled material produced from crushed

concrete is expected to present some microcracks, major porosity or inner flaws within the RCP likely due to past damage (i.e. exposure to aggressive agents), weathering or FRCA processing. Therefore, the crushing process is anticipated to have an important influence on the quality and thus long-term performance of FRCA concrete. A number of non-destructive, mechanical and accelerated procedures might be used to evaluate the durability performance of FRCA mixtures as presented hereafter.

4.3.3.1. Non-destructive tests (NDT)

A fast evaluation of the inner quality of concrete mixtures may be performed through the use of non-destructive techniques (NDT), such as ultrasonic pulse velocity (UPV) and surface electrical resistivity (ER). Such techniques have been verified to be suitable to appraise the overall quality of conventional concrete mixtures subjected to aggressive/harsh environments [42] along with the effects of RCA replacement on the inner quality of CRCA [43–46]. Literature results show that the higher the RCA replacement, the lower the UPV and ER results gathered over the test for CRCA mixtures [47,48].

4.3.3.2. Stress-strain relationship

It is usually verified in the literature that regardless of the mix-design technique used to proportion RCA concrete mixtures, the overall stiffness of concrete tends to be lower than the ones of conventional concrete mixes (CC) [3,15,49,50]. This is very likely due to the presence of residual paste (RP) or residual cement paste (RCP) which is found within coarse or fine aggregate particles, respectively.

In some cases, even when the RCA concrete achieves compressive strengths similar to CC mixes, it tends to present higher deformation due to the lower inner quality of the RCA particles [15,18]. Hence, the stress-strain relationship tends to present a less steep slope and thus lower values of modulus of elasticity (ME). Besides the ME, the stress-strain curve is a key parameter to evaluate the inner quality of concrete mixtures because it measures the ability of the material to respond to compressive (usually cyclic) loads. The energy dissipated along with the plastic deformation

over compressive loading-unloading cycles may clearly indicate the amount of inner defects or even porosity. In this context, the Stiffness Damage Test (SDT), as proposed by Sanchez et al. [51], has shown to be a very reliable tool to quantify physical damage in concrete; yet, it has never been used to evaluate the inner quality of FRCA concrete, although it is deemed to be a promising method in this regard.

The SDT comprises a series of five uniaxial loading-unloading cycles at a controlled rate of 0.10 MPa/s, in which a concrete specimen is loaded up to 40% of its 28-day compressive strength [52–54]. At this loading level, no deleterious effects are supposed to be generated to the sample; similar loading level is actually recommended for testing modulus of elasticity, as per ASTM C 469 [55]. Hence, cracks present within the materials' microstructure are closed while the loading-unloading cycles, dissipating energy and plastic deformation [51,56]. The method presents two main outcomes: the stiffness damage index (SDI), which evaluates the energy dissipated over the loading-unloading cycles and the plastic deformation index (PDI), which measures the unrecoverable deformation after five loading cycles. Finally, an additional feature of the SDT is its ability to gather the stiffness (i.e. modulus of elasticity) of the material by considering the average of the secant modulus of the cycles two and three [51,52].

4.3.3.3. Freeze-thaw resistance

Freeze-thaw (FT) resistance of RCA concrete has been investigated by a few authors [46,57,58], and all of them agreed that the higher the RCA replacement, the lower its resistance to FT cycles, especially when RCA microstructure is not accounted in the mix-proportioning. Otherwise, EMV-designed mixtures showed to perform quite well against FT and yielded comparable results when compared to similar CC mixes [58].

It is widely known that FT resistance of conventional concrete is linked to various factors such as the aggregate features, cement paste porosity and free water availability in the system. These parameters may be even more critical for RCA concrete since its higher inner porosity may contribute to increase the material's absorption and permeability and thus lead to further FT damage [59,60]. However, the role of permeability of highly porous aggregates such as RCA is

not fully understood yet, since it may play a dual role: highly porous aggregates are normally weaker and easily saturated whereas increased permeability leads to dissipation of internal hydraulic pressure which may improve FT resistance [61].

Bogas et al. [62] investigated two types of 100% replacement FRCA mixtures (i.e. normal and high strength) presenting water-to-cement (w/c) ratios of 0.53 and 0.35 and incorporating moderate to high cement contents of 350 kg/m³ and 420 kg/m³, respectively. The authors observed that normal strength concrete (i.e. 35 MPa) was not freeze-thaw resistant regardless the replacement ratio of FRCA but it is linked to the type of aggregate used and its quality, since aggregates themselves also play an important role in the inner structure of concrete. The air entraining agent was observed to be not as effective as for in CC mixes, due to the presence of important porosity of FRCA concrete. In fact, the porosity of aggregates and RCP from FRCA mixes was seen to be among the main factor decreasing the freeze-thaw performance of FRCA concrete.

4.4. Scope of Work

Most of the currently research on the durability and long-term performance of RCA concrete present in the literature has focused on using CRCA. Yet, there is currently a lack of literature data on the long-term performance of concrete mixtures incorporating fine recycled concrete aggregates (FRCA), especially with high amounts of replacement. This work aims to evaluate the impact of using FRCA (100% replacement) on the overall durability-related properties of recycled concrete mixtures. It can be divided into two main phases: a) production and characterization of FRCA, and b) appraisal of the durability properties of the material through non-destructive (UPV and ER), mechanical (stress-strain relationship) and accelerated (FT) test procedures in the laboratory.

The first phase evaluates the impact of the manufacturing process (i.e. crushing process) on the physical properties of FRCA. First, two types of 35 MPa conventional concrete (CC) mixtures are fabricated according to ACI standards with natural and manufactured sand and crushed afterwards to produce FRCA. Two distinct crushing processes were used to produce FRCA: crusher's fine (i.e. two series of crushing and sieving) and fully ground (i.e. multiple series of

crushing and sieving). Then, FRCA is characterized and the residual cement paste (RCP) quantified. In the second phase, the durability and long-term performance of FRCA mixtures proportioned through distinct techniques (i.e. DRM, EV, and PPM) is appraised and compared to each other. Discussions on the use of FRCA concrete under harsh climates along with the influence of the manufacturing process and mix-design technique on the long-term performance of FRCA concrete is then performed.

4.5. Materials and Methods

4.5.1. FRCA production and raw materials characterization

Two-hundred conventional concrete (CC) cylinders (100 mm x 200 mm) were fabricated for each of the concrete families used in this research incorporating natural (NA) and manufactured sand (MS), according to ASTM C 39 [63]. The samples were demolded after 24h and moist cured for 28 days. To evaluate the influence of the crushing process on the final FRCA inner-quality, two production methods (i.e. crusher's fine – CF and fully ground – FG) were employed as illustrated in Figure 4.2.

In the first method, both coarse and fine RCA are produced (Figure 4.2a). The CF process has a total of two series of crushing and three stages. First, concrete specimens are jaw crushed on a 19 mm maximum gap opening, then subjected to a second jaw crushing stage on a 5 mm gap opening. Finally, after sieving, only the fine fraction of the crushed material was used as per CSA A23.2-14 [64].

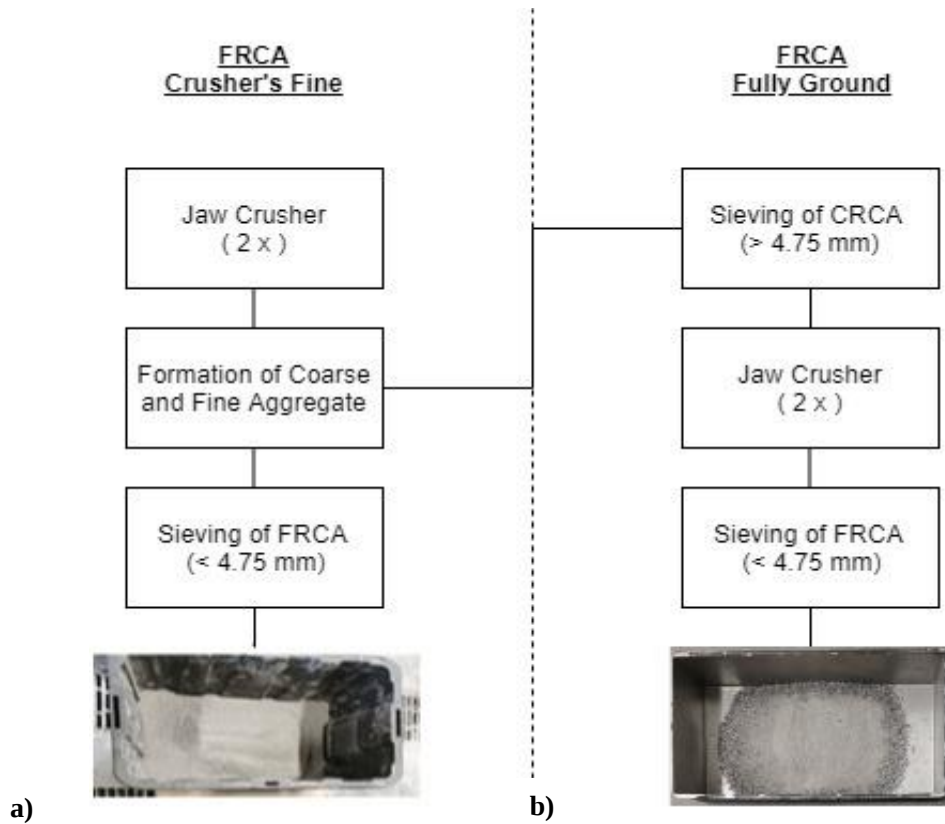


Figure 4.2: Summary of the two methods of FRCA production adopted in this experimental work.

In the second method (FG -Figure 4.2-b) only FRCA fractions are produced through multiple series of crushing (5 mm gap opening in the jaw crusher) and sieving as per CSA A23.2-14 [64]. It is worth noting that in both crushing methods, the particle size distribution (PSD) of the final FRCA ranged from 150 μm to 5 mm. Furthermore, regardless of the crushing process adopted, two FRCA families were produced in this work through the aforementioned processes described: FRCA from natural (FRCA-NS) and manufactured (FRCA-MS) sand.

Further characterization of the residual cement paste (RCP) content was performed in 2.5g of all the types of FRCA through the soluble silica sub-procedure according to ASTM C1084-15 [65] and C114-18 [66]. This procedure, as detailed in [67], was selected based on the fact that the limestone aggregates used in this work prevent the selection of other chemical procedures such as maleic acid digestion. Moreover, specific gravity and water absorption were evaluated according to the new method proposed by Rodrigues *et al.* [68], in which FRCA samples are first saturated in a 0.1% dispersant solution prior to continue with a similar procedure as per CSA-

A23.2-2A-14 [64]. This method was selected in order to prevent common issues observed during the analysis such as the cohesion of FRCA particles [68]. A summary of the FRCA characterization results and PSD analysis are presented in Table 4.2 and Figure 4.3, respectively. The properties of both natural and manufactured sand as per CSA A23.2-14 [64] are also presented.

Table 4.2: Properties of FRCA and natural aggregates.

Physical Property	FRCA NS-CF	FRCA NS-FG	NS	FRCA MS-CF	FRCA MS-FG	MS
RCP content (wt.%)	15.5	11.5	-	16.8	11.4	-
SSD specific gravity (kg/L)	2.47	2.56	2.70	2.51	2.58	2.76
OD specific gravity (kg/L)	2.32	2.42	2.67	2.36	2.44	2.74
Water absorption (%)	7.87	6.38	0.86	7.76	6.16	0.65
Fineness modulus	3.27	2.53	2.59	3.17	2.70	2.85

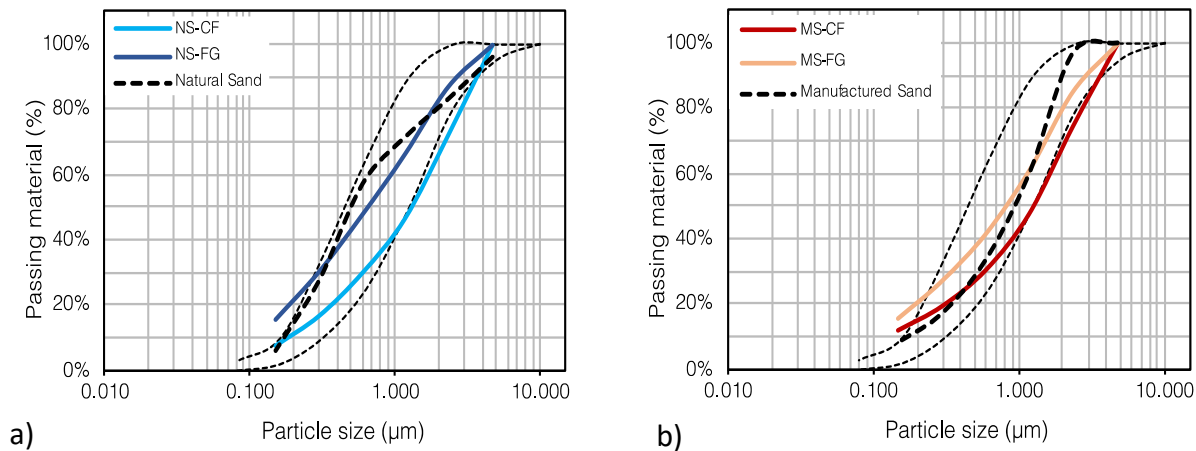


Figure 4.3: PSD curves for FRCA derived from natural (a) and manufactured sand (b) companion conventional concrete.

From Figure 4.3 one verifies that the quality of the FRCA can be significantly affected by the crushing process adopted. For instance, FRCA NS-CF (Figure 4.3a) is observed to be comprised of coarser particles, while the fully ground type (FRCA NS-FG) showed to have a higher amount of fine particles. In fact, the FRCA NS-FG presents a PSD quite similar to the one of natural sand (see Table 4.2). Likewise, FRCA MS materials were also observed to follow the same trend regarding physical properties (Figure 4.3b).

In order to produce the FRCA concrete mixtures, a general use (GU) Portland cement (PC) was used along with a limestone coarse aggregate with a nominal maximum size of 19 mm. Moreover,

a limestone filler with PSD smaller than the one of PC, known as performance filler - PF, was employed only in the mixes proportioned through the PPM method. A summary of the physical properties for both PC and filler are presented in Figure 4.4 (PSD curves) and Table 4.3 (specific surface area – SSA and specific gravity).

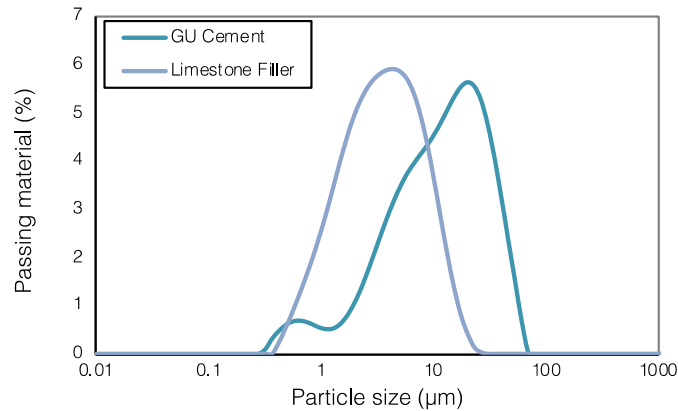


Figure 4.4: PSD of PC and limestone filler used in the PPM FRCA mixtures.

Table 4.3: Physical properties characterization.

Material	Mass (g)	Volume (cm ³)	Specific gravity (g/cm ³)	SSA (m ² /g)
GU cement	31.9	10.49	3.03	1.00
Filler	19.5	7.56	2.60	3.70

4.5.2. Mix-design procedures and proportions

Three distinct FRCA concrete mixtures mix-proportioned with distinct techniques (i.e. DRM, EV, and PPM) and containing 100% replacement of natural fine aggregates by FRCA were designed. Moreover, two control mixes (e.g. ACI method - 0% FRCA) incorporating natural (NS) and manufactured (MS) sand were also mix-proportioned for comparison purposes. The water-to-cement (w/c) ratio of all FRCA mixes was selected as 0.35 so that a target strength of 35 MPa might be achieved, which is usually the average strength selected for non-structural and structural concrete in the market. In addition, an air entraining agent (AEA) was used in all mixtures (i.e. control and recycled) to incorporate an amount of air of 7-8% according to CSA A23.1-14 [68], as required for structural concrete exposed to freeze-thaw cycles. Lastly, a combination of polycarboxylate-based high range (HRWR) and mid-range water reducer was used

in all mixtures at different amounts, in order to achieve a consistency (i.e. slump value) of 100 ± 20 mm. Table 4.4 displays a summary of all mixes.

Table 4.4: FRCA and control concrete mix-design proportions.

Mixture	Cement (kg/m ³)	FRCA (kg/m ³)	Natural FA (kg/m ³)	Natural CA (kg/m ³)	Filler (kg/m ³)	Water (kg/m ³)	AEA (%)	Mid-range + HRWR (kg/m ³)
ACI-NS	370	-	738	1032	-	174	0.65	-
ACI-MS	370	-	759	1032	-	174	0.65	-
DRM-NS CF	497	524		1032	-	174	0.45	-
DRM-NS FG	497	546		1032	-	174		-
DRM-MS CF	497	533		1032	-	174		-
DRM-MS FG	497	551		1032	-	174		-
EV-NS CF	374	714	-	1005	-	131	0.50	1.2
EV-NS FG	373	740	-	1014	-	131		1.2
EV-MS CF	372	732	-	1004	-	130		1.2
EV-MS FG	373	752	-	1006	-	131		1.2
PPM-NS CF	308	879	-	806	108	108	0.50	1.0
PPM-NS FG	333	907	-	797	83	117		1.0
PPM-MS CF	299	898	-	809	118	105		1.2
PPM-MS FG	332	915	-	798	84	116		1.2

The mixes proportioned through the DRM method (i.e. absolute volume method) treated the FRCA material as being the same as natural fine aggregates, resulting in mixtures with high amounts of PC (e.g. nearly 500 kg/m³). Otherwise, since the EV and PPM methods account for the RCP attached to the FRCA particles, the mixtures proportioned by these procedures presented much lower PC content. In the case of EV method, it was possible to obtain mixtures with PC contents (≈ 374 kg/m³) very similar to those of ACI method (i.e. 370 kg/m³). Likewise, mixtures designed through continuous PPM techniques (q-factor of 0.28) and with the use of inert fillers yielded final PC contents close to or even lower than 300 kg/m³ (using a minimum of chemical admixtures).

4.5.3. Methods

Non-destructive (UPV and ER), mechanical (compressive strength and stress-strain relationship) and accelerated FT tests were performed on all concrete families aforementioned and are fully described in the following sections.

4.5.3.1. Sample preparation

Cylindrical and prismatic samples from all concrete families were fabricated according to CSA A23.2-3C [64], demolded after 24h and moist-cured over 28 days prior to testing. A total of 108 concrete 100 x 200 mm cylinders were manufactured for each FRCA mixture along with 54 100 x 200 mm specimens for the CC mixes (i.e. ACI-NS and ACI-MS). Likewise, three 75 x 75 x 300 mm prisms per concrete mixture (recycled or conventional) were fabricated for the accelerated freeze-thaw tests as per ASTM C 666-15 [69].

4.5.3.2. Hardened properties

Non-destructive techniques (i.e. electrical resistivity – ER and dynamic modulus of elasticity through ultrasonic pulse velocity test – UPV) and compressive strength tests were performed on three specimens from each concrete mixture over time (i.e. 7, 14 and 28 days). Furthermore, the stress-strain relationship of each mixture was evaluated at 28 days through the use of the stiffness damage test (SDT) as per Sanchez et al. [51,52]. Thus, concrete cylinders from all FRCA and CC mixes were subjected to five compressive loading-unloading cycles at a controlled loading rate of 0.10 MPa/s up to 40% of the 28-day compressive strength. The output test parameters, namely the stiffness damage index (SDI) and plastic deformation index (PDI) were then evaluated as quantitative measures of inner quality of the mixes. Lastly, the modulus of elasticity (ME) was also calculated as being the average secant modulus of the cycles two and three from the SDT procedure.

4.5.3.3. Resistance to freeze-thaw cycles

Prismatic 75 x 75 x 300 mm concrete specimens from all mixtures fabricated in this research were tested against FT cycles through the use of the accelerated laboratory test procedure as per ASTM C 666 [69]. The procedure consists of storing the prisms in a freeze-thaw chamber (Figure 4.5), with temperature ranging from -18 to 4 °C at time intervals not less than two nor more than five hours and producing a total of 300 cycles.



Figure 4.5: Freeze-thaw chamber used for the test as per ASTM C 666.

Prior to the start of freezing-thawing cycles, all specimens had their mass, average length and fundamental transverse frequency (ASTM C 215 [70]) recorded. The specimens were removed from the FT chamber every 36 cycles of exposure (approximately one week) for further mass, length and frequency evaluations and were continuously monitored over time up until 300 cycles.

The relative dynamic modulus of elasticity of each sample was calculated based on the fundamental transverse frequency measurements, as shown in Equation 4.2.

$$P_c = \frac{n_1^2}{n^2} \times 100 \quad \text{Equation 4.2}$$

Where, the percentile relative dynamic modulus of elasticity after “c” cycles of freeze-thaw is represented by P_c ; n is the fundamental transverse frequency (Hz) at 0 cycles and n_1 is the fundamental frequency after “c” cycles of freeze-thaw. It is worth noting that the test is

performed up until 300 cycles or until the sample reaches 40% decrease of the initial relative dynamic modulus of elasticity value.

The length changes were measured according to ASTM C 490 [71] and calculated as per Equation 4.3, where: L_c (%) is the length change after “c” cycles of freeze-thaw; l_1 and l_2 are the comparator length readings at 0 and “c” cycles, respectively, and L_g is the effective gauge inner length measured between the gauge studs as shown in Figure 4.6. As per ASTM C 666, an expansion of 0.10% is considered to be the limit for distinguishing FT resistant vs non-resistant concrete.

$$L_c = \frac{l_2 - l_1}{L_g} \times 100 \quad \text{Equation 4.3}$$

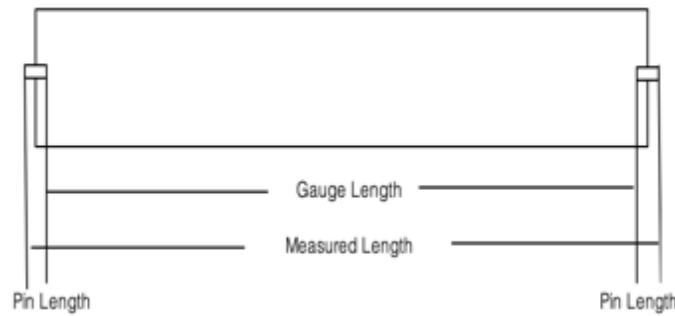


Figure 4.6: Illustration of specimen measurements as per ASTM C 490 [71].

Finally, the overall performance of the mixtures against freeze-thaw action was evaluated based on the durability factor (DF) as follows:

$$DF = \frac{P_N N}{M} \quad \text{Equation 4.4}$$

Where DF is the durability factor of the specimen (0-100%), which corresponds to the reduction of dynamic ME over freeze-thaw cycles; P_N (%) the dynamic ME after the N^{th} freeze-thaw cycle; N refers to the number of cycles at which the dynamic ME reaches the specified minimum value for discontinuing the test or the maximum number of cycles for the analysis (the lower value); and M is the specified number of cycles at which the exposure is to be terminated (i.e. 300 cycles).

4.6. Experimental Results

4.6.1. Surface electrical resistivity

Surface electrical resistivity (ER) readings were performed at 7, 14 and 28 days on the FRCA concrete samples. The surface electrical resistivity (ER) device selected for this research presented a setup called “4-probe array” and measured the electrical current over 4 channels (located at 90° from each other) in contact with the sample’s surface. It is worth noting that the test was performed on samples in SSD condition.

Figure 4.7 illustrates a summary of all surface electrical resistivity (ER) measurements performed on the distinct concrete mixes. In general, it can be observed that the electrical resistivity for all CC, EV and PPM mixes tend to increase as a function of concrete maturity. From the data gathered, one notices that the highest results are obtained from the PPM-mix-designed mixtures (ER values between 10.8 and 14.3 K Ω -cm at 28 days), followed by EV-proportioned mixes (ranging from 6.5 – 7.3 K Ω -cm) and then DRM mixes (3.9 – 4.4 K Ω -cm), respectively. Regarding the FRCA source (i.e. NS or MS), one can observe a good correlation between ER values and the of compressive strength presented in Table 4.5. The latter demonstrates that FRCA-MS mixes yield similar mechanical properties as FRCA-NS. Lastly, it can be noted that the type of FRCA (i.e. CF or FG) influences ER values since FRCA-FG mixes presented higher ER values than FRCA-CF, which is in also in agreement with the compressive strength results.

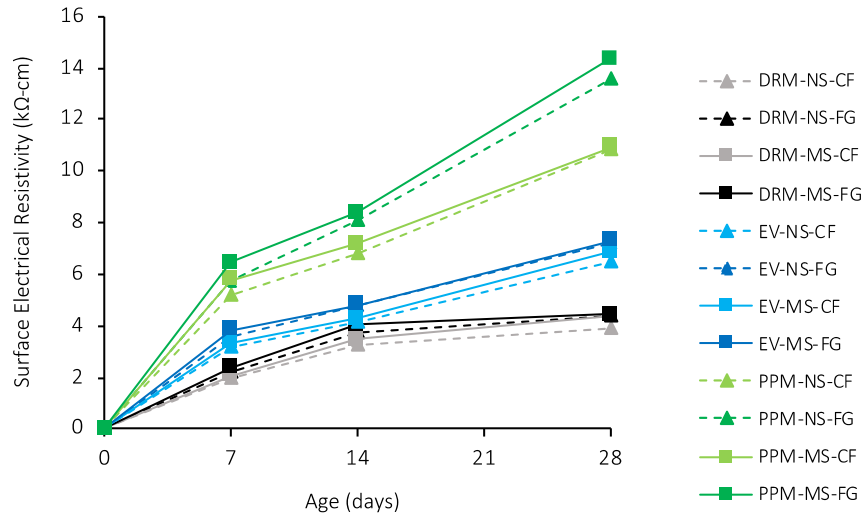


Figure 4.7: Surface electrical resistivity measurements for all FRCA mixtures.

4.6.2. Effect of FRCA on concrete mechanical properties

The compressive strength (f'_c) and dynamic modulus of elasticity (E) gathered over time for all mixes at 7, 14, and 28 days are presented in Table 4.5. It is important to note that all FRCA mixes are based on a companion CC mix and were initially proportioned aiming to reach an average 28-day compressive strength of 35 MPa. From the data in Table 4.5, one observes that the highest compressive strength results were obtained through the PPM method (i.e. ranging from 41 – 65 MPa at 28 days), whereas the mixtures DRM-designed yielded the lowest results (i.e. between 19 and 21 MPa at 28 days). EV-designed mixes lied in between PPM and DRM mixtures (i.e. range between 26 to 31 MPa). Finally, the control mixes designed with natural (AC-NS) and manufactured (ACI-MS) sand presented 28-day compressive strength results within the range of 35 – 40 MPa. These findings state that the mix-design method influences the inner quality of the concrete rather than the type of aggregate used (e.g. FG or CF type).

Table 4.5: Mechanical properties of FRCA CC mixes over time.

Mixture	f'c (MPa)			Dynamic E (GPa)		
	7d	14d	28d	7d	14d	28d
ACI-NS	26	35	36	48	49	49
ACI-MS	29	38	38	48	49	49
DRM-NS-CF	12	17	19	15	15	15
DRM-NS-FG	16	17	19	15	15	16
DRM-MS-CF	14	18	20	15	15	15
DRM-MS-FG	16	19	21	15	15	16
EV-NS-CF	19	25	26	26	27	27
EV-NS-FG	21	30	30	30	30	34
EV-MS-CF	20	26	27	27	27	29
EV-MS-FG	22	30	31	30	31	35
PPM-NS-CF	32	36	41	40	40	42
PPM-NS-FG	47	56	62	48	50	50
PPM-MS-CF	32	36	42	40	41	43
PPM-MS-FG	50	57	65	49	51	51

The dynamic modulus of elasticity seems to correlate quite well with the overall compressive strength as a function of concrete maturity. PPM mixes presented the highest results (i.e. ranging between 42 – 51 GPa at 28 days) followed by EV mixes (i.e. 27 – 35 GPa at 28 days) and then DRM mixtures (i.e. 15 – 16 GPa at 28 days). Both conventional concrete mixtures (NS and MS) obtained dynamic modulus of elasticity values close to 49 GPa.

4.6.3. Stress-strain parameters

Table 4.6 shows a summary of the SDT outcomes for the FRCA-CF and CC mixes with NS. It can be observed that the CC mix presented the highest static modulus of elasticity (i.e. 41 GPa), followed by PPM (i.e. 29.4 GPa), DRM (i.e. 25.5 GPa) and EV mixes (i.e. 21.4 GPa). Moreover, a trend could be observed when comparing both modulus of elasticity (E) and SDI; the higher the E values, the lower the SDI, as expected. However, this trend does not apply for the EV mix which

needs to be further investigated. Likewise, PDI showed the same trend (i.e. higher values for less stiff concrete).

Table 4.6: SDT test parameters for FRCA and CC mixes made with NS.

Mixture	SDI	PDI	E (GPa)
ACI-NS	0.11	0.03	40.8
DRM-NS-CF	0.12	0.09	25.5
EV-NS-CF	0.20	0.16	21.4
PPM-NS-CF	0.11	0.07	29.4

4.6.4. Freeze-thaw (FT) resistance

Results of freezing and thawing cycles and its related test outcomes are presented in the following sections. Therefore, a better understanding of the use of conventional and advanced mix-design techniques on the overall durability performance of distinct FRCA mixes might be assessed and compared to each other. It is worth noting that only recycled mixtures were evaluated against FT cycles.

4.6.4.1. Mass losses

Figure 4.8 presents the mass loss (%) results for all mixtures as a function of the number of cycles. It may be noticed that the higher the freeze-thaw cycles, the higher the mass loss percentage for all mixtures, as expected. Yet, PPM mixes were observed to have the best performance against freezing and thawing damage (about 20% mass loss after 300 cycles), followed by EV (from 30 to 40% mass loss) and DRM (from 35 to 45% mass loss), respectively.

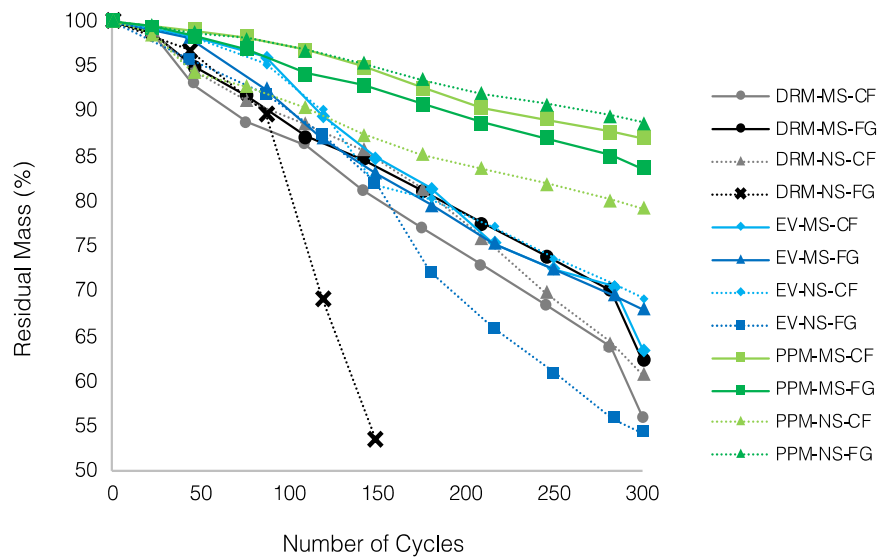


Figure 4.8: Mass loss over 300 freeze-thaw cycles for all FRCA mixes.

Although the mass loss found for the EV mixtures were only slightly better than the ones displayed by DRM mixes, the appearance of the sample (Figure 4.9) of these two mixtures were fairly different. At the end of the freeze-thaw test, it could be noticed that some of the specimens designed with the DRM method presented excessive spalling on the surfaces along with corners rounded. The EV specimens were also observed to present some deterioration due to spalling but at a much lower degree when compared to DRM. Lastly, the average PPM mixes demonstrated to have some minor spalling on the surfaces which emphasize having higher frost resistance.

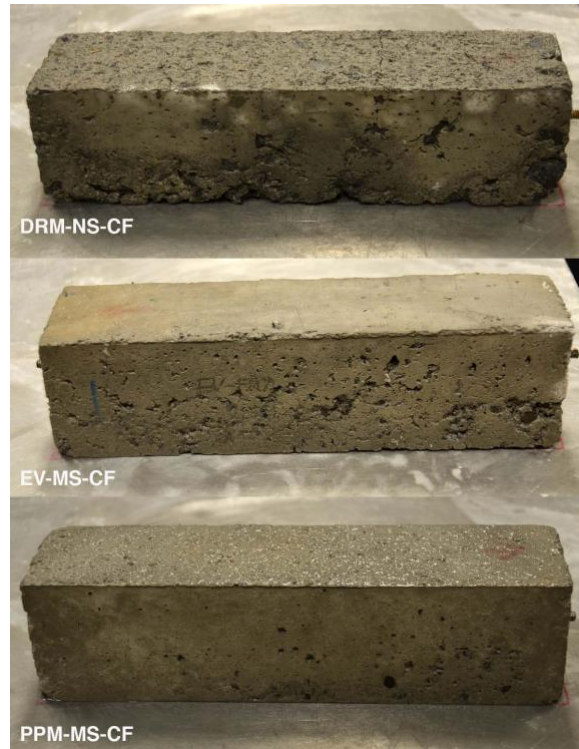
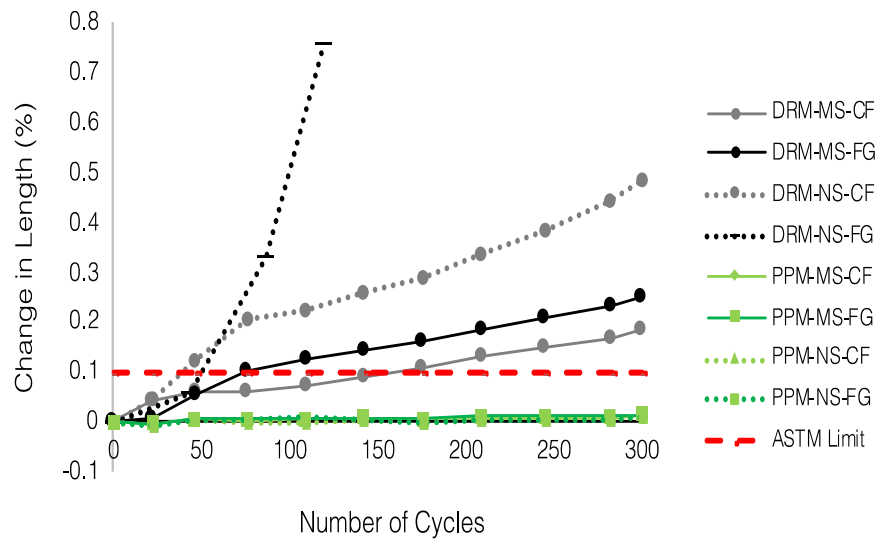


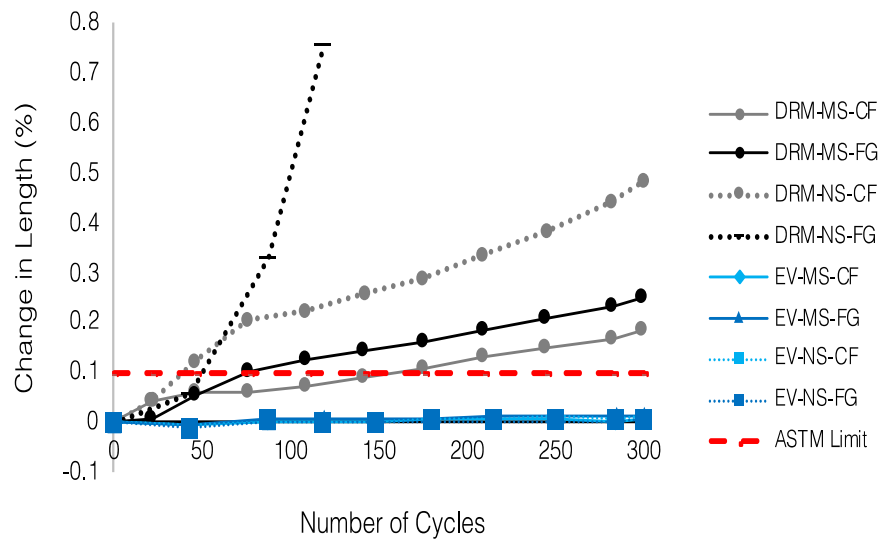
Figure 4.9: Degradation of FRCA mixes at the end of 300 freezing and thawing cycles.

4.6.4.2. Length changes

Figure 4.10 (a - DRM and PPM mixes and b - DRM and EV mixes) gives a plot for the length changes as a function of FT cycles. One can observe from both figures that the DRM yielded the lowest performance (highest length change) against FT resistance, as expected. Furthermore, all the DRM proportioned samples exceed the limit proposed by ASTM C 666 (0.10%) and some of them failed completely before the end of the test (i.e. 300 cycles). Otherwise, PPM and EV mix-designed FRCA mixtures presented a suitable behaviour against freezing-thaw, and their length change over the 300 cycles remained far below the proposed 0.10% limit as per ASTM C 666 [69].



a)



b)

Figure 4.10: Length change over 300 cycles for PPM (a) and EV (b) in comparison to DRM mixes.

4.6.4.3. Residual dynamic modulus of elasticity

Figure 4.11 illustrates the residual dynamic modulus of elasticity (ME) results for all mixtures evaluated in this research. It is worth noting that ASTM C 666 [69] considers concrete to be frost resistant when the reduction in dynamic modulus of elasticity is lower than 40% at 300 cycles. It may be observed that, once again, the DRM mixes yielded the lowest results among the different mixes, while PPM mixtures showed the best performance. The EV mixes also demonstrated

acceptable behaviour (i.e. about 38% damage at 300 cycles). Finally, no significant trend was observed while the use of different types of FRCA (i.e. CF or FG) regarding freeze-thaw performance, which means that the mix-design procedure is more important than the crushing type and process of FRCA.

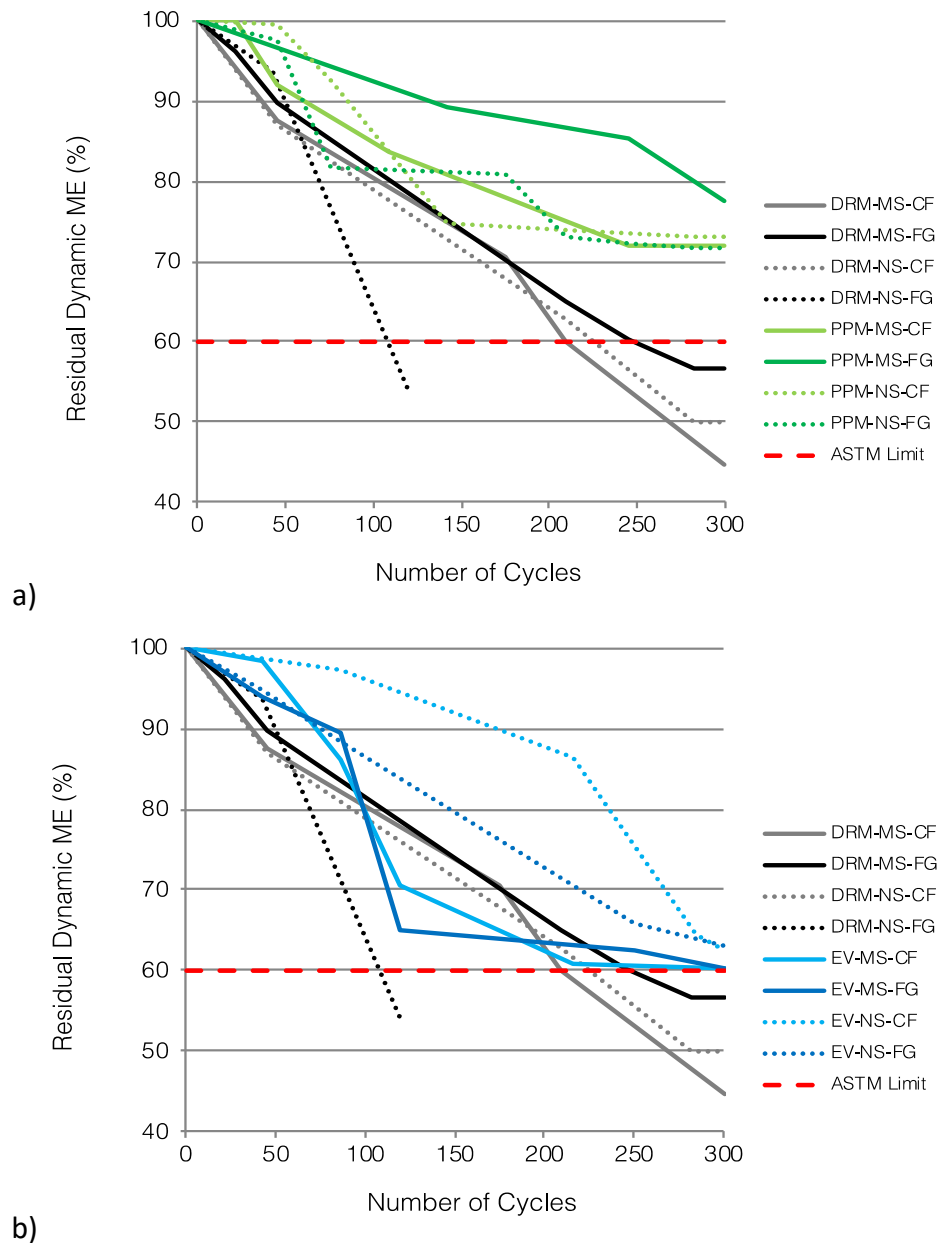


Figure 4.11: Residual dynamic ME over 300 cycles or PPM (a) and EV (b) in comparison to DRM mixes.

4.7. Analysis and discussion

4.7.1. Microscopic analysis

Qualitative microscopic analyses were performed to understand the differences on the microstructure of FRCA, which is a multiphase material partially composed of natural aggregates, yet having significant amounts of residual cement paste (RCP) adhered to the surface of its particles (Figure 4.12). The latter is considered to be the responsible for undesired features of the material such as lower specific gravity and higher water absorption capacity.

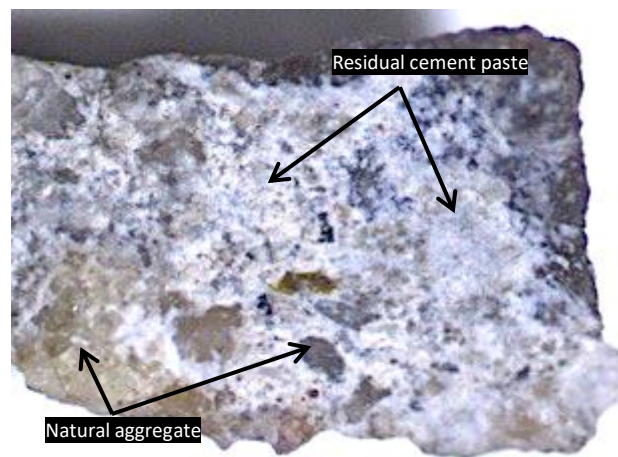


Figure 4.12: Composition of FRCA particle.

Two samples of FRCA material from distinct production processes were analysed, FRCA-CF - crusher's fine (Figure 4.13a) and FRCA-FG - fully ground (Figure 4.13b). It can be initially observed from the figures that FRCA-FG seems to present rough particles more angular in shape, also demonstrating to be of darker colour in comparison to FRCA-CF. The latter clearly represents the higher presence of residual cement paste (RCP) in the FRCA-CF material.

These findings correlate well with the fact that multistage crushing of concrete results in more detachment of RCP and thus, producing a FRCA of better physical properties (i.e. FRCA-FG). On the other hand, in the event of less crushing, less separation of adhered residual cement paste is obtained, thus providing FRCA with a rounded shape and smoother surface.

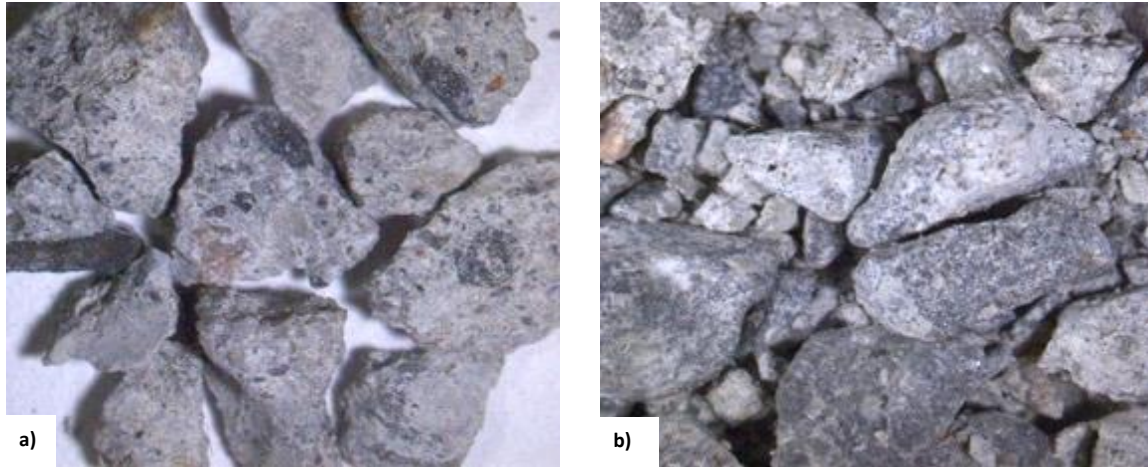


Figure 4.13: Microscopic observation of FRCA crusher's fine (a) and FRCA fully ground (b) types.

Based on the discussion above, another yet qualitative analysis was conducted by applying a phenolphthalein dye (Figure 4.14) in the same samples. Hence, FRCA-CF (Figure 4.14a) was deemed to be richer in RCP content, whereas FRCA-FG (Figure 4.14b) demonstrated to have significant presence of natural aggregate overcoming the RCP.

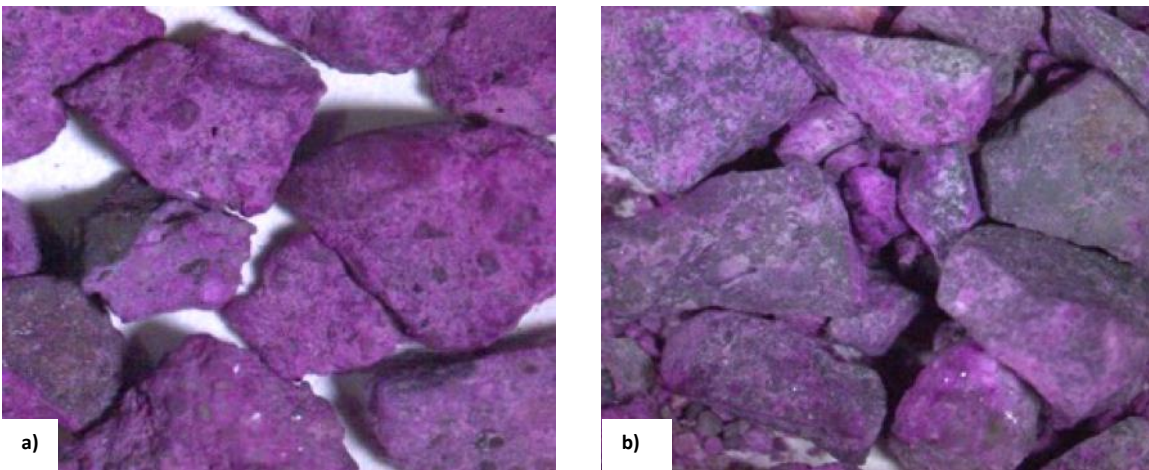


Figure 4.14: Phenolphthalein application on FRCA crusher's fine (a) and FRCA fully ground (b).

4.7.2. Mechanical properties

Figure 4.15 displays the analysis of the stress-strain curves of the CC and FRCA-CF mixes (Figure 4.15a) and both PPM mixtures (i.e. CF and FG, Figure 4.15b). Firstly, it can be observed from the stress-strain curves that the higher the slope of the curve, the higher is the modulus of elasticity

(ME), representing 21 GPa, 26 GPa, and 29 GPa for mixtures designed through EV, DRM and PPM respectively, whereas the CC mix reached approximately 41 GPa.

Despite the high variability of FRCA physical properties and the lack of procedures to control it, the material's quality will depend upon, among other factors, the presence of pre-existing cracks and their nucleation-propagation stage, which varies for example, with inner quality of the FRCA (i.e. CF vs FG). Thus, the SDT parameters (SDI and PDI), as previously described in section 4.3.3.2, were gathered in order to further evaluate the likely difference in microstructure of the materials.

From the data previously presented in Table 4.6, it has been observed that although the CC mix presents the highest modulus of elasticity, its stiffness damage index (SDI) parameter, which represents the amount of energy required to close inner cracks, is similar to the PPM mixtures. Thereby, PPM-designed mixtures may be seen as the ones with superior inner quality amongst all FRCA mixes. It may be explained as the enhancement of the system packing (i.e. through the use of limestone filler and PPM) plays a more important role than the multiphase ITZ presented in the FRCA mixtures. The plastic deformation index (PDI) also showed to correlate with the latter since the lowest values represent the mixtures with better inner quality as for CC (i.e. $PDI=0.03$) and PPM (i.e. $PDI=0.07$). It is worth noting that a similar trend was also observed for all the mixtures from MS source.

Interestingly, although the EV mixtures presented a better performance in terms of compressive strength than DRM mixtures, the ME was observed to not follow the same trend, since the RCP was accounted for in EV mixtures and disregarded in DRM. The difference in ME behaviour may be justified by higher FRCA content present in EV mixes (735 kg/m^3) when comparing to DRM mixtures (539 kg/m^3). In this case, the overall stiffness of the concrete is governed by the multiple ITZs found within the microstructure. Moreover, one can observe the correlation between PDI results presented in Table 4.6 and the stress-strain relationship (Figure 4.15-a). The EV mixtures present greater energy dissipation and plastic deformation over the 5 cycles in the SDT analysis, which is linked to the amount of FRCA (and thus ITZ) present in the concrete. Lastly, although the

PPM mix presented a similar stress-strain relationship to DRM, a significantly steeper slope is observed which means higher modulus of elasticity.

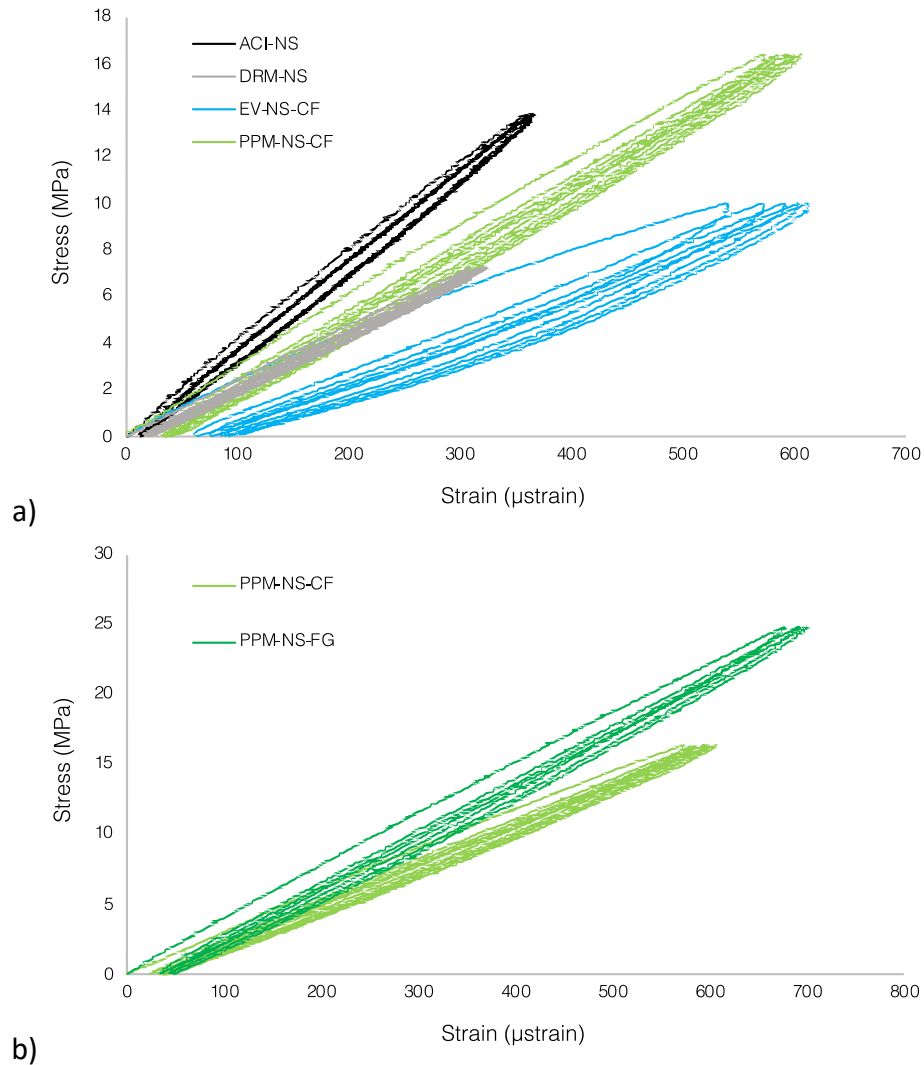


Figure 4.15: Stress-strain curves comparing a) FRCA-CF and CC mixes from NS source, and b) PPM with FRCA CF and FG types.

Finally, based on the compressive strength results presented in section 4.6.2, it was observed that the type of FRCA (i.e. crusher's fine or fully ground) had low influence on the results for DRM and EV mixes, but higher impact on the ones designed with PPM method. Mixtures proportioned with FRCA-FG aggregates yielded slightly better compressive results for the same water-to-cement ratio likely due to the fact that FRCA-FG presents less RCP attached to the particles, hence less limestone filler was added to the mixture. Therefore, the stress-strain relationship presented in Figure 4.15(b) validates two important factors observed throughout this experimental work.

First, the PPM-NS-FG presented higher modulus of elasticity than PPM-NS-CF mixtures, since the former one presents less RCP and thus ITZ in the particles when compared to CF. Second, although PPM mixtures demonstrated improved behaviour (i.e. stiffness of FRCA concrete) when compared to DRM and EV mixes, the SDT parameters (i.e. SDI and PDI) were not affected by the crushing process type.

4.7.3. Durability factor (DF) for freeze-thaw resistance

Figure 4.16 displays a summary of the durability factors (DF) obtained for each mixture after all the FT analyses previously discussed. This plot relates the three mix-design methods adopted in this research (i.e. DRM, EV and PPM) along with the type of FRCA used in the mixtures (i.e. crusher's fine – CF and fully ground – FG) and the initial aggregate's source selected (NS vs MS). Analyzing the results, one sees that PPM mixes yielded the best performance (all mixtures above 70%), followed by the EV (above 60%) and DRM (from 20 to 55%). No significant trend was observed while the use of different types of FRCA (i.e. CF or FG) and/or aggregate's sources (i.e. NS or MS). The latter may be attributed to the lower amount of total cement paste in the mixes designed with PPM and EV in comparison to DRM, since resistance to FT is very likely related to the inner porosity of concrete along with porosity of aggregates and cement paste.

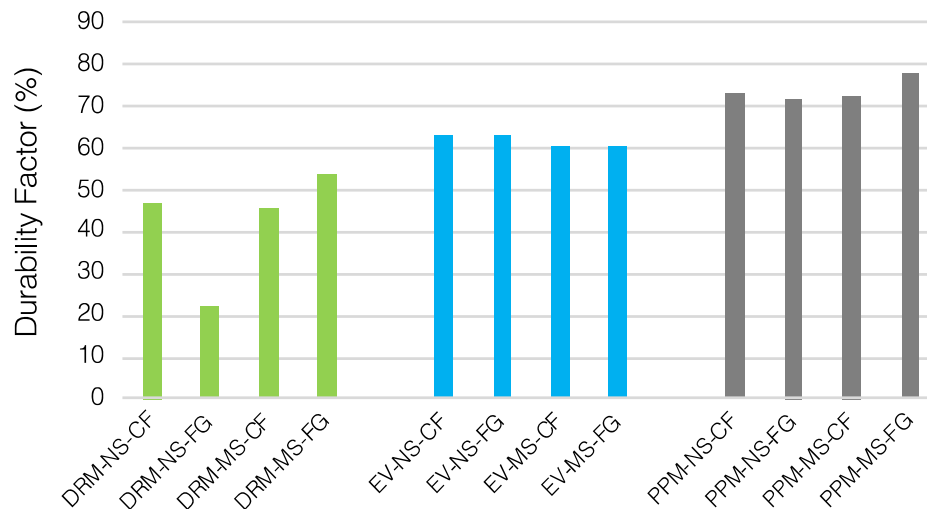


Figure 4.16: Summary of the DF of concrete mixes subjected to accelerated freezing and thawing cycles.

4.7.4. Efficiency of FRCA concrete mixtures

Portland cement (PC) industry is by far one of the main contributors related to the carbon footprint in the construction industry. Actually, there is a common misconception related to the cement content and strength of the final concrete, which is usually seen as a linear relationship between these two parameters. Although it is well-known that the compressive strength of CC can be predicted through the Abrams law (i.e. mixture w/c), some mixtures are still produced with high amount of cement content aiming the improvement of concrete compressive strength resulting in a non-eco-friendly material. In order to appraise concrete eco-efficiency, the binder index was proposed by Damineli *et al.* [72]. The index accounts for the amount of (binder (kg/m³) necessary to obtain one unit of any mechanical property, for example, 1 MPa of compressive strength at 28-days (Equation 4.5).

$$bi = \frac{BC}{f'_c} \quad \text{Equation 4.5}$$

In order to evaluate the overall performance along with the eco- efficiency of the FRCA mixtures studied in this work, a comprehensive assessment was conducted on all mixtures. Parameters such as *bi factor* (based on the f'_c), compressive strength and dynamic modulus of elasticity along with durability-related properties were selected for analysis (**Error! Reference source not found.**). The Portland cement content is also expressed in the plot and divided by 10 in order to fit the same scale as the other factors.

Analyzing the plot's data, one observes that mix-designing FRCA concrete with the PPM method seems to be very effective for producing eco-efficient concrete with superior mechanical and long-term performances yet reduced binder content. Amongst the FRCA mixtures, the PPM mixes presented considerable lower *bi* values (i.e. overall of 8.3 kg.m³.MPa⁻¹), followed by EV and DRM mix-designed mixes, respectively. Similar trends were also found for PC content, DF factor and modulus of elasticity. Otherwise, no significant overall difference was observed when considering the two distinct types of FRCA material used (CF or FG).

Finally, these results emphasize once more the promising character of using advanced mix-design techniques to proportion FRCA concrete such as PPMs and indicate that the mix-design method is more important than the crushing process on the performance of FRCA concrete.

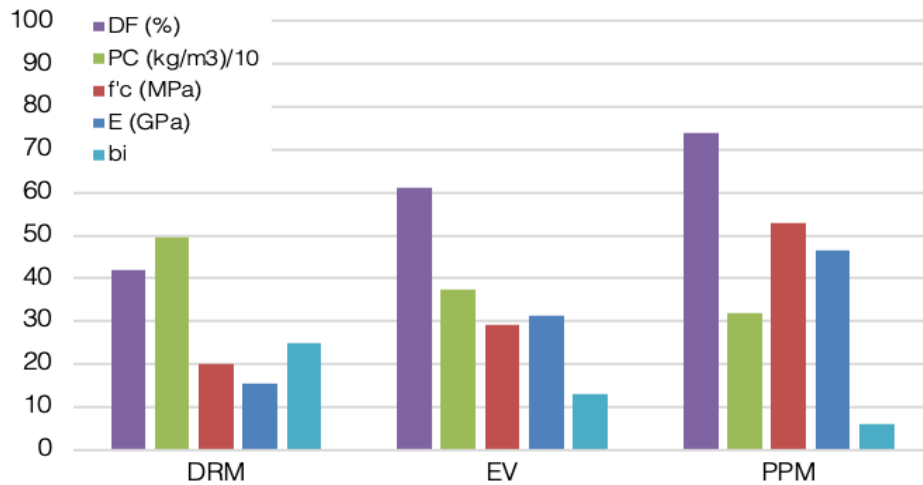


Figure 4.17: Comparison between mechanic and durability-related properties with cement content for the three FRCA mix-design methods studied in this work.

4.8. Conclusions

Three types of mix-proportioning techniques (DRM, EV and PPM) were used in this work to assess the mechanical and durability-related properties of FRCA concrete designed with 100% replacement of fine aggregates by fine recycled aggregates. Moreover, two aggregate sources were selected for this research: natural (NS) and manufactured sand (MS). After all the analyses, the main findings can be highlighted hereafter:

- The compressive strength, stiffness, and freeze-thaw resistance of FRCA mixtures demonstrated superior results through the use of both EV and PPM mix-design techniques which account for the different microstructure of FRCA material;
- The overall durability factor (DF) of all FRCA mixes subjected to freeze-thaw cycles was observed to have considerable variation between the mix-design methods rather than the type of FRCA (i.e. FC or FG). Higher DF factor was observed for PPM mixes, followed

by EV and DRM. This clearly demonstrates that the mix-design procedure adopted to design FRCA concrete is more important than the material's quality;

- The mixtures designed with DRM method demonstrated the worst mechanical and durability performance throughout this experimental work. Conversely, PPM mix-design method was deemed to be the most suitable procedure to mix-proportion eco-friendly concrete with 100% FRCA material. Through this method it was possible to mix-design low-cement content (i.e. about 300 kg/m³) concrete with superior mechanical properties along with suitable resistance to harsh environmental conditions such as freeze-thaw cycles;

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Chapter Five: Summary and Conclusions

Most of the research carried out on recycled concrete aggregates (RCA) has focused specifically on the use of coarse RCA (CRCA) for concrete, and thus a number of characterization and mix-design procedures can be retrieved in the literature for this type of recycled aggregate material. Nonetheless, there is still a considerable gap in literature available regarding the suitability of concrete mixtures incorporating fine recycled concrete aggregates (FRCA), particularly when full replacement ratio of fine natural aggregates by FRCA is considered.

In this experimental program, concrete mixtures containing 100% of crushed FRCA material were mix-proportioned through the use of two promising mix-design procedures (i.e. Equivalent Volume and Particle Packing Models), having their fresh (i.e. slump and rheological profiles) and hardened states (i.e. compressive strength, modulus of elasticity) assessed along with durability-related properties (i.e. non-destructive tests, stress-strain relationship and accelerated freeze-thaw tests). Chapter 3 discussed on the FRCA material characterization and performance of mixtures proportioned through the use of three method direct replacement methods (DRM), EV and PPM, highlighting PC content as low as 332 kg/m³. Chapter 4 followed with the durability-related properties and mix-design efficiency assessment presenting FRCA mixes with *bi values* of 25, 13.1 and 8.3 kg.m³.MPa⁻¹ for DRM, EV and PPM mixes, respectively. The main conclusions of this experimental program are presented hereafter:

Influence of FRCA production and physical properties

- The overall quality of FRCA material was observed to be dependent on the crushing technique adopted during the manufacturing process. For instance, simple stage crushing of concrete produces FRCA (i.e. FRCA crusher's fine) usually deemed of lower quality at some extent, resulting in coarser PSD, irregular shape, and high amounts of adhered RCP. Multistage crushing of production was observed to produce FRCA (e.g. FRCA fully ground type) with particle size distribution similar to natural aggregate, and presented less

residual cement paste attached to the particles due to further separation of mortar during crushing;

- Quantification of residual cement paste attached to FRCA particles correlates adequately with FRCA's manufacturing method. The more crushing stages involved in the process, more detachment of RCP will occur improving the overall quality of the material;
- Specific gravity and water absorption are also parameters that may define the quality of a given FRCA. Such properties are linked to the amount of residual cement paste which causes the matrix to be extremely porous and yields elevated water absorption capacity and lower specific gravity with high variation between SSD and OD conditions;
- Gap aperture size does not have a significant influence on the particle size distribution, but rather affects the amount of powder material produced during crushing;

Mix-design efficiency

- It was possible to mix-proportion eco-efficient concrete with 100% FRCA material with superior performance yet having overall binder efficiency as low as $8.3 \text{ kg.m}^3.\text{MPa}^{-1}$ (i.e. PPM mixes).

Fresh state behaviour

- Fresh state properties of FRCA mixtures proportioned through the optimized EV and PPM methods demonstrated acceptable performance with the emphasis on PPM mixtures, which yielded better performance regarding rheological parameters (i.e. minimum torque required, lower viscosity and possibility of pumping applications);
- The distinct FRCA materials by crushing method (i.e. crusher's fine – CF, or fully ground – FG) seems to have low or almost no impact on the behaviour of fresh state FRCA mixtures.

Hardened state performance

- Interesting hardened state properties (i.e. compressive strength and stiffness) were achieved with the use of both EV and PPM techniques. The DRM method yielded, in general, the worst performance obtained in this work;
- The type of FRCA (i.e. CF vs FG) was observed to have low impact on the compressive strength of DRM and EV mixes, and a more significant one on the PPM-mix proportioned mixtures. In general, FRCA with FG type aggregate yielded better strength results for the same w/c ratio. The latter is likely due to the fact that FRCA-FG is comprised of less RCP adhered to the surface of the particles besides being more angular in shape;
- It was observed that an increase in binder content does not necessarily reflect an increase in mechanical properties. Among all FRCA mixes, the ones mix-designed with PPM method yielded the highest 28-day compressive strength (i.e. nearly 53 MPa) while presenting average low binder content (i.e. less than 335 kg/m³);

Durability-related properties

- In fact, mixtures designed with the DRM method demonstrated the worst mechanical and durability performance throughout this experimental work. Nevertheless, PPM method of mix-design was deemed to be the most suitable procedure to mix-proportion eco-friendly concrete with 100% FRCA material. Through this method it was possible to mix-design low-cement content (i.e. about 300 kg/m³) concrete with superior mechanical properties along with suitable resistance to harsh environmental conditions such as freeze-thaw cycles;
- The overall durability factor (DF) of all FRCA mixes subjected to freeze-thaw cycles was observed to have considerable variation between the mix-design methods rather than the type of FRCA (i.e. FC or FG). Higher DF factor was observed among PPM mixes, followed by EV and DRM. This clearly demonstrates that the mix-design procedure adopted to design FRCA concrete can be more consistent than the material's quality;

- Even though both the aggregate's type (NS vs MS) and crushing process (CF vs FG) play an important role on the overall FRCA quality (CRP content, particle's shape, etc.). Yet, the results obtained from durability-related tests clearly demonstrated that even more important than the recycled material's features and inner quality is the mix-design procedure adopted to make FRCA concrete.

Chapter Six: Recommendations for Future Work

After conducting this experimental program, further investigations can be drafted, as presented hereafter:

- Microscopic analysis need to be assessed considering disntinct FRCA concrete mixes through the use of both EV and PPM methods in order to investigate the different failure mechanisms of FRCA concrete, specially when subjected to harsh environmental conditions. This would propose valuable remarks on the mechanical and durability-related properties of FRCA mixes against CC mixes as well as potential improvements on the EV mixes;
- An in-depth evaluation of the impact of FRCA aggregate features (i.e. shape, texture and hardness) on the properties of FRCA mixes;
- Further analysis of FRCA concrete's microstructure may be investigated under the scanning electron microscope (SEM);
- Development of a protocol for quality control procedures in FRCA mixes designed with PPM mix-design method;
- Include additional parameter for binder index (bi) evaluation such as "RCA Index" or "FRCA Index" and maybe correlate it with durability factor (DF).

Appendix A: EV Mix-Design Calculations

This section demonstrates in practice the mix-design procedure according to the optimized Equivalent Volume Method for FRCA concrete.

- 1) The first step is to mix-design a conventional concrete (CC) mix that will be used as the control mix. The final CC mix shall be presented in unit basis (in mass);

Table A-1: Conventional Concrete Proportions

Conventional Concrete				
Mass	Specific Gravity	Volume compounds ₁	Volume Paste ₂	Volume Aggregates
1	3.13	0.32	0.67	1.31
1.36	2.67	0.51		
2.22	2.78	0.80		
0.35	1.00	0.35		
Total		1.98	1.98	

Where the volume compounds₁ are the mass proportions divided by the specific gravity of each material, and the volume paste₂ is simply the summation of cement and water;

- 2) Next, knowing the residual cement paste content (% RCP) from lab measurements, the residual fine aggregate content (RFA) value may be calculated as 100-RCP;

Table A-2: RCP and RFA Inputs

RCP (%)	RFA (%)
15.5	84.5

- 3) The third step is to gather the specific gravity values for the aggregates used in the mix; i.e. FRCA and coarse aggregate (CA) ;

Table A-3: Specific Gravity Inputs

Measured Specific Gravity	
SSD (FRCA)	2.53
SSD (CA)	2.80

- 4) The main concept of the EV is that the FRCA concrete has to have the same amount of both cement paste and aggregates in volume than the reference concrete (CC), as shown in the equations below. In this case, since 100% FRCA is being used, and knowing that FRCA is comprised of both residual sand and residual cement paste (RCP), the portion of residual sand is considered in the mix (e.g. number 6 from Table A-4) in order to match the total volume of aggregates with the CC mix. Additionally, the new and old cement in the FRCA mix are calculated and their summation is matched to the amount of cement (in unit basis) in the CC mix (e.g. the sum of 1+2 from Table A-4) as shown below:

$$V_{CP}^{FRCA-concrete} = V_{CP}^{CC}$$

$$V_{Ag}^{FRCA-concrete} = V_{Ag}^{CC}$$

Where: $V_{CP}^{FRCA-concrete}$ is the total volume of paste in the FRCA mix; V_{CP}^{CC} and V_{Ag}^{CC} are the cement paste and aggregate volumes (both fine and coarse), respectively, in the reference CC mixture; $V_{Ag}^{FRCA-concrete}$ is the total volume of both coarse and fine aggregates in the FRCA mix, being the volumetric summation of new aggregate (e.g. NA: coarse limestone) and the original virgin aggregate (e.g. OVA: residual sand) in the FRCA mix.

- 5) Since we do not have the specific gravity of the residual cement paste as it has not been measured in the lab, and we need this value to estimate the materials proportions of FRCA concrete, the specific gravity value for the RCP should be estimated, as shown in Table A-4 (e.g. 5 – RCP and 7 – RCP supp FA). Therefore, once this value is properly estimated, the measured specific gravity value of FRCA should match with a theoretical value as shown in Table A-5;

Table A-4: Calculated Supplementary Amounts of Materials (FRCA, Cement, RCP and Natural Aggregates)

RCA Concrete					
	Mass RCA	Specific Gravity	Volume compounds	Volume Paste	Volume Aggregates
¹ New cement added	0.83	3.13	0.26	0.67	1.31
² Old cement	0.17	3.13	0.06		
³ Coarse aggregate	2.22	2.78	0.80		
⁴ FRCA	1.15	2.67	0.43		
⁵ RCP	0.21	0.50		0.08	1.00
⁶ Residual sand	0.21	2.67	0.08		
⁷ RCP supp FA	0.01	0.50			
Water	0.35	1	0.35	RCA paste	RCA aggregates
Total			1.98	0.67	1.31

Table A-5: Specific Gravity Inputs

Specific Gravity			
Measured (FRCA)	Theoretical (FRCA)	Residual Fine Aggregate (RFA)	Residual Cement Paste (RCP)
2.32	2.32	2.26	0.06

Where the specific gravity of RFA is defined as $RFA\% \text{ (from Table A-2)} \times FRCA4 \text{ (from Table A-4)}$, and for the RCP as $RCP5 \times RCP\% \text{ (from Table A-2)}$.

- 6) Once all the specific compounds are calculated from the previous steps, it is now possible to calculate the materials proportions in mass for the FRCA mix as shown in Table A-6;

Table A-6: FRCA Mix Proportions in Mass

FRCA Mix Proportions	
Cement	1.0
FRCA	1.9
Coarse	2.7
Water	0.35

Where, in unit basis, the cement is the summation of new¹ and old² cement; the FRCA is based on the summation of all the FRCA and its supplementary compounds (e.g. items 4, 5, 6 and 7 from Table A-4).

- 7) Finally, converting the unit basis mix proportions to mass, one obtains the following FRCA mix-design proportions according to the optimized EV method:

Table A-7: Mix Proportions in Mass

Final FRCA Mix-Design		
	Unit	kg/m³
Cement	1	374
FRCA	1.9	714
Coarse	2.7	1005
Water	0.35	131