Contribution to the Understanding of the Rheological Behaviour of Recycled Concrete Aggregate Mixtures Made of Coarse and Fine Particles

By

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Abstract

The use of recycled concrete aggregates (RCA) has gained increased attention in the past few decades as an alternative to decrease the carbon footprint of concrete construction. Yet, most of the research performed so far demonstrates that RCA concrete displays inferior performance in the fresh and hardened states when compared to conventional concrete (CC). The latter is believed due to the fact that very often the different microstructure of RCA is not accounted for while the mix-proportioning of RCA concrete.

Recently, a number of mix-design procedures accounting for RCA microstructure have been proposed. Amongst them, the Equivalent Volume (EV) method seems to be quite promising. The EV method may proportion RCA concrete made of coarse (CRCA) or fine (FRCA) RCA and is based on a companion CC. Previous research has demonstrated that the fresh and hardened properties of EV mix-designed CRCA are suitable for structural applications. Yet, very few research, analysis and quantification have been conducted on the fresh behaviour of EV mix-proportioned FRCA concrete. This work presents a comprehensive study on the rheological behaviour of EV mix-designed CRCA and FRCA concrete presenting distinct features (i.e. inner qualities, mineralogy, fabrication process, etc.) through the use of a planetary rheometer (IBB). Results show that the EV is capable of proportioning low embodied energy CRCA and FRCA concrete with shear thinning profiles. The latter suggests that these mixtures are suitable for applications under high torque regimes such as vibrated or pumped concrete.

Keywords: Recycled concrete aggregate (RCA), Coarse recycled concrete aggregate (CRCA), Fine recycled concrete aggregate (FRCA), Residual mortar (RM), Residual cement paste (RCP), Equivalent volume (EV), Rheological behaviour, Yield stress, Apparent viscosity (AV)

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List of Symbols/Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
AEA	Air Entraining Agent
AV	Apparent Viscosity
Bi	Binder Intensity
CC	Conventional Mix
CF	Crusher Fines
CRCA	Coarse Recycled Concrete Aggregate
CSA	Canadian Standards Association
CO_2	Carbon Dioxide
CWD	Construction Demolition Waste
ER	Electrical Resistivity
EV	Equivalent Volume
EMV	Equivalent Mortar Volume
EMV-mod	Modified Equivalent Mortar Volume
f'_c	Concrete Compressive Strength
FG	Fully Ground
FRCA	Fine Recycled Concrete Aggregate
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
MS	Manufactured Sand
N	Flow Behaviour Factor
NA	Natural Aggregate
NS	Natural Sand
OD	Oven-Dry
OVA	Original Virgin Aggregate
PC	Portland Cement
PPMs	Particle Packing Models
PSD	Particle Size Distribution
RCA	Recycled Concrete Aggregate
RCP	Residual Cement Paste
RP	Residual Paste
RM	Residual Mortar
SCMs	Supplementary Cementitious Materials
SSD	Saturated Surface Dry
TM	Total Mortar
w/c	Water-to-cement
Γ	Rotation
P	Fluid Density
T	Torque
τ_o	Yield Torque

1. Introduction

1.1 General

Concrete is the most widely used construction material with aggregates (i.e. coarse and fine) and Portland cement (PC) being its major constituents. PC production is the largest source of CO_2 emissions from decomposition of carbonates and has rapidly increased after world war II, especially in developing countries such as China [1]. Furthermore, the global aggregate's demand has also doubled from 21 billion tons in 2007 to 40 billion tons in 2014. In summary, the production of new concrete produces approximately 7% of global CO_2 emissions [2].

Besides the use of PC and aggregates for new construction, it has been found a significant increase in construction waste (i.e. returned concrete - RC and or construction demolition waste - CDW), which is often managed as waste for landfill [3], being another major issue currently faced by the construction industry [4]. With the scarcity of landfills and its inevitable and related pollution, an effective alternative is required [5].

The re-use of construction waste, either RC or CDW, has the potential to reduce carbon footprint and thus produce eco-friendly materials. Due to the inevitable increase in demand and natural resources depletion, studies on reducing carbon footprint by incorporating recycled concrete aggregate (RCA) in new concrete is gaining popularity over the past few decades. Yet, a number of issues in the fresh state along with uncertainties in the long-term behaviour of RCA concrete prevents its use in a daily basis. The primary focus of this research is to evaluate the fresh and hardened state performance of RCA concrete incorporating distinct aggregate types (fine or coarse recycled) and natures (mineralogy), designed through distinct mix-design procedures, and made of RC (i.e. materials crushed after hardening at the concrete plant and re-used in new concrete) [6].

1.2 Research on Recycled Concrete Aggregate (RCA)

RCA is often reported as an inferior material when compared to natural aggregates due to its negative impact on the fresh and hardened state performance of RCA concrete [7–10] as well as long term properties like creep and shrinkage [11,12]. The latter is believed to happen due to the use of conventional mix-design techniques, the so-called direct replacement methods (DRM); in

DRM approaches, RCA is adopted in the same way as a natural aggregate (NA), without any further consideration such as the measurement of the residual mortar (RM) content of the RCA particles. Literature presents a wide range of data where RCA concrete designed through DRM displayed inferior mechanical properties such as lower compressive strength and stiffness (i.e. modulus of elasticity) than conventional concrete (CC) [10]; yet, similar or even better performance than CC can be achieved when lower w/c is selected to mix-design RCA mixtures. It is also reported in most of the studies that the fresh state performance (i.e. rheological properties) of RCA concrete has decreased with the increase of RCA in the mix. [13]. Hence, it is important to account for the inner features of the RCA while proportioning RCA concrete.

RCA is a multi-phase material comprised of original virgin aggregate (OVA) and residual mortar (RM) [14]. If RCA concrete is proportioned through DRM procedures, the RM adhered to the particles will not be accounted for and thus the final recycled mix will have higher volume of cement paste (and lower volume of aggregates) when compared to a companion CC. Trying to fix this issue, Fathifazl et al. developed a new mix-proportioning approach, the so-called *Equivalent Mortar Volume (EMV)* [6]. The primary idea of the EMV is to proportion an RCA concrete presenting the same amount of coarse aggregates and mortar than a companion CC [6]. RCA concrete proportioned through the EMV usually presents, not only volumetric match to CC, but also similar (or even improved) behaviour in the hardened state. However, EMV mix-designed RCA concrete often experiences some issues in the fresh state and thus moderate to high amounts of PC and chemical admixtures are required to make workable recycled mixes. The latter may offset in some cases the eco-friendly character of using RCA concrete.

The limitation of EMV mixtures in the fresh state triggered the development of two mix-design approaches: a) the modified EMV as per Hayles et al. [15] and, b) the *Equivalent Volume (EV) method* as per De Souza et al. [16]. While the modified EMV aimed to let the designer to select the sand-to-cement ratio of the mortar and thus select the percentage of PC to be accounted for in the RM, the EV aims to proportion RCA mixtures that present the same amount of paste and aggregates (in volume) when compared to companion conventional concrete mixes. Preliminary research has demonstrated that both the modified EMV and EV methods may solve, at least partially, some of the fresh state issues faced by RCA concrete. Furthermore, the EV method may be utilized to proportion RCA concrete made of coarse (CRCA) and fine (FRCA) recycled aggregates, although very little research was conducted on FRCA to date. Thus, comparisons between performance of CC and EV mix-proportioned recycled mixtures made of returned concrete and incorporating different RCA types (fine and coarse), natures (lithotypes) and qualities (residual mortar strength) in the fresh and hardened states are still lacking and need to be addressed.

1.3 Objectives and Scope of the work

In this work, the EV method as per De Souza et al. [16] will be further appraised to mix-proportion CRCA and FRCA made of returned concrete presenting distinct features. Comparisons between the fresh and hardened state performance of recycled mixtures proportioned with the above technique will be compared to conventional concrete. Overall, this work aims to understand the influence of the aggregate type (manufactures vs natural sand), crushing procedure (i.e. crushers fine vs fully ground) and mix-design technique (i.e. EV) on the fresh state behaviour (slump and rheological profile) of FRCA mixtures.

It is worth noting that both fine and coarse RCA were produced in the laboratory and thus they both simulate a “returned concrete” produced at a concrete plant. They were fabricated and moist cured over 28 days, being crushed and sieved afterwards.

1.4 Overview of the thesis

The current document is a paper-based Thesis composed of five chapters as follows. Chapter 1 illustrates the introduction of the project and states about Portland cement and aggregate production with their impacts on environment, advantages of RCA, scope and objective of the current research.

Chapter 2 provides a detailed literature review representing the studies conducted on coarse and fine RCA, challenges of mix-proportioning RCA and promising mix-design techniques for improved fresh and hardened state performance.

Chapter 3 is a scientific paper and is prepared in a journal format. It will be submitted for publication after the Thesis completion. This chapter has its own literature review, scope of the work, materials and methods and conclusion sections and thus some duplications with the Thesis sections might happen. The paper discusses the rheological behaviour of CC mixtures designed through ACI method and CRCA and FRCA mixtures designed through EV mix-design method.

Chapter 4 presents a summary and conclusion of the experimental work performed and Chapter 5 suggests further studies still required in the field.

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2. Literature Review

2.1 Recycled concrete aggregate (RCA)

Recycled material is essential in this modern era due to increasing demand of natural aggregates and diminishing resources [1,2]. In addition, recycled concrete aggregate (RCA) has potential for sustainable future with environmental and economical benefits [3–6]. However, most of the studies on RCA have observed inferior performance of recycled mixes for fresh and hardened properties [2,7–16]. Therefore, utilizing knowledge of materials microstructure there is urgency for advanced mix designs to enhance performance of recycled mixes.

Pressure is mounting in the construction industry to reduce its carbon footprint. Recycled concrete aggregates (RCA) has gained increased attention in the past decades as an alternative for a greener future of concrete construction. RCA may be obtained from two sources: Construction and Demolition waste (CDW) and Returned concrete (RC). CDW is a major source of RCA generated in large volume due to inevitable reasons (i.e. new construction, natural disaster and deterioration of structure), concrete structures are demolished well before their service life [17]. Environmental Protection Agency (EPA) of U.S has reported a considerable increase of CDW production, which raised about 20 million tons from 2012 to 2014 [18]. The second source of recycled aggregates is RC which is concrete returned to plant due to an issue such as, overestimated quantity, unprepared site conditions or unattained the required specification. To produce RCA, RC is crushed after hardening and separated based on the particle size distribution required on the standard. Although it is a minor source of RCA, RC occupies considerable space; hence, it is a major concern for concrete plants. From a report, the estimated RC varies from 1% to 10% of the concrete delivered to site [19]. Higher return volumes are often reported from projects with broad specifications and placement requirements or challenging delivery schedules. In such cases, managing RC is difficult as the amount of RC is generally unpredictable [19]. In 2006, the estimated RC was around 5% out of 348 million cubic meters of concrete produced and supplied by ready mix concrete (RMC) plants in U.S [20]. By crushing the hardened RC discharged in the concrete plant, around 30 million tons/year of RCA can be produced [20].

RCA can be further classified based on its particle size distribution. Coarse recycled concrete aggregates (CRCA) are RCA containing particle larger than 4.75 mm, while fine recycled concrete aggregates (FRCA) are produced from the fine portion of the RCA (i.e. <4.75 mm). Although during the production of CRCA a small portion of FRCA is also manufactured, most of the previous studies are focused on CRCA. Moreover, in order to investigate the fresh and hardened state performance of CRCA concrete mixtures, conventional mix-design methods are normally used replacing the coarse aggregate by a percentage of CRCA [2,3,7,8,10,21–23]. Since on this methods the CRCA is considered as a one-phase material (similar to the natural aggregate), the studies concluded that CRCA concrete mixtures present an inferior performance in the fresh and hardened states when compared to conventional concrete (CC) [4,7,8,24–28]. As a result, RCA is normally labelled incorrectly as an inferior material. Nevertheless, RCA is a multi-phase material comprised of residual mortar (RM) adhered to original virgin aggregates (OVA) as shown in Figure 2.1. When using conventional mix-design for manufacturing RCA concrete, the total mortar volume increases due to existing RM in RCA. This increases the amount of weaker and porous interfacial transition zones (ITZ) in concrete, while reducing the volume of natural aggregates when compared to a CC. Hence, to produce CRCA concrete mixtures with suitable performance, two steps must be followed: 1) proper characterization of CRCA to quantify the amount of RM and; 2) use of advanced mix-design techniques for RCA concrete mixtures to avoid increasing of overall mortar.

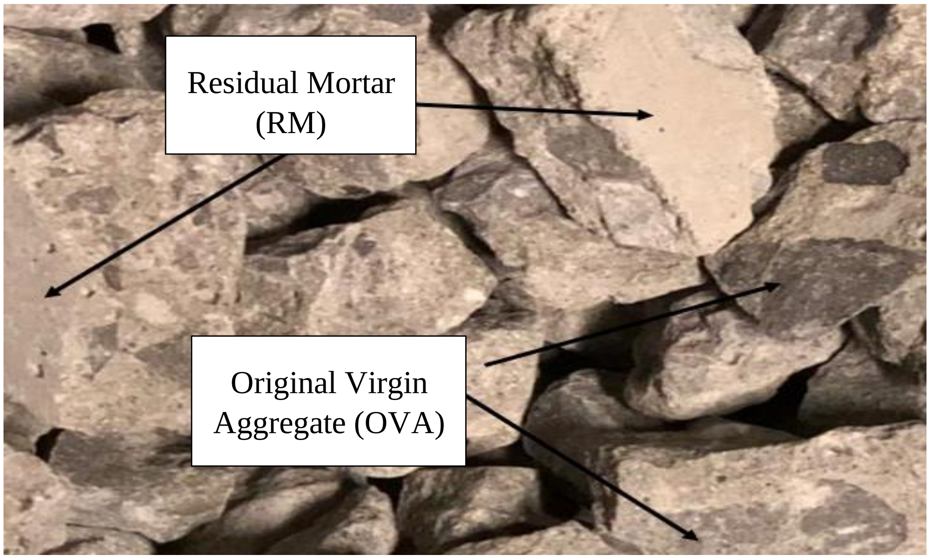

Figure 2.1: Residual mortar attached to OVA in RCA

Although a number of studies have focused on CRCA concrete, very few researches has investigated FRCA [12,26,29–31]. Similar to CRCA, FRCA concrete is also reported as a low-quality material due its inferior fresh and hardened state performance [9,27,31–33]. This occurs due to two main reasons. First, FRCA is treated as a one-phase material and no proper characterization is performed to quantify the amount of residual cement paste (RCP) attached to the OVA. Second, simple replacement methods are used, leading to lower performance of FRCA concrete mixtures.

2.1.1 Residual mortar (RM) and Residual cement paste (RCP)

As mentioned before, the multi-phase CRCA consists of OVA and RM which changes CRCA microstructure when compared to natural aggregates [34–36]. It is important to quantify the amount of RM as it affects the specific gravity and water absorption capacity of CRCA. To quantify RM, standard test protocols such as the soundness test as per ASTM C88 [37] were mainly used. However, Abbas et al. have further investigated and developed a modified version to quantify accurately the RM amount. The test procedure involves soaking of weighed sample of CRCA in 26% by weight solution of sodium sulphate. The soaked sample is subjected to five cycles of freeze and thaw (i.e. 16 h at -17_0 C in a freezer and 8 h at 80_0 C in oven) to dissolve the attached RM in solution. The mass loss is accounted as the percentage of RM, which can be calculated by Equation 2.1 The amount of RM may be up to 60% of total volume of CRCA and it is related to type and physical properties of OVA and inner characteristic of RM [4].

$$\mathrm{RM\%} = \left(\frac{Wrca-Wova}{Wrca}\right) \mathrm{x}\ 100 \qquad \text{Equation 2.1}$$

Where: Wrca = oven dry mass of RCA before immersing in solution and Wova = final oven dry mass after draining residual mortar from RCA.

In FRCA, RCP consists of deleterious amount of cement paste attached to natural aggregates (NA) during manufacturing process. The highly porous RCP yields different properties to FRCA when compared to NA such as lower density, higher absorption and inferior hardened state properties [38]. RCP can be quantified using soluble silica sub-procedure provided by ASTM C1084-15 [39] and C114-18 [40]. A sample of 2.5 g of each produced FRCA was used for RCP analysis. FRCA produced by crushing of returned concrete often has significantly low RCP content (11%-17%) [41].

2.2 Mix design methods for RCA concrete

For proportioning CRCA concrete mixes, ACI–555R [42] provides guidelines to choose CRCA with desirable qualities. Yet, a standard mix-design method for CRCA concrete is not provided [6,43]. An advance mix-design technique for RCA, the so-called Equivalent Mortar Volume (EMV), was developed to consider the RM content of CRCA and treat it as a multi-phase material [43]. When the distinct microstructure of CRCA is considered to develop the mix-design, interesting results are found in hardened state similar to CC mixes [44–46]. Yet, very few researches are using advanced mix-design techniques to develop FRCA concrete mixtures [41].

2.2.1 Equivalent mortar volume (EMV) method

Equivalent Mortar Volume (EMV) was proposed to mix-design RCA concrete mixtures overcoming the issues found on replacement methods [34,43]. The primary idea behind this method is to have the same volume of mortar in new concrete (new mortar + residual mortar) when compared to a conventional mix [43] as shown in Figure 2.2. This technique helps to fabricate RCA concrete with constituent ingredients similar to CC. Equation 2.2 and Equation 2.3 represents the conditions of EMV method to be satisfied to mix design coarse RCA mixes.

$$V_{\text{TMRCA-concrete}} = V_{\text{RMRCA-concrete}} + V_{\text{NMRCA-concrete}} \qquad \text{Equation 2.2}$$

$$V_{\text{TNARCA-concrete}} = V_{\text{OVARCA-concrete}} + V_{\text{NARCA-concrete}} \qquad \text{Equation 2.3}$$

Where: $V_{\text{TMRCA-concrete}}$ is volume of total mortar in RCA concrete; $V_{\text{RMRCA-concrete}}$ is volume of residual mortar in RCA concrete; $V_{\text{NMRCA-concrete}}$ volume of new mortar in RCA concrete; $V_{\text{TNARCA-concrete}}$ is volume of total natural coarse aggregate in RCA concrete; $V_{\text{OVARCA-concrete}}$ is volume of original virgin coarse aggregate in RCA concrete and $V_{\text{NARCA-concrete}}$ is volume of new coarse aggregate in RCA concrete.

Previous studies show that when RCA concrete mixtures were developed through EMV, its hardened state performance was similar to companion CC mix [34,43,45]. Yet, fresh state of EMV mixtures is compromised and indicated the need of higher amounts of cement and chemical admixtures, which completely offsets the eco-efficient behaviour of RCA [34,43,45]. Moreover, it is worth noting that EMV was created only for CRCA mix design [43] and no attempt has been made to date to mix design FRCA concrete. Furthermore, since this method was developed to account for RM, the amount of CRCA that can be incorporated in the recycled mixture may be lower than 100%; the latter is dependent on the amount of RM adhered to CRCA particles. Therefore, novel mix proportioning method was required to improve drawbacks of EMV and produce eco-friendly RCA mixes.

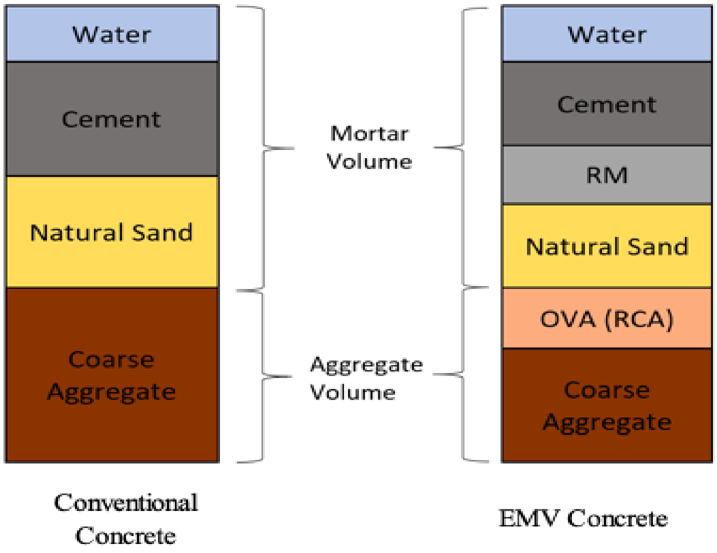

Figure 2.2: Volumetric comparison of EMV concrete with its conventional concrete mix, adapted by Ahimoghadam et. al. [45].

2.2.2 Modified-Equivalent mortar volume (EMV-mod) method

In order to improve the fresh state properties faced by EMV, especially with low cement content, a modification to EMV (EMV-mod) was proposed by Hayles et. al. [44]. This method introduced an additional factor to optimize the "cement-to-sand mass ratio" of RM, allowing appropriate proportioning of cement to be accounted for in the mixture. As expected, improved fresh state was observed for the RCA mixtures designed by EMV-mod [44]. However, the cement efficiency was decreased to achieve a targeted strength similar to mixes designed by the EMV method [44].

2.2.3 Equivalent volume method (EV) method

The Equivalent Volume (EV) method was later proposed by Ahimoghadam et al. to enhance the fresh state performance of RCA concrete without compromising the benefits of EMV and EMV-mod [45]. Similar to the two previous method, the RM must be quantified to properly account for the RCA microstructure. However, its primary objective is to mix proportion RCA concrete with the same volume of cement paste (CP) and total aggregates (i.e. fine + coarse aggregates) than a companion CC (Equation 2.4 and 2.5). This concept is the main difference between the EV and EMV method. Therefore, the total volume of CP in EV mixture is described as summation of Residual Paste (RP) and fresh paste (FP).

$$V_{\text{CPRCA-Concrete}} = V_{\text{CPCC}} \qquad \text{Equation 2.4}$$

$$V_{\text{AgRCA-Concrete}} = V_{\text{AgCC}} \qquad \text{Equation 2.5}$$

The fresh state behaviour of RCA mixtures designed through the EV method is enhanced as the amount of coarse aggregates is reduced and the amount of fine aggregates is increased. However, very few research has been conducted on the rheological behaviour of coarse and fine RCA concrete designed by EMV and EV method. Although all these three RCA mix-design methods were developed for CRCA, the later one (EV method) has recently been adapted and now is able to also proportion FRCA concrete [41]. After the quantification of RCP, it is possible to produce FRCA concrete mixtures with up to 100% of FRCA based on the EV method. Following the conditions of equivalence from Equation 2.4 and Equation 2.5, FRCA mixtures are produced with constituents proportioned as illustrated in Figure 2.3.

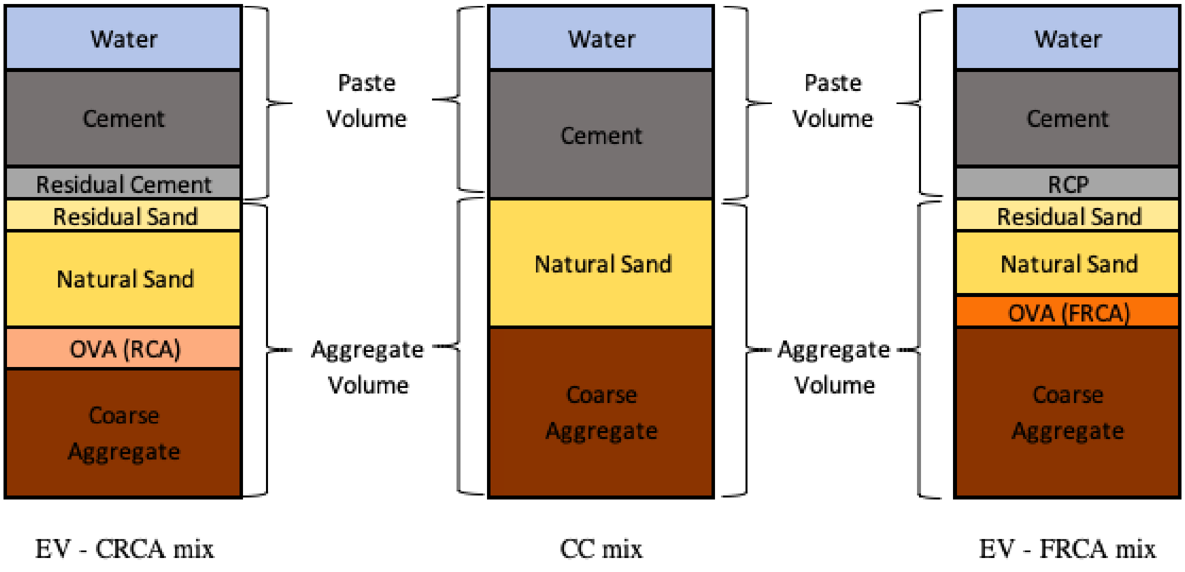

Figure 2.3: Volumetric comparison of CC with EV-CRCA and EV-FRCA mixture proportion.

2.3 Properties of Recycled Concrete

The state-of-the-art about the fresh state (i.e. rheology) and mechanical performance of RCA concrete is presented hereafter:

2.3.1 Fresh state behaviour

The fresh state is one of the main challenges of RCA concrete mixtures. Although slump is the main test performed to appraise the fresh performance of concrete mixtures, it is only a single-point test. Instead, rheometers are used to fully describe the concrete fresh state behaviour and rheological profile [47]. Rheology is defined as the science that characterizes flow and deformation of fluids using fundamental principles of shear stress and shear rates [48]. Using rotational rheometers, the shear stress and shear rate can be obtained from any type of concrete (not limited to self-compacting or highly flowable mixtures) enabling the evaluation of the concrete rheological profile. Concrete mixtures may display six distinct types of rheological profile, as represented in Figure 2.4, which can be divided into two main groups: a) fluids with no yield stress and, b) fluids with yield stress different than zero. Yield stress represents the minimum amount of energy (i.e. torque) required to enable the mixtures' flow. Self-consolidating concrete is an example of mixtures with no yield stress, whereas vibrated concrete falls into the second group. Moreover, the slope of the shear stress versus shear rate curve represents the viscosity of the fresh mix. When the viscosity does not change as a function of the shear stress applied, the fresh mix is classified as Newtonian (Group A) or Bingham (Group B). Furthermore, fresh mixtures may also be classified as shear-thinning or shear-thickening whether their viscosity decreases or increases as a function of the shear stress applied, respectively.

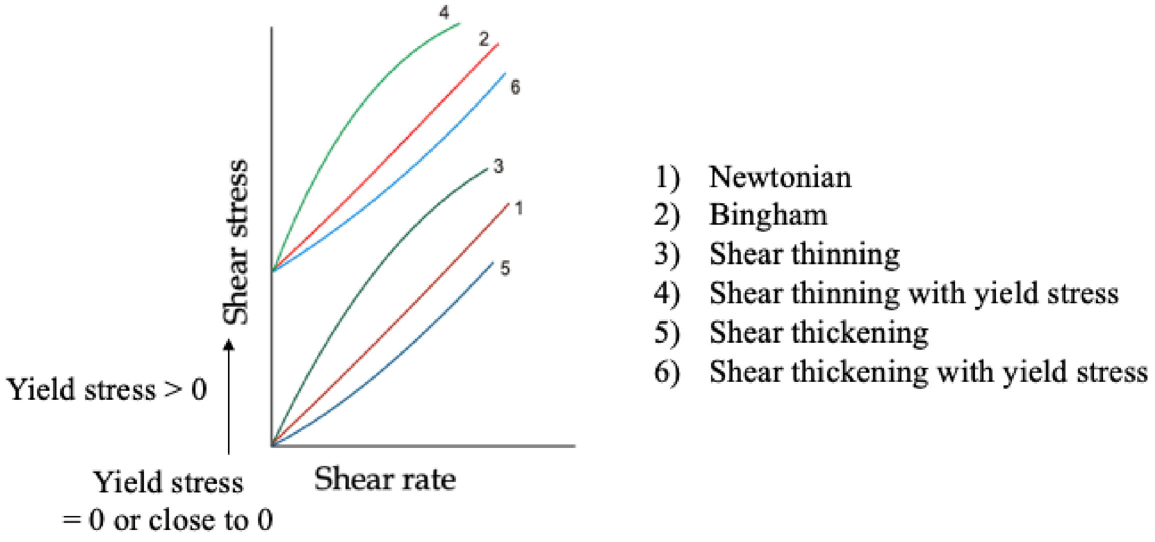

Figure 2.4: Types of time-independent rheological behaviour of concrete [47].

Several rheological parameters (e.g. viscosity, hysteresis area, maximum and minimum torque) can also be calculated based on rheology tests. It is worth noting that these parameters are influenced by distinct factors such as water to cement (w/c), aggregate angularity, gradation, packing of particles, and surface texture.

The rheological behaviour of RCA concrete also depends on the RM attached which is very irregular and rough, and may jeopardize the material’s flowability [49]. Barra et. al. investigated the performance of CRCA and FRCA self-compacting concrete (SCC), designed through conventional methods. The CRCA SCC presented a shear thickening behaviour (i.e. an increase in viscosity as the shear rate increases), which may compromise the performance of the material in the field. Conversely, the FRCA SCC presented a better flow behaviour, throughout the whole shear stress - shear strain spectrum [50].

Rheological studies on EMV proportioned mixtures (i.e. RM is accounted for in the mix-design), showed increase in the plastic viscosity for low and high torque regimes when compared to CC mixes. This can be explained by the higher amount of coarse aggregates involved in the system with RM, which affects negatively the fresh state of the material [51]. According to Faleschini et. al., RCA concrete mixes designed through EMV with 35% of replacement of NA showed lower slump and the yield stress was increased by 50% when compared to CC [3]. Furthermore, to decrease the plastic viscosity and achieve similar behaviour to CC, the dosage of superplasticizer has been increased from 1% to 1.7% [3].

2.3.2 Mechanical performance

Mechanical performance of RCA concrete mixes should also be appraised to ensure desirable requirements for structural applications. The two most important mechanical properties are the compressive strength and modulus of elasticity. Literature shows variable results on compressive strength [7,9,52,53] and elasticity modulus [7,54,55] depending on the mix-design adopted and whether the RM is considered or not. According to Tam et al. the compressive strength depends on strength of the original concrete and the quality of the interfacial transition zone (ITZ) [6]. Furthermore, when conventional mix-design techniques are used, the CRCA concrete presents lower modulus of elasticity [7,54,55], which occurs due to the presence of unquantified residual mortar (RM). Based on Kaigama et. al. work, the 28-day compressive strength of 100% CRCA concrete was reduced by 53% compared to its control mix [2]. However, for replacement ratio up to 30%, the compressive strength of CRCA are equal to CC mixes [2,7,13,31,52,53]. In terms of advanced mix-design techniques (i.e. EMV, EMV-mod and EV) which account for the RM content, the hardened state properties of CRCA concrete mixtures are similar or even better than the CC mixes [43–45]. Similar trend is observed for FRCA mixtures; yet, when direct replacement methods are used, the compressive strength also decreases while drying shrinkage increases [13]. However, 100% FRCA mixes designed through EV method yielded the target compressive strength [41]. The above results suggest that mechanical properties of RCA mixtures may be somehow controlled whenever proper proportioning is performed. However, the fresh state ability of recycled mixtures is still unknown.

2.4 Concrete eco-efficiency

Portland cement (PC) is the concrete component with the highest contribution to its carbon footprint [56]. The increasing demand of PC at alarming rate has led researchers to cogitate and reduce the binder content of concrete mixtures. To better quantify the eco-efficiency of concrete mixtures, Damineli et. al. [57] proposed an index called *Binder Intensity* (bi), that calculates the amount of binder required per 1 desired unit of performance (e.g. PC required in kg/m^3 for 1 MPa of compressive strength at 28 days; Equation 2.6)

$$bi = \frac{B}{CS} \qquad \text{Equation 2.6}$$

Where, B is amount of binder in kg/m^3 and P is performance of concrete (e.g. compressive strength in MPa).

It was highlighted that concrete having high compressive strength (>50MPa) result naturally in lower bi factor. However, conventional concrete used in civil infrastructure (20-40 MPa), which represents over 90% of concrete’s use worldwide, are considered less eco-efficient due to its high bi factor (10-12 kg m^{-3} MPa^{-1}). Therefore, efforts to decrease the carbon footprint of conventional concrete are still required [57].

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3. Rheological Behaviour of Recycled Concrete Aggregate (RCA) Mixtures Proportioned by the Equivalent Volume (EV) Method

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Abstract:

Recently, a number of mix-design procedures accounting for the distinct microstructure of recycled concrete aggregate (RCA) have been proposed. Amongst them, the Equivalent Volume (EV) method seems to be quite promising. The EV method may proportion RCA concrete made of coarse (CRCA) or fine (FRCA) RCA and based on a companion conventional concrete (CC). Previous research has demonstrated that the fresh and hardened properties of EV mix-designed CRCA are suitable for structural applications. Yet, very few research, analysis and quantification were conducted on the fresh behaviour of EV mix-proportioned FRCA concrete. This work presents a comprehensive study on the rheological behaviour of EV mix-designed CRCA and FRCA concrete presenting distinct features (i.e. inner qualities, mineralogy, fabrication process, etc.) through the use of a planetary rheometer (IBB). Results show that the EV is capable of proportioning low embodied energy CRCA and FRCA concrete with shear thinning profiles. The latter suggests that these mixtures are suitable for applications under high torque regimes such as vibrated or pumped concrete.

Keywords: Recycled concrete aggregate (RCA), residual mortar (RM), residual cement paste (RCP), equivalent volume method (EV), rheological behaviour, shear thinning.

3.1 Introduction

Recycled concrete aggregate (RCA) has gained increased attention in the past decades to decrease the carbon footprint of concrete construction [1]. A wide number of studies have been performed on the use of RCA in concrete so far; yet the majority of the outcomes demonstrate that RCA concrete is an inferior material when compared to a companion conventional concrete (CC) [2–9]. RCA is a two phase material comprised of residual mortar (RM) or residual cement paste (RCP) (depending on whether the material is coarse or fine) and the original virgin aggregate (OVA) [10]. It has been found that whether its distinct microstructure is accounted for while the mix-proportioning of the recycled concrete, suitable performance in the fresh and hardened properties may be achieved [11–14]. In this context, some mix-design procedures that consider the microstructure of RCA have been recently proposed and amongst them, the Equivalent Volume (EV) method has shown to be quite promising.

3.2 Background

3.2.1 RCA microstructure and performance (coarse and fine particles)

Whenever RCA is considered as a natural aggregate (NA), RCA concrete tends to yield inferior performance when compared to conventional concrete (CC) [2,4,5,8,11–16]. The latter was found due to the intrinsic nature and distinct microstructure of RCA.

RCA may be divided in two types: coarse (CRCA) and fine (FRCA). CRCA is comprised of NA and RM whereas FRCA is composed of NA and RCP [20,21]. It has been found that the amount and quality of adhered RM (or RCP) plays a vital role in the properties of RCA concrete. Abbas et. al. [22] modified ASTM C88 [23] standard protocol to determine the amount of RM in RCA with more accuracy. Likewise, the soluble silica sub-procedure provided in ASTM C1084-15 and C114-18 may be conducted to measure the amount of RCP in the FRCA [24,25] .

Previous studies on CRCA show that the higher the RM content, the lower the RCA concrete mechanical properties for mixtures proportioned with conventional mix-design methods [8,22,26–31]. Moreover, it has been proven that the hardened performance of CRCA is not only dependent on the RM amount, but rather on the amount and quality of the adhered RM to the RCA particles [13]. However, the fresh state behaviour (rheological profile) of CRCA concrete with high replacement ratios is still a challenge and mostly unknown, since the RM acts as an aggregate in the fresh state while being a mortar in the hardened state [20] .

Although a number of studies have investigated the use of CRCA in concrete, very few research has been conducted on FRCA [26,28,29,31,32]. Similar to CRCA, FRCA is also reported to be a low-quality material due to the important presence of residual cement paste (RCP) adhered to the particles. As a result, some researchers report unsuitable hardened behaviour of FRCA concrete [8,15,31]. Furthermore, important concerns have been raised to the fresh state performance of FRCA mixtures with high replacement ratios; yet very few (if any) consideration has been given to the amount and quality of RCP adhered to the fine particles.

The previous scenario makes an urgent need to discuss and adopt mix-proportioning techniques able to account for the unique CRCA and FRCA microstructure while the mix-proportioning of recycled concrete.

3.2.2 RCA Mix-design methods

Several mix-design methods were recently proposed to account for the RM and enhance RCA concrete properties [13]. Amongst those, the Equivalent Mortar Volume (EMV), the modified Equivalent Mortar Method (EMV-mod) and the equivalent volume (EV) are three of the most promising techniques.

The Equivalent mortar volume (EMV) method was introduced by Fathifazl et. al. [10]. The basic assumption of this method is that the RCA concrete should have similar volumetric amounts of coarse aggregates and mortar (i.e. residual mortar + new mortar) when compared to a companion CC mix. It is worth noting that whenever one equation between Equations 3.1 and 3.2 is satisfied, so does automatically the second.

$$V_{TMRCA\text{-}concrete} = V_{RMRCA\text{-}concrete} + V_{NMRCA\text{-}concrete} \qquad \text{Equation 3.1}$$

$$V_{TNARCA\text{-}concrete} = V_{OVARCA\text{-}concrete} + V_{NARCA\text{-}concrete} \qquad \text{Equation 3.2}$$

Where: $V_{TMRCA\text{-}concrete}$ is volume of total mortar in RCA concrete; $V_{RMRCA\text{-}concrete}$ is volume of residual mortar in RCA concrete; $V_{NMRCA\text{-}concrete}$ volume of new mortar in RCA concrete; $V_{TNARCA\text{-}concrete}$ is volume of total natural coarse aggregate in RCA concrete; $V_{OVARCA\text{-}concrete}$ is volume of original virgin coarse aggregate in RCA concrete and $V_{NARCA\text{-}concrete}$ is volume of new coarse aggregate in RCA concrete.

It is worth noting that the EMV method was developed to proportion CRCA mixtures. No attempt has been made to date to mix-design FRCA concrete. Moreover, since it is a method that depends on the RM, the addition of 100% RCA may not be possible for aggregates containing high amounts of RM, which is a limitation of the method [10]. Therefore, depending on the RCA features, it is not possible to always proportion a recycled mix with 100% of RCA.

Results show that whenever the EMV is adopted, similar or superior hardened state properties of recycled mixtures may be achieved when compared to companion CC mixes. However, the fresh state behaviour of EMV proportioned mixtures is found to be a challenge. Hence, EMV designed mixtures require moderate to high amounts of Portland cement (PC) and superplasticizer which may offset the environmental benefits of using RCA in concrete [13,19].

The Modified Equivalent Mortar (EMV-mod) method was proposed by Hayles et. al. [14]. The method contains the same principals of EMV, but it was modified by adding a parameter to improve the fresh state behaviour of EMV recycled mix. The parameter enabled the designer to select the sand-to-cement mass ratio; and thus, select the amount of cement for the new recycled concrete mix. Although EMV-mod significantly enhanced the fresh state properties of RCA concrete, it lost some performance in achieving cement efficiency (i.e. higher cement content for same targeted strength) [14].

The Equivalent volume (EV) method was initially developed to mix-design CRCA concrete mixtures enhancing the fresh state issues faced in EMV and EMV-mod designed mixtures without compromising their benefits [13]. Similar to EMV, the amount of residual mortar (RM) attached to original virgin aggregate (OVA) is accounted for to enhance RCA concrete performance. However, the main difference between EV and EMV (or EMV-mod) is that this procedure requires that the proportioned RCA concrete needs to have the same amount of cement paste and aggregates (i.e. coarse and fine), in volume, than a companion CC mix. (Equation 3.3 and 3.4). Therefore, the total volume of CP in EV mixture is described as summation of RP and fresh paste (FP).

$$V_{CPRCA\text{-}Concrete} = V_{CPCC} \qquad \text{Equation 3.3}$$

$$V_{AgRCA\text{-}Concrete} = V_{AgCC} \qquad \text{Equation 3.4}$$

The EV method has recently been modified and now is able to also proportion FRCA concrete [20]. Moreover, it has been found that the EV method is able to enhance the fresh state behaviour (i.e. consistency) of recycled concrete since the amount of coarse aggregates is reduced from the system while the increase of fine particles. However, very few research has been conducted on the quantification of the rheological profile of EV-mix proportioned CRCA and FRCA. Figure 3.1

illustrates a volumetric comparison between CC mixtures and EV mix-proportioned CRCA and FRCA mixes.

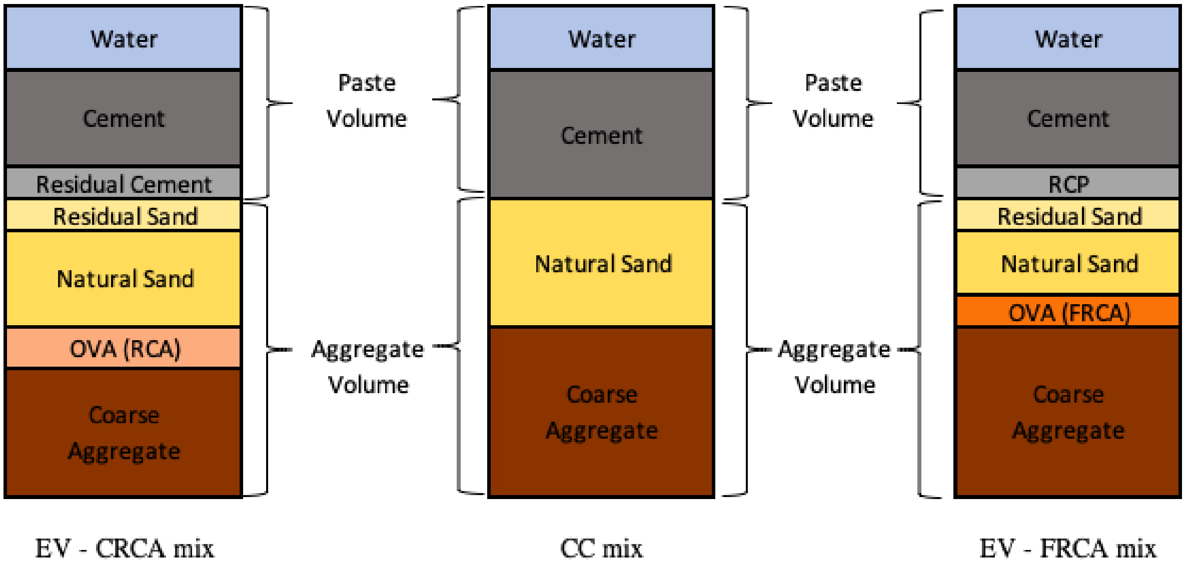

Figure 3.1: Volumetric comparison of CC with EV-CRCA and EV-FRCA mixture proportion.

3.2.3 Rheology of concrete mixtures

It is widely known that the fresh state and durability performance are the two main challenges and concerns of RCA concrete. The fresh state behaviour of concrete can be fully evaluated and quantified through rheology [33]. Factors such as the water-to-cement ratio, aggregate angularity, texture, gradation, etc. are known to influence on the rheological profile of conventional concrete and should be similarly important for RCA concrete.

Previous studies have mainly investigated the fresh state properties of RCA concrete mixtures through the slump test [30,34–36]. Except for RCA self-compacting concrete (SCC), where additional tests are also often performed such as slump flow diameter, T_{500} slump flow time, V-funnel flow time and L-box height ratio [37–39]. However, it is well-known that they are single-point and/or specific tests and cannot fully describe the fresh state behaviour of concrete mixtures. Therefore, recent studies have used rheometers to fully evaluate the fresh state properties of RCA concrete mix [12,38–40]. The two main parameters measured through the rheometer analysis is the yield stress and plastic viscosity [12,38–40]. A study has reported negative influence on flowability and rheological profile for EMV designed recycled mixes with increase in yield stress and plastic viscosity [12,40]. Yet, very few research (if any) has appraised the rheology of EV-designed CRCA and FRCA mixes.

3.3 Scope of work

As discussed in the literature review, there is a lack of information on the rheological behaviour of recycled concrete mixtures incorporating coarse or fine recycled particles, especially for RCA mixtures developed through methods that account for the RM (or RCP) adhered to the OVA. This work aims to comprehensively appraise the fresh state properties (i.e. slump and rheological profile) of CRCA and FRCA EV-proportioned mixtures presenting distinct mechanical properties and incorporating recycled aggregates with distinct features (i.e. minerology, texture, density, RM quality, manufacturing process, etc.)

The current research is divided into two streams. In the first stream, six types of CC mixtures proportioned through the absolute volume method (i.e. ACI method) are fabricated with distinct targeted compressive strengths (i.e. 25, 35 and 45 MPa) and incorporating different coarse aggregate types (limestone - LS and granite - GR). First, each of these mixes are evaluated in the fresh state and their rheological profile quantified. Then, the specimens made of CC were moist cured over 28 days, jaw crushed, and sieved to produce coarse RCA of known features. Finally, the RM of all mixtures is quantified. The six CRCA materials were used to mix-proportion six recycled concrete through the EV method, targeting a 35 MPa mix. Their fresh state was again appraised and compared to the previous evaluated CC mixes (Figure 3.2 – left portion).

In the second stream, four FRCA materials were fabricated from 35 MPa concrete mixtures designed with the ACI method and incorporating either natural or manufactured sand. At 28 days, they were crushed to produce two types of FRCA as follows: a) crusher fine (FRCA obtained after two series of crushing and sieving); and b) fully ground (FRCA obtained after multiple series of crushing and sieving). Then, the RCP was quantified in all FRCA materials and they were used to mix-proportion FRCA concrete using the EV method. Evaluations of their fresh state (rheological profile) were performed and compared to CC mixes (Figure 3.2 – right portion).

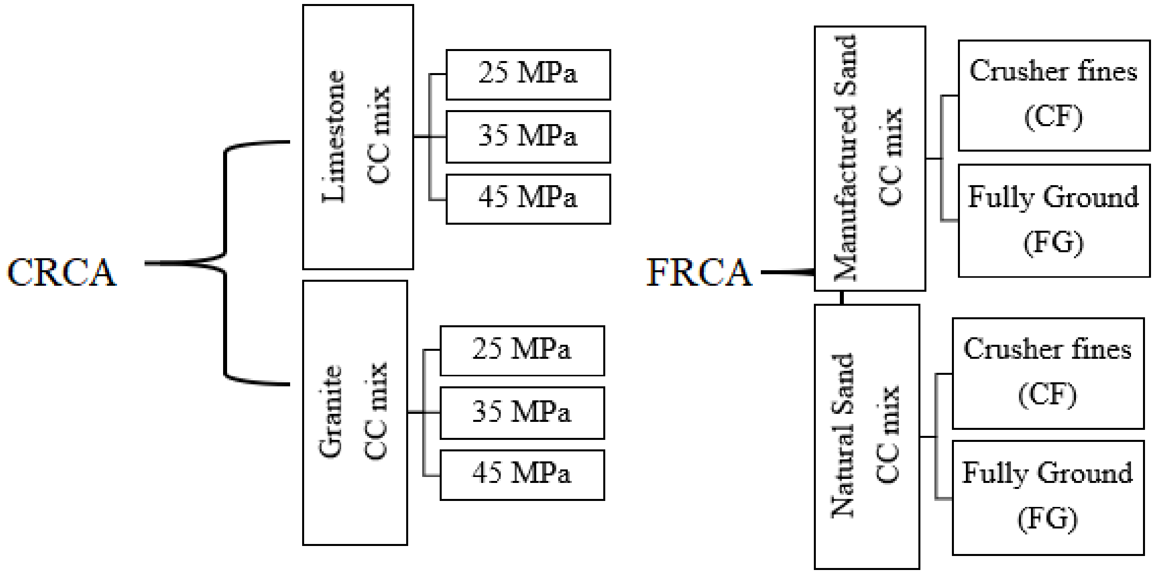

Figure 3.2: Flowchart representing CRCA and FRCA produced for the experimental work.

3.4 Materials and methods

3.4.1 Materials and mixtures

- CRCA Production

Six CC mixtures incorporating distinct coarse aggregates (i.e. crushed limestone and granite), natural sand, and displaying three targeted compressive strengths (i.e. 25, 35, and 45 MPa) were mix-designed through the absolute volume method (ACI method). Concrete cylinders (100 x 200 mm) were fabricated for each concrete mix as per ASTM C39[41]. Table 3.1 illustrates the detailed proportion of the CC mixtures. These cylinders were demoulded after 24 hours and moist cured for 28 days. Later, cylinders were crushed using a jaw crusher to produce CRCA.

- FRCA Production

Two CC mixtures incorporating a crushed limestone and two types of fine aggregates (i.e. natural and manufactured) were produced using the ACI method. Table 3.1 illustrates the detailed proportion of the CC mixtures fabricated to produce the FRCAs. Concrete cylinders (i.e. 100 x 200 mm) were fabricated and jaw crushed (19.0 mm opening). The material obtained was then sieved as per CSA A23.2-14 [42] and divided into CRCA and FRCA. The FRCA obtained after two stages of crushing was called as crusher fines (CF). The second type of FRCA was also produced by multiple series of crushing of the remaining CRCA. The material obtained was sieved as per CSA A23.2-14 [42] and called as fully ground (FG). Figure 3.3 illustrates the CRCA and two types of FRCA used in this study.

Table 3.1: CC mixture proportions of CRCA and FRCA.

	CRCA					
Aggregate type	**Crushed Limestone**			**Granite**		
Concrete strength (MPa)	**25** **kg/m3**	**35** **kg/m3**	**45** **kg/m3**	**25** **kg/m3**	**35** **kg/m3**	**45** **kg/m3**
Cement	314	370	424	314	370	424
Fine aggregate	840	840	840	806	806	806
Coarse aggregate	1050	1050	1050	1182	1182	1182
Water	192	174	157	192	174	157
Water/Cement	0.61	0.47	0.37	0.61	0.47	0.37

	FRCA	
Aggregate type	**Natural sand**	**Manufactured sand**
Concrete strength (MPa)	**35** **kg/m3**	**35** **kg/m3**
Cement	370	370
Fine aggregate	898	934
Coarse aggregate	1032	1032
Water	174	174
Water/Cement	0.47	0.47

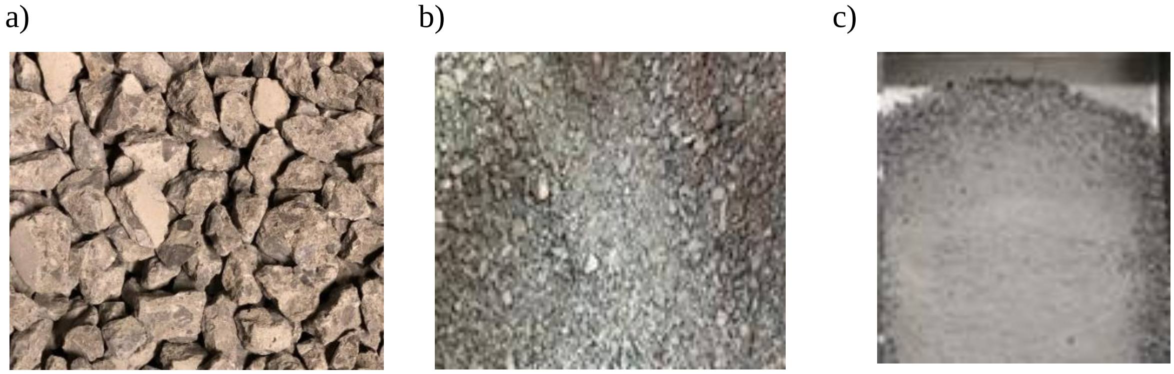

Figure 3.3: a) CRCA, b) FRCA-CF and c) FRCA-FG produced in lab.

3.4.2 Assessment of Residual mortar (RM) and Residual cement paste (RCP)

a) Residual Mortar

The residual mortar adhered to CRCA was determined according to the method proposed by Abbas et. al. [22]. The RM content is tested and obtained for each of the coarse fractions used in the mix, as follows: 1000 g sample for 4.75-9.50 mm, 2000 g sample for 9.50-12.50 mm and 2000 g sample 12.50-19.00 mm. The final RM value is then the average of these three fractions.

The test protocol consists of oven-drying the analyzed samples for 24 h at 105$_{o}$C and then immerse them into a 26% sodium sulphate solution (by weight) for 24 h. The RCA materials are then subjected to 5 cycles of freeze and thaw (i.e. 16 h at -17$_{o}$C in the freezer and 8 h at 60$_{o}$C in the oven) [23]. The attached RM damages and detaches itself from the natural coarse aggregate particles [19]. The solution is finally drained, and aggregates are washed with running tap water over the 4.75 mm sieve. The obtained aggregates are then oven dried for 24 h and weighed. The percentage weight loss gives the RM content for each CRCA fraction, as per Equation 3.5.

$$\text{RMC\%} = \left(\frac{W_{RCA}-W_{OVA}}{W_{RCA}}\right) \text{ x } 100 \qquad \text{Equation 3.5}$$

Where: W_{RCA} is weight of oven dried RCA and W_{OVA} is weight of oven dried aggregate obtained after five freeze and thaw cycles.

b) *Residual Cement Paste*

The residual cement paste adhered to fine recycled particles is measured through the soluble silica sub-procedure as per ASTM C1084-15 [24] and C114-18 [25]. This method was preferred due to the use of a limestone coarse aggregate in the production of FRCA, which restricted from using other methods such as maleic acid digestion. From each type of FRCA, a sample of 2.5 g was used for RCP analysis.

The test procedure involved selective extraction of silica from PC using cold and diluted hydrochloric acid with analysis of the soluble silica converted to silicon tetrafluoride through the treatment of hydrofluoric acid. It is assumed that the silica dissolved in cold diluted hydrochloric acid is only from PC and not from the aggregates. Equation 3.6 is then used to calculate the unhydrated PC. The silica value within RCP was assumed to be 21%, which typically ranges from 18%-21% (Equation 3.7) as per ASTM C1084-15 [24].

$$C_{SiO2}\text{, wt. (\%)} = \left(\frac{100\ x\ mSiO2}{mFRCA}\right) \quad \text{Equation 3.6}$$

$$C_{cement}\text{, wt. (\%)} = \left(\frac{1000\ x\ mSiO2}{21\ x\ mFRCA}\right) \quad \text{Equation 3.7}$$

Where: C_{SiO2} is percent weight of silica in cement; C_{cement} is percent weight of cement in FRCA; $mFRCA$ is weight of FRCA sample and $mSiO2$ is weight of silica in cement.

3.4.3 CRCA and FRCA characterization

Table 3.2 presents the characterization of CRCA produced for this study. The bulk specific gravities and water absorption were determined as per ASTM C127-15 [43].

Table 3.2: Detailed characterization of CRCA.

Crushed material identification		**RMC**	**Specific gravity**	**Absorption capacity**
Strength (MPa)	**OVA Type**	**(%)**	**(g/cm^3)**	**(%)**
25	Granite	45.6	2.63	5.63
35	Granite	48.0	2.65	5.32
45	Granite	50.2	2.67	5.20
25	Crushed Limestone	40.0	2.40	5.40
35	Crushed Limestone	45.6	2.41	5.09
45	Crushed Limestone	52.1	2.43	4.88

The standard procedure for specific gravity and water absorption provided by CSA-A23.2-2A-14 [42] is not suitable for FRCA due to its cohesiveness and binding nature. Thus, a method proposed by Rodrigues et.al. [44] was used for this research. The FRCA samples were saturated in a 0.1% of sodium hexametaphosphate solution, which is a clay dispersant generally used in the soil analysis for clay suspension. For each sample, a concentration of 0.1 g/l of dispersant was used to avoid agglomeration of particles. Later, the procedure provided by CSA-A23.2-2A-14 [42] was adopted, except for a few initial steps as per Rodrigues et al. [44]. The procedure adopted in this study for characterization may be found hereafter:

- The FRCA samples were soaked in a sodium hexametaphosphate solution for 24 h and the SSD weight was recorded as M1.

- The sample was placed in a pycnometer and filled with water. After 24 h, the material was removed, and the dried mass was recorded as M2;
- The sample was later placed in an oven at 110$_o$C for 24 h and the oven dried mass was recorded as M4 and the mass of the pycnometer filled with sodium hexametaphosphate solution was recorded as M3.

The oven dry specific gravity and water absorption was calculated using Equation 3.8 and Equation 3.9, respectively. The density of the sodium hexametaphosphate solution (P$_w$) was assumed to be equal to water at 20$_o$C [45].

$$P_{OD} = \left(\frac{M4}{M1-(M2-M3)/Pw}\right) \qquad \text{Equation 3.8}$$

$$w_{\%} = \left(\frac{100\ x\ (M1-M4)}{M4}\right) \text{ x } 100 \qquad \text{Equation 3.9}$$

Table 3.3 shows the characterization of FRCA produced by both natural and manufactured sand used for this study.

Table 3.3: Detailed characterization of FRCA.

Crushed material identification		**RCP**	**Specific gravity**	**Absorption capacity**
Fine aggregate type	**FRCA type**	**(%)**	**(g/cm$_3$)**	**(%)**
Natural sand	CF	15.5	2.47	7.87
Natural sand	FG	11.5	2.56	6.38
Manufactured sand	CF	16.8	2.51	7.76
Manufactured sand	FG	11.4	2.58	6.16

3.4.4 EV mix-proportioned RCA mixes

Six 100% CRCA concrete mixtures (with distinct strengths and coarse aggregate types) were proportioned through the EV method (w/c = 0.45) and are illustrated in Table 3.4. A High range water reducing (HRWR) admixture was added to all mixtures to achieve a targeted slump of 100±20 mm. Moreover, 1.4% to 1.5% of air entraining admixture (AEA) was also added to the mixtures so that they might be used under exposed conditions in North America (e.g. C1) as per CSA.A23.1-09. It is worth noting that based on the EV method, the amount of cement must be reduced to match with the cement paste volume of the companion CC mix. Furthermore, the amount of HRWR and AEA are mentioned as percentage of the cement by mass.

Table 3.4: Detailed CRCA mixture proportion using EV method for CRCA.

	35 MPa RCA Concrete					
Aggregate type	**Crushed Limestone**			**Granite**		
RCA strength (MPa)	**25**	**35**	**45**	**25**	**35**	**45**
Component Name	**kg/m$_3$**	**kg/m$_3$**	**kg/m$_3$**	**kg/m$_3$**	**kg/m$_3$**	**kg/m$_3$**
Cement	291.67	283.32	273.75	284.24	281.15	278.64
Fine aggregate	789.78	787.11	783.95	699.91	696.19	693.31
Coarse aggregate	1108.36	1130.86	1161.01	1308.46	1325.86	1344.92
Water	131.25	127.5	123.19	127.91	126.52	125.39
Water/Cement	0.45	0.45	0.45	0.45	0.45	0.45
HRWR (%)	0.75	0.75	0.75	0.75	0.75	0.75
AEA (%)	1.5	1.5	1.5	1.4	1.4	1.4
Slump (mm)	120	100	95	140	110	100
RM (%)	40.0	45.6	52.1	45.6	48.0	50.2

Four 100% FRCA (35 MPa mixes with distinct fine aggregate types – manufactured and natural sand - and crushing processes – crusher fines and fully ground) were also proportioned through the EV method (w/c= 0.35) are illustrated in Table 3.5. One may note that, although the EV mixtures presented the same cement paste volume as the companion CC mix, the w/c was reduced in the recycled mixtures to achieve the targeted strength of 35 MPa. Therefore, the cement content of EV-proportioned FRCA mixes are similar to the companion CC mix. As for the CRCA mixes, HRWR and AEA were added to FRCA mixes. It is worth noting all mixtures presented an initial slump value of 100±20 mm.

Table 3.5: Detailed FRCA mixture proportion using EV method for FRCA.

	35 MPa RCA Concrete			
FRCA type	**NS-CF**	**NS-FG**	**MS-CF**	**MS-FG**
RCA strength (MPa)	**35**	**35**	**35**	**35**
Component Name	**Kg/m3**	**Kg/m3**	**Kg/m3**	**Kg/m3**
Cement	373	373	372	373
Fine aggregate	714	740	732	752
Coarse aggregate	1005	1014	1004	1006
Water	131	131	130	131
Water/Cement	0.35	0.35	0.35	0.35
HRWR (%)	1.2	1.2	1.2	1.2
AEA (%)	1.9	1.9	1.8	1.8
RCP (%)	15.5	11.5	16.8	11.4

3.4.5 Fresh state assessment of CRCA and FRCA mixtures

The fresh state performance of the CRCA and FRCA mixtures was appraised by consistency measurements (i.e. slump test) and rheological characterization using a planetary rheometer (IBB; Figure 3.4 a and b). The rheological characterization (profile) was obtained by shearing the concrete sample placed in a 20 liters pan from 0 rpm to approximately 40 rpm and lowering the shear rate gradually until rest. The H-shaped impeller with dimensions of 100 mm x 139 mm and covering area of 4002.3 mm_2 rotates for about three minutes and measures the torque applied at each stage of increasing and decreasing rotational speed. This computer-controlled device provides raw data of torque with respect to rotational speed and requires further processing for the rheological characterization of concrete mixtures.

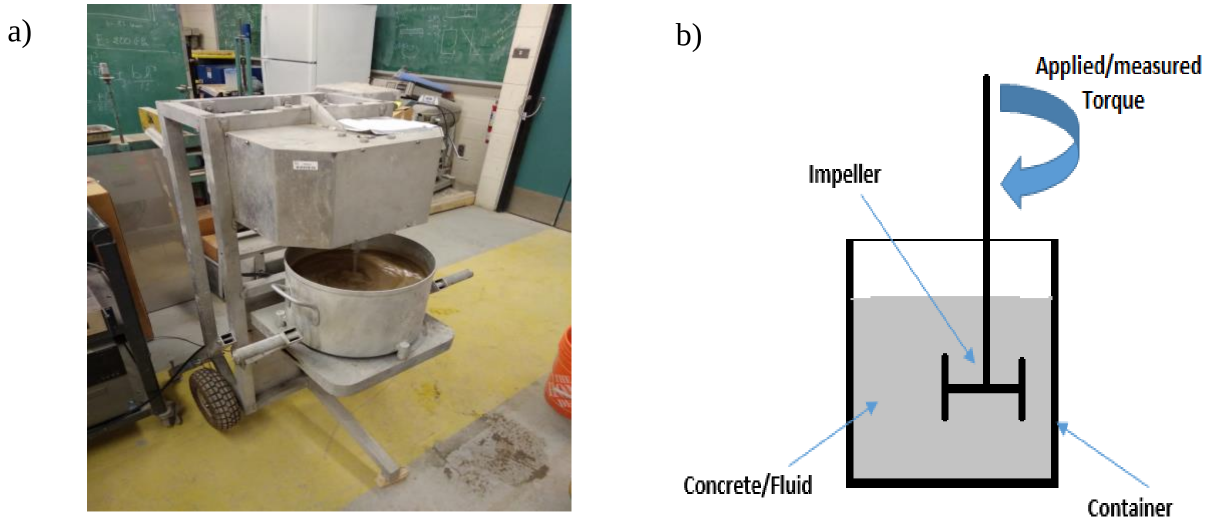

Figure 3.4: a) IBB rheometer and b) Rotating impeller.

3.5 Results

3.5.1 Rheology of CC mixes used to produce CRCA

Figure 3.5 presents the rheological profiles of CC mixtures designed using ACI method. All the mixes exhibited shear thinning behaviour, i.e. decrease in viscosity as a function of torque applied regardless of the water-to-cement and aggregate type. Table 3.6 shows the slump measurements and the three key rheological parameters measured in this study: 1) apparent viscosity; 2) minimum torque or yield stress; and 3) maximum torque applied. It is worth noting that the apparent viscosity (AV) was measured by the ratio of shear stress to shear rate at the first deceleration point. The data shows that the lower the water-to-cement ratio, the higher the AV, the higher the yield stress (or minimum torque to enable flow), the higher the maximum torque achieved, and the lower the consistency measured. Furthermore, the AV, minimum and maximum torques, and slump obtained for CC made of granite were slightly higher than the ones made of limestone. Except for mixes CC-GR-45MPa and CC-GR-25MPa, where the former one obtained a lower minimum torque than CC-LS-45MPa and the latter presented a slightly lower slump compared to CC-LS-25MPa. The apparent viscosity values range from 0.16 Nm/rpm to 0.70 Nm/rpm and is inversely proportional to slump values ranging from 150 mm to 40 mm. The minimum torque measured ranges from 0.69 N.m to 10.98 N.m and maximum torque value ranges from 11.65 N.m to 32.95 N.m.

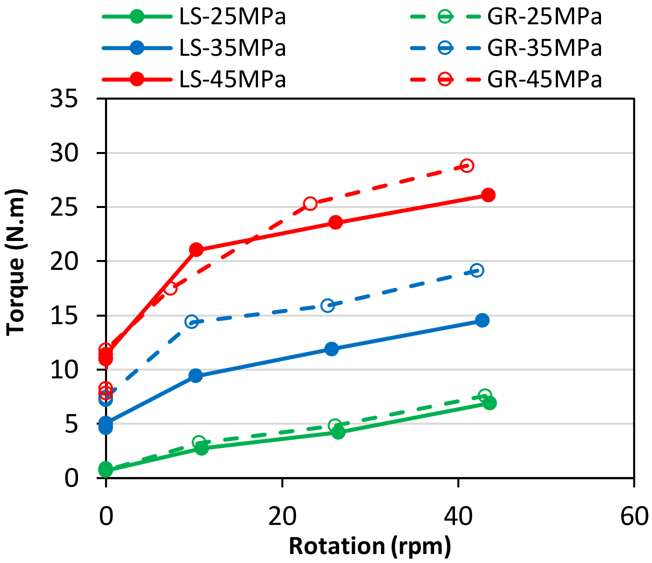

Figure 3.5: Rheological profile of CC mixtures used to produce CRCA

Table 3.6: Rheological parameters assessed for CC mixtures

Name mix	Apparent Viscosity (Nm/rpm)	Minimum Torque (Nm)	Maximum Torque (Nm)	Slump (mm)
CC-LS-25MPa	0.16	0.69	11.65	150
CC-LS-35MPa	0.34	4.59	18.29	90
CC-LS-45MPa	0.60	10.98	29.87	40
CC-GR-25MPa	0.18	0.71	12.78	140
CC-GR-35MPa	0.45	7.21	23.3	95
CC-GR-45MPa	0.70	7.82	32.95	45

3.5.2 Rheology of CC mixes used to produce FRCA

Figure 3.6 displays the CC designed by ACI method to produce FRCA. Both natural and manufactured sands concrete exhibited a shear thinning behaviour. However, the results from the two mixtures were quite different. Table 3.7 presents the slump and the three key rheological parameters measured, similar to the CRCA mixtures. As one may notice, all the parameters measured are higher for the concrete made of manufactured sand, except for the slump value.

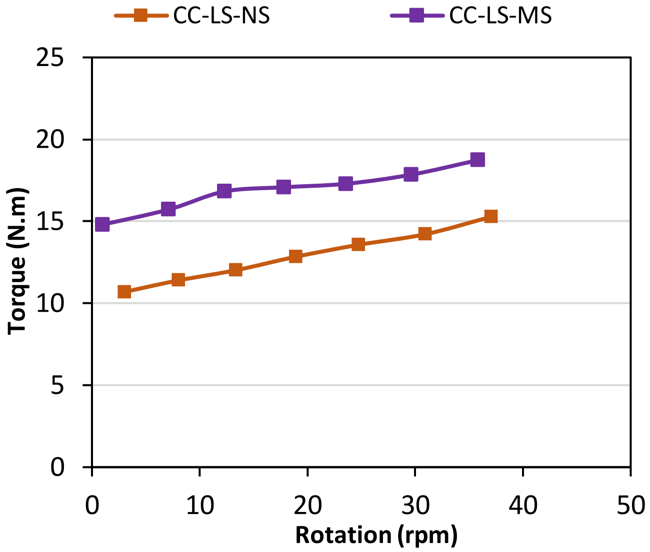

Figure 3.6: Rheological profile of CC mixtures used to produce FRCA

The rheological profile of CC-LS-NS and CC-LS-35MPa CC mix with natural sand is similar for the descending curves. As they represent shear thinning behaviour with similar descending values.

Table 3.7: Rheological parameters assessed for CC mixtures

Mix Name	**Apparent Viscosity (Nm/rpm)**	**Minimum Torque (Nm)**	**Maximum Torque (Nm)**	**Slump (mm)**
CC-LS-NS	0.37	10.7	16.11	110
CC-LS-MS	0.46	14.81	19.47	95

3.5.3 Rheology of EV designed CRCA concrete

Figure 3.7 displays the rheological profiles of CRCA concrete mixtures designed through the EV method. It is worth noting that all mixtures incorporate air entraining and superplasticizer admixtures. Moreover, the slump value of all mixtures was fixed to 100±20 mm, since it is a common slump requirement for structural and non-structural concrete applications.

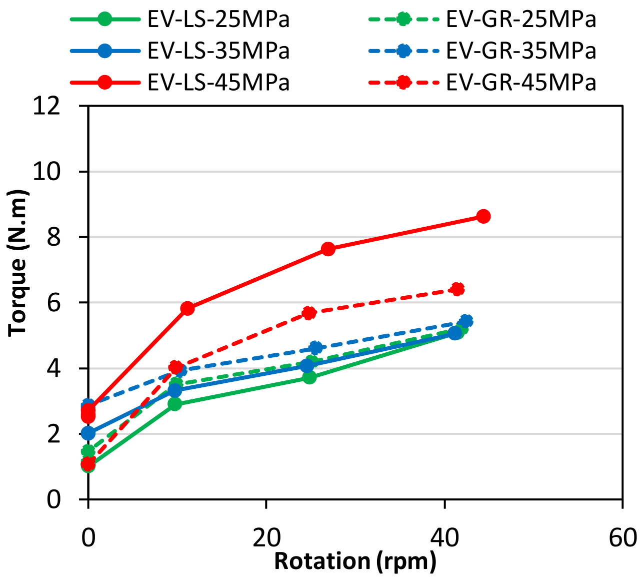

Figure 3.7: Rheological profile of CRCA concrete mixtures designed by EV method

Analyzing the data, one sees that all the mixes show a shear thinning behaviour regardless of the amount of water and aggregate type. Furthermore, the substantial influence of the higher strength mixtures seen in section 1.5.2 is not presented on CRCA concrete mixtures, since 45 MPa mixtures (i.e. EV-LS-45MPa and EV-GR-45MPa) displayed only a slight increase on the minimum or maximum torque when compared to other mixes.

Table 3.8 shows the rheological parameters measured for EV designed CRCA concrete mixtures similar to CC mixtures. The data clearly shows a trend of increasing apparent viscosity, minimum initial torque and maximum initial torque with higher strength of CRCA. However, a narrow range of values is obtained when compared to CC mixes. The minimum initial torque measured for all EV mixes is in the range of 1.08 N.m to 1.91 Nm; while the maximum torque values ranged from 6.72 N.m to 10.12 N.m. The apparent viscosity values range from 0.12 Nm/rpm to 0.19 Nm/rpm. Moreover, one may notice that the AV and viscosity at 43 rpm are similar regardless the aggregate type and compressive strength; except for 45MPa (EV-LS-45MPa and EV-GR-45MPa), which reached slightly higher values.

Table 3.8: Rheological parameters assessed for CRCA mixtures

Mix Name	Apparent Viscosity (Nm/rpm)	Minimum Torque (Nm)	Maximum Torque (Nm)	Slump (mm)
EV-LS-25MPa	0.12	1.08	6.72	110
EV-LS-35MPa	0.12	1.64	6.83	100
EV-LS-45MPa	0.19	1.91	10.12	90
EV-GR-25MPa	0.12	1.27	6.88	120
EV-GR-35MPa	0.13	1.51	7.32	100
EV-GR-45MPa	0.15	1.83	8.54	85

3.5.4 Rheology of FRCA concrete mix designed by EV method

Figure 3.8 shows the rheological profile of EV designed FRCA mixtures. Shear thinning behavior is exhibited by all the mixes regardless of crushing method and aggregate type. However, the crushing method clearly affects the rheological parameters. In contrast to CC mixes, the four parameters investigated are higher for FRCA made of natural sand, as shown in Table 3.9. The apparent viscosity value ranges from 0.58 Nm/rpm to 0.73 Nm/rpm. The minimum and maximum torque values are in the range of 7.33 N.m to 11.33 N.m and 21.88 N.m to 31.97 N.m respectively. Moreover, CF-FRCA of natural sand has lower values compared to FG ones. In contrast, the parameters of FG- FRCA of manufactured sand has reduced minimum and maximum torque values compared to CF-mixes. The data and plots clearly show the difference in FRCA quality (i.e. crusher fines-CF and fully ground-FG).

Table 3.9: Rheological parameters assessed for FRCA mixtures

Mix Name	Apparent Viscosity (Nm/rpm)	Minimum Torque (Nm)	Maximum Torque (Nm)	Slump (mm)
EV-NS-CF	0.69	7.33	28.97	115
EV-NS-FG	0.73	11.33	31.97	120
EV-MS-CF	0.58	10.12	24.78	105
EV-MS-FG	0.63	7.48	21.88	115

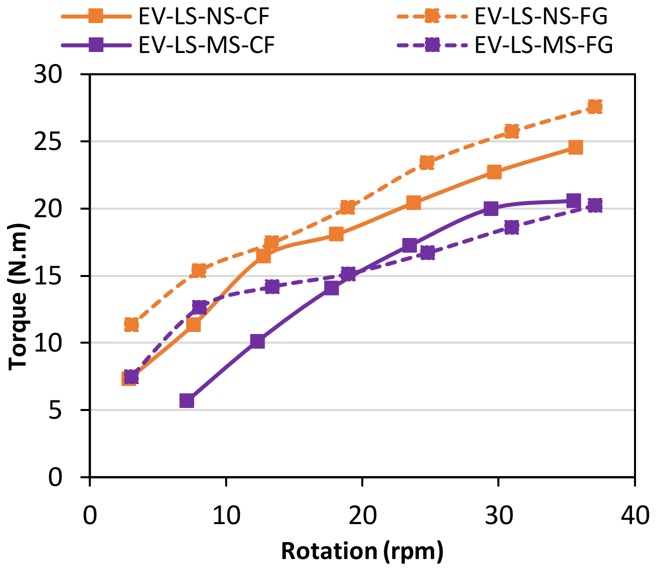

Figure 3.8: Rheological profile of FRCA concrete mixtures designed by EV method

3.6 Discussion

3.6.1 Consistency (Slump test)

It is a common misconception to utilize the slump test to evaluate concrete fresh state performance and workability [46]. Although the slump test is the most commonly used procedure in-situ, it is a single-point test that can only describe an initial portion of the materials fresh state behaviour, the so-called consistency. Consistency is defined as the easiness of a given material such as concrete to flow under its own weight. Therefore, two different concrete mixtures may have similar consistencies, but present very different flow behaviours when a torque/vibration is applied; hence, presenting different flowability and apparent viscosity at distinct torque regimes [47].

In order to achieve a target slump value without changing the w/c, various chemical admixtures (i.e. low, mid and high range water reducers) may be used [12]. In this work, an HRWR admixture was added to all CRCA and FRCA mixtures to set a target slump of 100±20 mm. Analyzing the results previously presented and the rheological profile differences among the mixtures, it is evident that a single-point test such as slump cannot fully describe the fresh state performance of cementitious materials.

3.6.2 Rheological behaviour: CC versus CRCA mixes

Figure 3.9 a) and b) illustrate the descending curves for CC mixes used to manufacture the CRCAs and EV mixtures, respectively. It is worth noting that no chemical admixtures were added to the CC mixes and all mixtures presented below display the same slump of 100±20mm. Although the yield stress is directly related to the slump value, it is clear that CRCA mixtures present lower yield stress, which may have occurred due to the addition of HRWR and AEA admixtures. Moreover, the CRCA mixtures demonstrate lower apparent viscosity (i.e. viscosity at the highest rotation) than CC mixtures, which ranged from 0.14 to 0.20 and from 0.34 to 0.45, respectively.

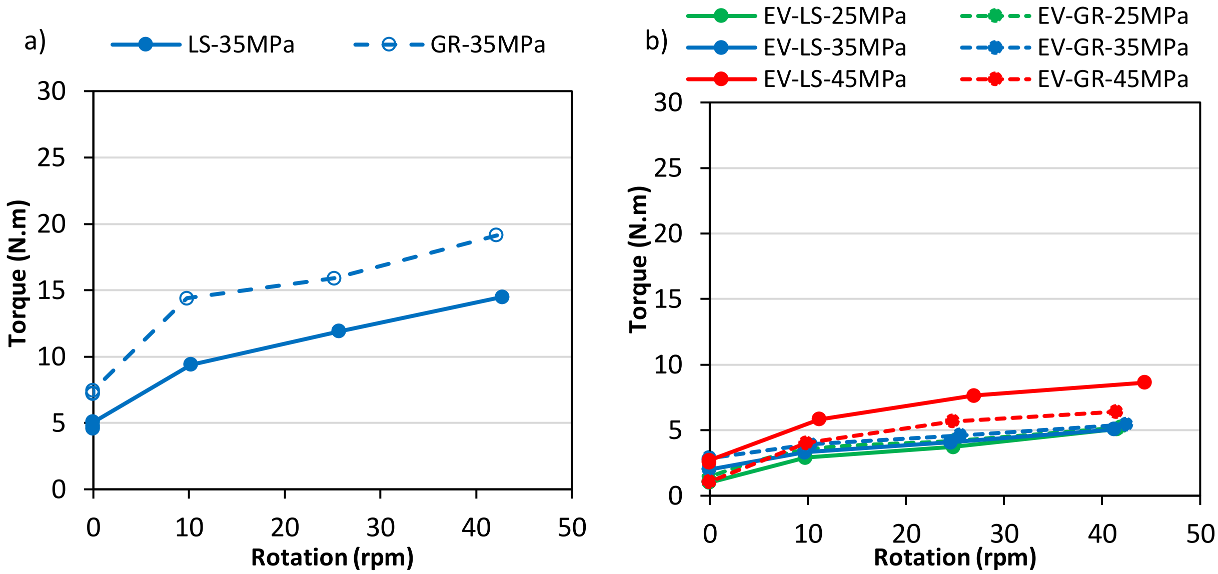

Figure 3.9: Descending curves from second cycle of a) CC and b) CRCA concrete mixtures

Moreover, one may notice that the higher CRCA residual mortar strength (i.e. the lower the w/c of CC) the higher the yield stress and apparent viscosity throughout the whole torque-rotation regime. This difference is more pronounced for 45 MPa mixes when compared to 25 and 35 MPa, and might be, at least partially, linked to the amount of RM adhered to the recycled particles; i.e. the higher the targeted strength the higher the amount of RM adhered (see Table 3.5).

3.6.3 Rheological behaviour: CC versus FRCA mixes

Figure 3.10 a) displays the descending curve of 35 MPa CC mixes of FRCA (w/c = 0.47), while Figure 3.10 b) presents the descending curve for EV designed FRCA mixes (w/c = 0.35). Both CC and FRCA mixes were designed for 35 MPa and all the mixes display a shear thinning behaviour (i.e. decrease in viscosity as a function of torque).

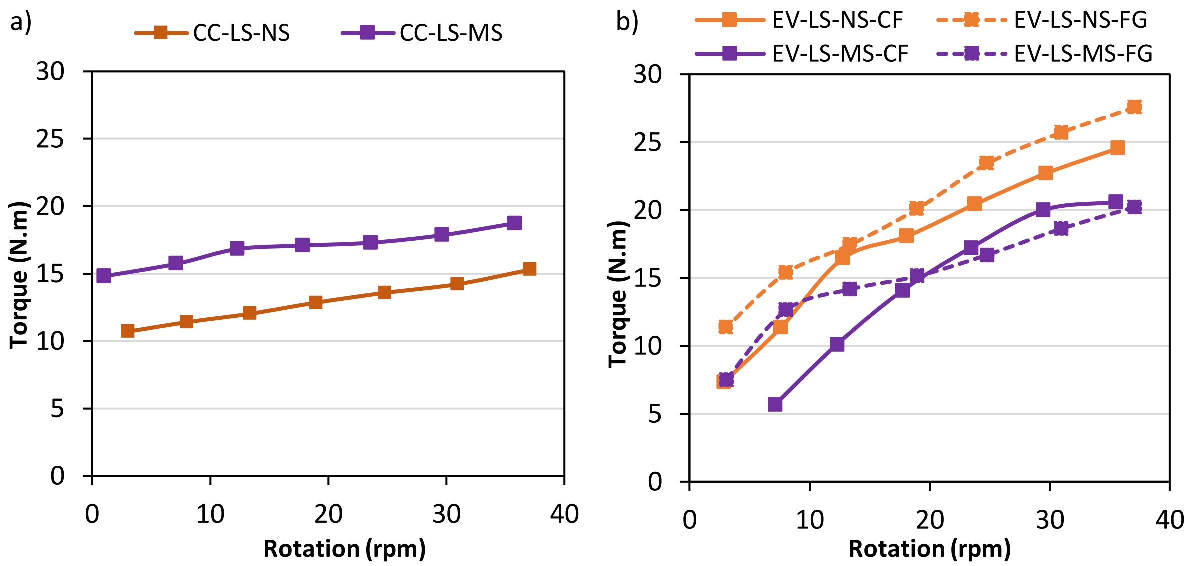

Figure 3.10: Descending curves from second cycle of a) CC and b) FRCA concrete mixtures

Figure 3.10 a) shows that the manufactured sand mixture reached a higher torque and apparent viscosity throughout the torque-rotation regime when compared to the natural sand mix. This can be explained by the angularity of the manufactured sand particles resulting in a negative effect on the mix flow. In Figure 3.10 b), no clear trend is observed based on the FRCA production (CF and FG). However, the two manufactured sand mixtures exhibited slightly lower minimum torque and apparent viscosity. Although the RCP content of the natural and manufactured mixtures manufactures with the same process is quite similar (e.g. 11.4% and 11.5% respectively for the FG process), the rheological profile of the former one is slightly shifted upward, which might only be an imprecision of the test.

3.6.4 Rheological Behaviour: CRCA versus FRCA mixes

Figure 3.11 a) and b) displays the descending curve of CRCA (w/c = 0.45) and FRCA (w/c = 0.35), respectively. Although the slump values of all mixtures are within the same range of 100±20 mm, FRCA mixtures exhibited much higher yield stress and torque values (for the same rotation) when compared to CRCA mixes, which means that the use of FRCA has a greater impact on the rheological profile of recycled mixtures than CRCA. This clearly shows, once again, that the slump value is not a reliable tool for the evaluation of the fresh state properties of cementitious mixtures.

Instead, the viscosity (torque vs rotation slope) is a more accurate measurement to describe the flowability of a material at given torque-rotation regimes [40].

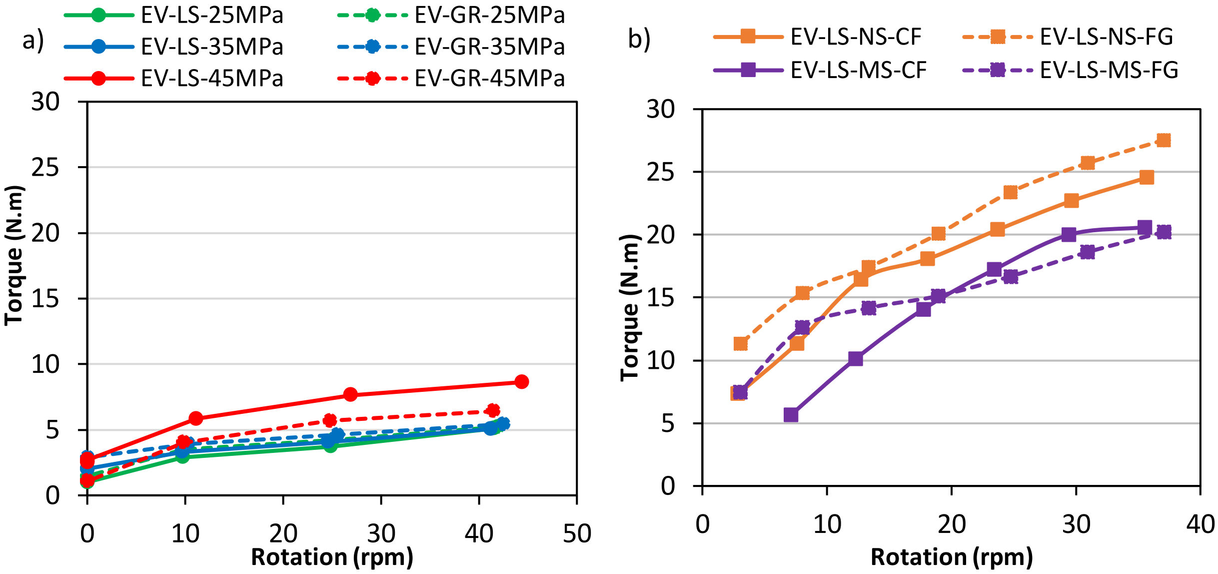

Figure 3.11: Descending curves from second cycle of a) CRCA and b) FRCA concrete mixtures

Analyzing the AV, CRCA mixtures present lower AV than FRCA mixes, which leads to a more flowable concrete at this rotation. Lastly, by observing the plots above, it is clear that EV designed CRCA and FRCA mixes are both exhibiting a shear thinning behaviour. Hence, such mixtures may be very suitable for applications under high torque regimes such as pumping and vibrating of concrete [20].

3.6.5 Modelling the rheological behaviour of CRCA and FRCA concrete

The rheological behaviour of CC can sometimes (especially for fluid mixtures) be described by the Bingham model [12,48], which presents a linear relationship between shear stress and shear rate. Equation 3.10 expresses the aforementioned relationship.

$$\tau = \tau_0 + k_B.\gamma \qquad \text{Equation 3.10}$$

where: τ is shear stress or torque applied, γ is shear rate or rate of rotation, τ_0 is yield stress or torque and k_B is viscosity constant.

However, concrete mixtures may not always behave in a linear fashion. Instead, it can exhibit a shear thinning (decrease in viscosity as a function of applied torque) or thickening (increase in viscosity as a function of applied torque) behaviour. Therefore, to represent non-linear behaviours of concrete, an additional parameter is required. Studies have proven that the Hershel-Bulkley (HB) model can represent quite well non-linear behaviours of cementitious materials [33,49] as per Equation 3.11.

$$\tau = \tau_0 + k_{BH}.\gamma_n \qquad \text{Equation 3.11}$$

Where: τ is shear stress or torque applied, γ is shear rate or rate of rotation, τ_0 is yield stress or torque, k_{BH} is viscosity constant for Herschel-Bulkley model and n is the additional (compared to Bingham) flow parameter for concrete (n<1 exhibits shear thinning behaviour and n>1 exhibits shear thickening behaviour).

Figure 3.12 a) and b) illustrates the rheological profiles of all CRCA mixes with their models from Bingham and Herschel-Bulkley approach, respectively; while the same results for FRCA mixes are presented in Figure 3.12 c) and d). Table 3.10 and Table 3.11 shows the rheological parameters of Bingham and Herschel-Bulkley models calculated for each CRCA and FRCA mixtures investigated. On comparing the experimental initial torque with the yield stress obtained by modelling the data, the Herschel-Bulkley provides better results (i.e. less variation with actual measured torque) compared to the Bingham model. The concave shape of Herschel-Bulkley curves and flow parameter values lower than one (i.e. n<1) validates the shear thinning behaviour.

Table 3.10: Bingham and Herschel-Bulkley parameters for CRCA concrete mixtures.

CRCA Mixture	**Bingham**			**Herschel-Bulkley**			
	Initial torque (N.m)	**τ_0**	**K_{HB}**	**Initial torque (N.m)**	**τ_0**	**K_{HB}**	**N**
LS-25MPa	1.01	1.28	0.09	1.01	1.07	0.34	0.67
LS-35MPa	2.01	2.14	0.07	2.01	2.04	0.17	0.8
LS-45MPa	2.53	3.19	0.12	2.53	2.61	1.16	0.44
GR-25MPa	1.03	1.56	0.09	1.03	1.23	0.54	0.56
GR-35MPa	2.74	2.9	0.06	2.74	2.83	0.12	0.85
GR-45MPa	1.07	1.59	0.12	1.07	1.07	0.93	0.49

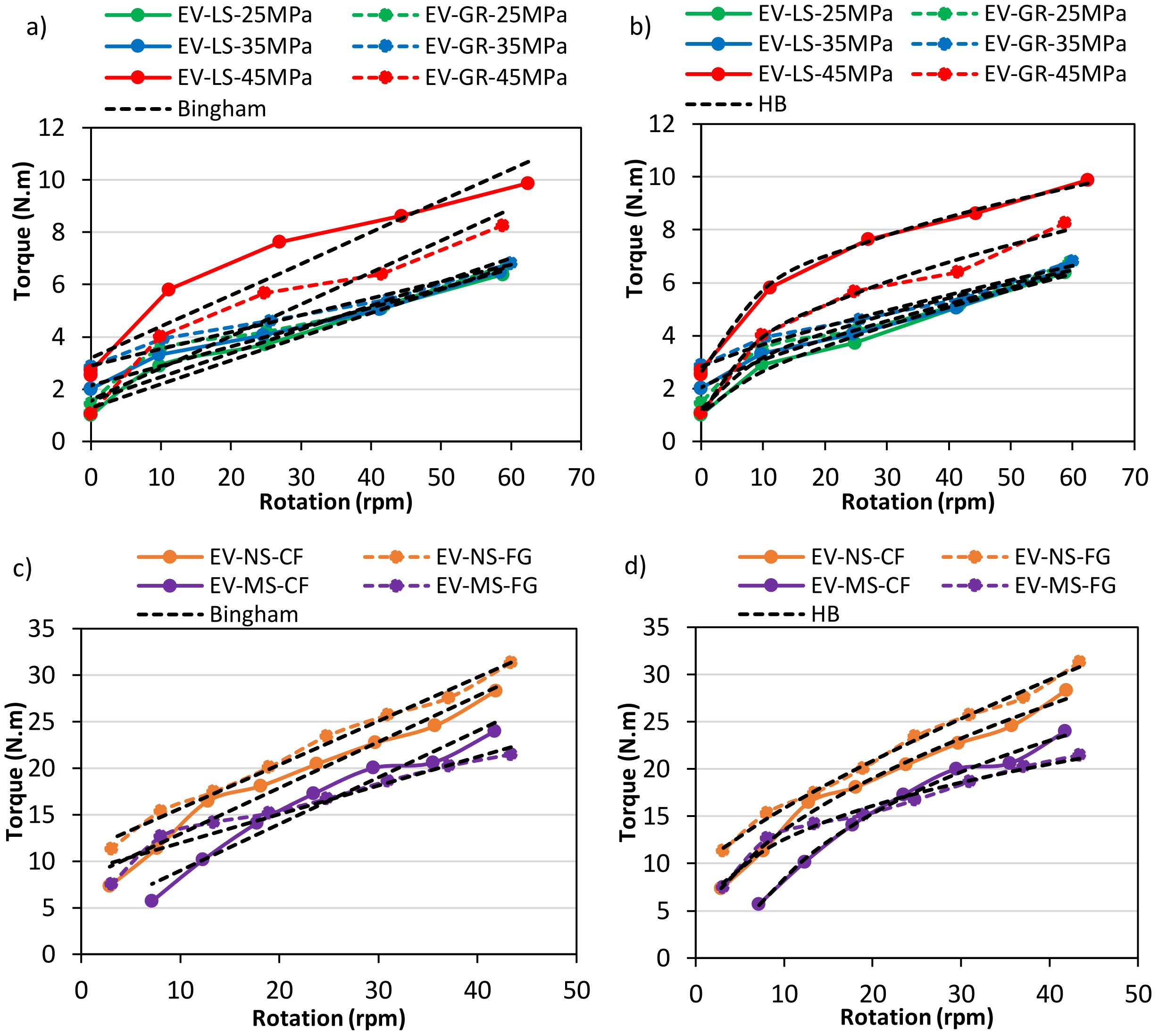

Figure 3.12: a) Bingham and b) Herschel-Bulkley model for rheological profiles of CRCA concrete mixtures, c) Bingham and d) Herschel-Bulkley model for rheological profiles of FRCA concrete mixtures.

According to the Herschel-Bulkley model, the yield stress and apparent viscosity constant are lower for CRCA mixtures when compared to FRCA mixes. This difference is more pronounced for the yield stress. Moreover, the yield stress and apparent viscosity values of CRCA made of limestone are quite comparable of CRCA made of granite. Similar results were also found for CF and FG processes.

Table 3.11: Bingham and Herschel-Bulkley parameters for FRCA concrete mixtures.

FRCA Mixture	**Bingham**			**Herschel-Bulkley**			
	Initial torque (N.m)	**τ_0**	**K_{HB}**	**Initial Torque (N.m)**	**τ_0**	**K_{HB}**	**N**
EV-NS-CF	7.33	7.98	0.49	7.33	0.28	4.18	0.5
EV-NS-FG	11.3	10.97	0.47	11.3	8.80	1.18	0.78
EV-MS-CF	10.12	3.97	0.50	10.12	0.20	1.71	0.71
EV-MS-FG	7.48	8.88	0.31	7.48	1.77	4.03	0.42

3.7 Conclusion

The objective of this research was to appraise and compare the fresh state behaviour of CRCA and FRCA mixes designed through the EV method. CRCA was produced in the lab using concrete with known microstructure (i.e. 25, 35 and 45 MPa), using limestone and granite as coarse aggregate. Likewise, FRCA was produced from 35 MPa concrete with natural and manufactured sand and two different crushing process (i.e. CF and FG). The results obtained in this work prove the suitable performance of EV proportioned RCA concrete mixtures in the fresh state and opens a wide range of opportunities for using this EV-proportioned recycled material towards a sustainable and greener future of concrete construction. The main findings gathered in this work are presented hereafter:

- The RM and RCP adhered to the coarse and fine aggregate particles depend on the type of the aggregate and the manufacturing process;
- The slump test is an unsuitable tool to appraise the fresh state performance of CRCA and FRCA concrete recycled;
- CRCA mixtures proportioned with the EV showed a shear thinning behaviour (decrease of viscosity as a function), with low yield stress and apparent viscosity for higher torque regimes. The latter demonstrates that EV designed mixtures are suitable for applications such as pumping and vibrating concrete;

- FRCA mixtures also demonstrated a shear thinning behaviour with higher yield stress and slightly higher apparent viscosity than CRCA mixes. Yet, they are still considered suitable for vibrated and or pumped applications;
- The HB model seems accurate to predict EV-proportioned CRCA and FRCA concrete behaviour in the fresh state. Yet, further studies using a wider range of mixtures is still necessary;
- The type (fine vs coarse; natural versus manufactured), nature (minerology) and manufacturing process impact on the rheological profile of recycled concrete mixtures. Yet, the mix-proportioning method looks like more critical than the ingredients themselves.
- Finally, the EV method seems to be quite promising to proportion recycled mixtures with suitable fresh state performance.

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4. Conclusions

Most of the previous research performed on the use of recycled concrete aggregates (RCA) considers the recycled material as a natural aggregate (NA) and thus disregards the residual mortar (RM) or residual cement paste (RCP) adhered to the coarse and fine particles, respectively. Therefore, inferiority of fresh and hardened state performance is often reported in the literature. Recent studies propose to account for the RM (or RCP) while the mix-proportioning and results are quite promising, especially in the hardened state. Techniques for considering the RM have been created such as the EMV and EMV-mod methods; yet, issues in the fresh state were still often found.

In this research, coarse RCA derived from concrete displaying different compressive strengths (i.e. 25, 35 and 45 MPa) and incorporating two sources of aggregates (i.e. limestone and granite) was produced. Similarly, fine RCA was manufactured from 35 MPa concrete using two sources (i.e. natural sand and manufactured sand) and different crushing methods (i.e. crushers fine and fully ground). Both coarse and fine RCA mixtures were mix-proportioned using a novel procedure, the so-called Equivalent Volume (EV) method, aiming to improve the fresh state properties of CRCA and FRCA concrete. Chapter 3 discusses the rheological behaviour of CRCA and FRCA mixes and their comparison with companion CC mixes. The main findings of this study and current Thesis are presented hereafter:

- **Quality of CRCA and FRCA**

The amount of residual mortar (RM) adhered to OVA varies as a function of the aggregate type and compressive strength of concrete for CRCA particles. Granite, presenting a more angular shape and rough texture, displayed a higher amount of adhered RM than limestone, except 45 MPa mix. Moreover, the inner quality of the CRCA particles directly affects the performance of RCA concrete. Likewise, the amount of residual cement paste (RCP) is in section 3.4.2 using soluble silica sub-procedure according to ASTM C1084-15 and C114-18. From table 3.3, slightly higher for manufactured sand when compared to natural sand for a two stage crushing process (i.e. crusher fines). The latter is believed to be due to the more angular and rough texture of this material. Otherwise, FRCA obtained after a series of crushing (i.e. fully ground) presented similar RCP for both natural and manufactured sands; this result suggests that the higher the amount of crushing series, the lower the impact of the aggregate features.

- **Fresh state assessment of CRCA and FRCA mixes**

With the use of a planetary rheometer (i.e. IBB), the fresh state of CRCA and FRCA concrete mixtures proportioned through the EV method was assessed. CRCA mixes exhibited very good fresh state performance in terms of rheological parameters (i.e. minimum torque and low apparent viscosity). Although the rheological parameters found were higher for FRCA concrete, the results obtained were still considered quite suitable for application in the field. Moreover, significant influence of the RCA quality was observed on the rheological behaviour of recycled mixtures. Furthermore, all mixtures exhibited a shear thinning behaviour regardless the RCA features. Finally, for both FRCA and CRCA mixes, lower minimum torque and apparent viscosity were observed when compared to companion CC mixes.

- **Modelling of RCA mixtures (Herschel-Bulkley model)**

For highly flowable concrete mixtures, the Bingham model can be applied, which represents a linear relationship between the shear stress and shear rate. It can be represented with Equation 5.1

$$\tau = \tau_0 + k_B\gamma \qquad \text{Equation 5.1}$$

where: τ is shear stress or torque applied, γ is shear rate or rate of rotation, τ_0 is yield stress or torque and k_B is viscosity constant.

However, concrete may also exhibit a non-linear behaviour (i.e. shear thinning or shear thickening). In such cases, an additional parameter is required to model their rheological behaviour. Herschel-Bulkley (HB) model can be successfully applied for such non-linear behaviours of concrete. It can be represented using Equation 5.2

\ $$\tau = \tau_0 + k_{BH}\gamma_n \qquad \text{Equation 5.2}$$

where: τ is shear stress or torque applied, γ is shear rate or rate of rotation, τ_0 is yield stress or torque, k_{BH} is viscosity constant for Herschel-Bulkley model and n is flow parameter of concrete i.e. for $n<1$ exhibits shear thinning behaviour and $n>1$ exhibits shear thickening behaviour.

All the CRCA and FRCA mixes used in this study exhibited a shear thinning. Bingham model holds good for some mixtures which are almost linear, but it cannot be applied to all the concrete mixtures. Furthermore, Herschel-Bulkley model holds good and can be used to represent all the RCA mixes used in this study.

➢ Efficiency of EV designed RCA concrete

Another objective of this research was to produce eco-friendly RCA concrete as numerous mix-proportioning methods used by researchers in the past to design RCA concrete required moderate to high cement content. To verify the eco-efficiency of the RCA mixtures studied in this work, Damineli et. al. index, the so-called *Binder Intensity* (bi), was appraised. It is defined as the amount of binder required per 1 desired unit of a given performance; e.g. PC required in kg/m^{3} for 1 MPa of compressive strength at 28 days calculated using Equation 5.3

$$\text{bi} = \frac{\mathbf{B}}{\mathbf{CS}} \qquad \text{Equation 5.3}$$

Where, B is amount of binder expressed in kg/m^{3} and CS is compressive strength in MPa. The bi indices worldwide were benchmarked and it has been noticed that for high compressive strengths (>50MPa), concrete mixtures often present a lower bi factor; yet, for conventional concrete used in civil infrastructure (20-40 MPa), which likely represents over 85% of concrete's production around the globe, bi factors are very high (i.e. 10-12 kg m^{-3} MPa^{-1}).

In this research work, the bi factors of conventional concrete were found to be 12.0, 10.3 and 9.2 kg/m^{3} for 25, 35 and 45 MPa concrete mixes respectively. However, the EV mix designed recycled concrete mixtures presented low bi factors with average of 7.6 and 7.2 kg/m^{3} for limestone and granite CRCA. Similarly, FRCA recycled mixes presented average bi factor of 12.4 and 13.1 kg/m^{3} for manufactured and natural sand respectively, which is comparatively higher.

5. Recommendations for future work

With promising results for 100% CRCA and FRCA concrete observed in this study, the following further investigations are suggested.

- Considering durability aspects for CRCA and FRCA concrete such as freeze & thaw, sulphate attack, chloride penetration, etc., on EV designed recycled concrete.
- Further microscopic analyses are required to fully understand the mechanical behaviour of EV-mix designed concrete incorporating recycled coarse and fine aggregates.
- Structural performance of reinforced CRCA and FRCA concrete designed by the EV method.
- Influence of the age of the RCA obtained from returned crushed concrete on the fresh and hardened state properties of RCA concrete.
- Advanced recycling techniques to produce CRCA and FRCA with least variability and their characterization in large quantity to incorporate in RCA concrete.
- Quality control on the production of CRCA and FRCA materials.

Appendix

The first step of equivalent volume (EV) method is to mix design a conventional concrete (CC) which will be used as control mix. We have used ACI mix design method as it is widely used in North America.

Table A- 1: Conventional concrete mix proportions

Mass*	Specific gravity	Volume compounds**	Volume paste***	Volume aggregates
1.00	3.13	0.320	0.77	1.85
2.27	2.69	0.844		
2.83	2.80	1.011		
0.45	1.00	0.450		
	Total	**2.625**		

Mass* is the mixture proportion mass presented in ratio (i.e. ingredient/cement). Volume compounds** are the ratio of Mass* and specific gravity of ingredient. Volume paste*** is the summation of cement and water.

Second step is to determine the amount RM attached to CRCA. From RM the amount of OVA in RCA can be calculated using 100-RM.

Table A- 2: RM and OVA of CRCA

RMC %	RA %	Sand in Mortar %	Cement in mortar %
40	60	83.61	16.39

Third step is to measure specific gravity of CRCA and aggregates to be used for EV mix

Table A- 3: Specific gravity of constituent materials

Measured specific gravity	
SSD (CA)	2.83
SSD (CRCA)	2.40

Fourth step is to satisfy the salient features or conditions of EV method which is to have same amount of cement paste and aggregate in EV mix as in control mix.

$$V_{CPRCA\text{-}Concrete} = V_{CPCC}$$

$$V_{AgRCA\text{-}Concrete} = V_{AgCC}$$

Where: $V_{CPRCA\text{-}Concrete}$ is the total volume of paste in the FRCA mix; V_{CPCC} and V_{AgCC} are the cement paste and aggregate volumes (both fine and coarse), respectively, in the reference CC mixture; $V_{AgRCA\text{-}Concrete}$ is the total volume of both coarse and fine aggregates.

Next step since the specific gravity of RM is unknown and it is required to estimate the proportions of CRCA concrete volume can be calculated (Table A-4). Hence, the specific gravity of RM has to be estimated as shown in Table A-4 (i.e. RM and RM Supp). With accurate estimation of this value, the measured specific gravity value of FRCA should match with theoretical ones (TableA-5).

Table A- 4: Calculation of supplementary amounts of material

			RCA Concrete			
	Mass RCA	**Mass CC**	**Specific gravity**	**Volume compounds**	**Volume paste**	**Volume aggregates**
New cement	0.803	1.00	3.13	0.257		
Residual cement	0.197		3.13	0.063	0.77	1.88
New sand	1.268	2.27	2.69	0.471		
Residual sand	1.002		2.69	0.373		
RCA	1.698	2.83	2.80	0.606		
RM	1.132		**1.80**	0.629		
Supp. FA	0.908		2.69	0.338		0.77
Supp. CA	0.156		2.80	0.093		
RM supp CA	0.067		**1.80**	0.037		
water		0.45	1.00	0.450	RCA Paste	RCA Aggregates
			Total	2.651	0.77	1.88

Table A- 5: Specific gravity values

Specific gravity			
Measured (CRCA)	Theoretical (CRCA)	Residual Aggregate (RA)	Residual Mortar (RM)
2.4	2.40	1.68	0.72

In sixth step, using specific gravities calculated in previous step the material proportion in mass for CRCA mix is calculated (Table A-6)

Table A- 6: Mix proportions of CRCA in mass

Mass RCA	
Cement	1
Sand	2.71
CRCA	3.80
Water	0.45

The final step involves conversion of unit basis mix proportions to mass. Thus, mix design proportion using optimized EV method is obtained.

Table A-7: Mix proportions of CRCA

	Mass RCA	
	Unit	kg/m$_3$
Cement	1	291.67
Sand	2.71	789.78
CRCA	3.8	1108.36
Water	0.45	131.25