Open Access

Recent Progress in Materials

LIDSEN Publishing Inc.

Original Research

Influence of Recycled Concrete Aggregate Type on Rheological Behaviour of Mixtures Proportioned Using the Equivalent Volume Method

Mayra De Grazia †, Cassandra Trottier †, Sergio R. A. Dantas †, Yathiraj Nagaraju †, Rouzbeh Ziapour †, Hian F. Macedo †, Leandro F. M. Sanchez †, *

Department of Civil Engineering, University of Ottawa, 161 Louis-Pasteur Private, K1N 6N5, Ottawa, Canada; E-Mails: mayra.grazia@uottawa.ca; ctrot059@uottawa.ca; sandrade@uottawa.ca; ynaga017@uottawa.ca; rziap098@uottawa.ca; hdefr095@uottawa.ca; leandro.sanchez@uottawa.ca

† These authors contributed equally to this work.

* **Correspondence:** Leandro F. M. Sanchez; E-Mail: leandro.sanchez@uottawa.ca

Academic Editor: Farhad Aslani

Special Issue: Wastes, Residues and Byproducts for the Production of Construction Materials

Recent Progress in Materials
2022, volume 4, issue 3
doi:10.21926/rpm.2203017

Received: July 11, 2022
Accepted: August 30, 2022
Published: September 07, 2022

Abstract

The ever-growing urgency to combat climate change has led the civil construction industry to develop and adopt sustainable construction materials and methods. The so-called recycled concrete aggregate (RCA) emerges as an alternative to decrease the carbon footprint of new concrete construction, the disposal of waste concrete, and the use of non-renewable natural resources such as cement and aggregates. RCA can be produced from crushing waste concrete; yet challenges remain when using RCA in concrete especially its fresh state behaviour due to its distinct multi-phase nature and microstructure (i.e., presence of residual mortar (RM)/residual cement paste (RCP)). In this context, this work presents a comprehensive study of the rheological behaviour of recycled concrete mixtures through the use of a planetary rheometer (IBB). The recycled mixtures were proportioned using the Equivalent Volume (EV) method, a mixture proportioning technique that accounts for the RM and RCP, respectively, and improves the recycled mixture's hardened state properties, incorporating distinct: 1) coarse RCA having various inner qualities (i.e., 25 MPa, 35 MPa and 45 MPa) and mineralogy (i.e., limestone and granite) and 2) fine RCA made from natural or manufactured sand while having different degrees of processing (i.e., crushed once vs continuously crushed). All recycled mixtures produced in this study present shear-thinning profiles, suggesting that these mixtures are suitable for applications under high torque regimes such as vibrated or pumped concrete. Additionally, they were produced with 100% recycled concrete aggregate (either fine or coarse RCA), classifying them as low embodied energy mixtures.

Keywords
Recycled concrete; recycled concrete aggregates (RCA); equivalent volume (EV); fresh state; rheological behaviour; shear-thinning; concrete technology

1. Introduction

Construction and demolition waste (CDW) is among the new sources of materials used in concrete by recycling and repurposing surplus or used materials such as the so-called recycled concrete aggregates (RCA). Recently, many efforts have been made to incorporate RCA into new concrete construction yet, is still limited to non-structural applications and in percentage due to its generally lower performance when compared to conventional concrete (CC). The reluctance towards the use of RCA is partially derived from the material's variability, presence of impurities (i.e., other debris, corrosion products, alkali-aggregate reaction – AAR, etc.), and the attached residual mortar (RM). Ideally, knowing the concrete's properties (i.e., mix-design, compressive strength, water-to-cement ratio – w/c, modulus of elasticity, etc.) and history (i.e., age, loading, weathering, exposure, etc.) can help to avoid certain issues that may arise when used as RCA; however, the source of the material (i.e., parent concrete) may not always be known, especially when mixed with other source concrete. It is therefore imperative to adopt new techniques to account for such issues and reduce the overall variability of the recycled mixtures' performance and produce concrete that is deemed eco-efficient [1, 2]. As such, RCA presents a distinct multi-phase nature comprising of original virgin coarse aggregate (OVA), RM and the interfacial transition zone (ITZ) formed between both components thus, RCA differs significantly compared to natural aggregate (NA). Generally, coarse RCA is composed of OVA and RM while the fine RCA is mainly or completely composed of RM (depending on the crushing sequence); further divided into residual cement paste (RCP) and residual sand. Consequently, the reported lower performance of concrete made with RCA has immensely been attributed to the RM [3-5]. Evidently, the adhered RM may present a higher absorption capacity resulting in an overall higher water demand in the recycled mixture to achieve the desired fresh state performance while compromising the hardened state behaviour (i.e., compressive strength, porosity, etc.). As such, mixture proportioning techniques (i.e., Equivalent Mortar Volume – EMV, its modified version EMV – mod and Equivalent Volume – EV) developed specifically for RCA which account for the presence of RM/RCP have shown to improve the overall performance of coarse RCA [6-10] while also reducing the new cement content. Among those, the EV method [10] is the most recent and optimized technique used in various studies [11-

14]. Yet, the rheological behaviour of distinct recycled mixtures designed through the EV must be evaluated to better understand their further applications in the field.

2. Background

Table 1 provides a summary of the acronyms used throughout this study to enhance text flow and readability about RCA mixtures.

Table 1 Acronyms definitions.

Acronyms	Stands for	Description
CRCA	Coarse recycled concrete aggregates	Aggregate obtained by crushing concrete waste. It refers to coarse RCA (>5 mm)
CDW	Construction and demolition waste	-
CC	Conventional Concrete	Concrete developed with standard mix-design methods and materials.
CF	Crusher fines	A method used to crush conventional concrete into FRCA
DRM	Direct replacement method	Mix-design method used to replace fine or coarse aggregate
EMV	Equivalent mortar volume	Mix-design method for RCA concrete that accounts for the RM attached to coarse particles
EMV-mod	Equivalent mortar volume modified	Mix-design method for RCA concrete based on the EMV technique. It was created to enhance the fresh state performance of RCA mixtures.
EV	Equivalent volume	Mix-design method for RCA concrete that accounts for the RM or RCP attached to coarse or fine RCA particles. This method is based on the EMV and EMV-mod
FRCA	Fine recycled concrete aggregates	Aggregate obtained by crushing concrete waste. It refers to fine RCA (<5 mm)
FG	Fully ground	A method used to crush conventional concrete into FRCA
MS	Manufactured sand	-
NA	Natural aggregate	Natural aggregate obtained from crushed stone or gravel
NM	New Mortar	
NS	Natural sand	-
OVA	Original virgin aggregate	A portion of RCA that contains only the natural aggregate
RCA	Recycled concrete aggregates	Aggregate obtained by crushing concrete waste. It refers to both coarse (>5 mm) and fine (<5 mm) aggregates

RCP	Residual cement paste	The portion of hydrated/unhydrated cement attached to RCA
RM	Residual mortar	The portion of mortar comprised of natural or manufactured sand and hydrated/unhydrated cement attached to the surface of RCA particles

2.1 Recycled Concrete Aggregates (RCA)

RCA is manufactured by crushing, sieving, and washing concrete that was: a) returned to the concrete plant as surplus or rejected on-site (i.e., returned concrete), or b) provided by CDW (i.e., demolished concrete). The final product of this process is coarse and fine RCA (i.e., CRCA and FRCA) respectively. Generally, the FRCA is considered a by-product of CRCA production and is not used in new concrete construction. As such, CRCA has been the focus of many works throughout the last years. As aforementioned, RCA is a multi-phase material comprised of RM adhered to coarse original virgin aggregate (OVA); the RM can further be divided into RCP and residual sand (Figure 1) thus, distinguishing an RCA particle from a natural aggregate. As a result, RCA particles usually have a lower density and higher absorption capacity due to their more porous nature as well as induced micro-cracks present in the RCA particle due to the RCA crushing process [15, 16]. Consequently, the increase in the RCA's absorption capacity can be as high as 12% [17-19]. In general, the direct replacement method (DRM) is used to proportion recycled mixtures where the RCA particles replace the natural aggregates thus, increasing the overall porosity of the recycled mixture and its water demand. Although additional cement can be used to counteract the adverse effects of the RCA's physical properties on the recycled mixture's performance, this approach contradicts the eco-efficient nature of concrete made with RCA.

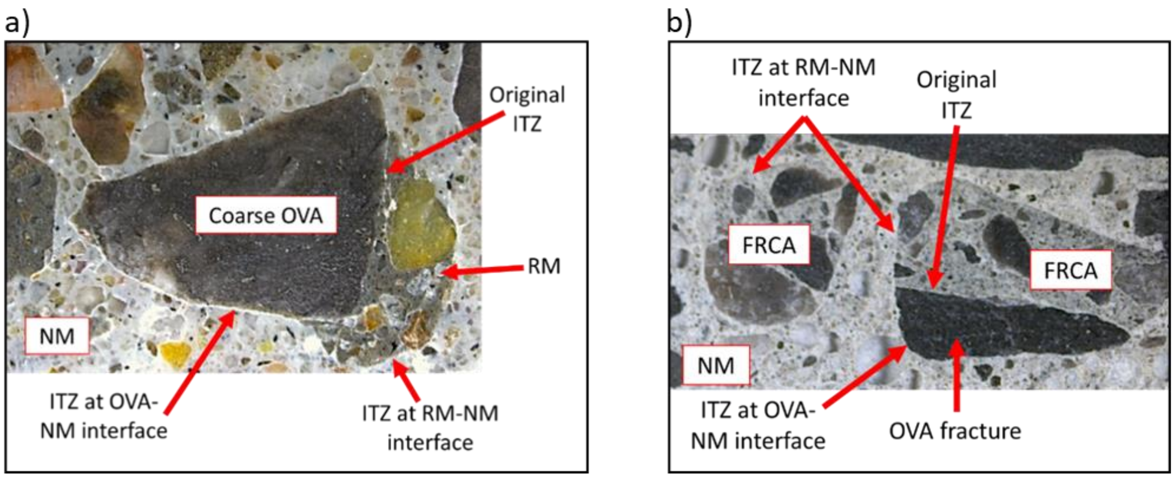

Figure 1 RCA multi-phase nature in a) coarse and b) fine RCA particles. Note: RM: Residual Mortar; OVA: Original Virgin Aggregate; NM: New Mortar; FRCA: Fine Recycled Concrete Aggregate; ITZ: Interfacial Transition Zone.

Previous studies on concrete made with CRCA show that the higher the RM content, the lower the RCA concrete mechanical properties for mixtures proportioned with the DRM [20-26] yet, the quality of the RM also plays an important role in the recycled concrete's mechanical properties [10]. Moreover, recent studies have been conducted to improve and evaluate the performance of concrete made with FRCA [12-14, 27]. Indeed, the multi-phase nature of FRCA is influenced by its crushing procedure where a more severe crushing sequence results in a lower RCP content which in turn influences the concrete's properties and performance.

2.2 Mix-Design Methods Using RCA

Despite the notion of RCA being an inferior type of aggregate, targeted mechanical properties can be achieved using the DRM when using RCA as a partial replacement of natural aggregate [28-31]. However, such variability among studies enhances the need to use new techniques thus, increase the predictability of the recycled mixture's behaviour. As such, several proportioning techniques were recently proposed to account for the RM or RCP and enhance properties of concrete made with RCA and thoroughly discussed in a literature review by De Souza et al. [32]. The first attempt to proportion concrete while taking into account the RM adhered to the RCA particles was proposed by Fathifazl et al. [6] through the Equivalent Volume Method (EMV) where the recycled mixture was designed such that the total volume of mortar (i.e., residual and new mortar) matched that of a so-called companion CC. However, this technique presented issues in the fresh state which were addressed in its modified version proposed by Hayles et al. [9] by allowing the designer to have better control over the sand-to-cement mass ratio yet, resulting in a higher cement content required to achieve the targeted compressive strength. The EV method [10] was then developed based upon the drawbacks of both techniques by accounting for the RM/RCP and matching the total amount of cement paste (i.e., residual and new cement paste) and the total amount of aggregate (i.e., OVA, coarse aggregate, residual and new sand) to that of the companion CC resulting in an eco-efficient concrete. Moreover, work has shown that the EV method produces suitable concrete despite the type of RCA used [11]. Furthermore, the EV method was further used while incorporating FRCA which showed an overall better performance compared to using the DRM [12-14]. Figure 2, therefore, illustrates the volumetric comparison of concrete proportioned through the EV method using CRCA and FRCA along with its companion CC.

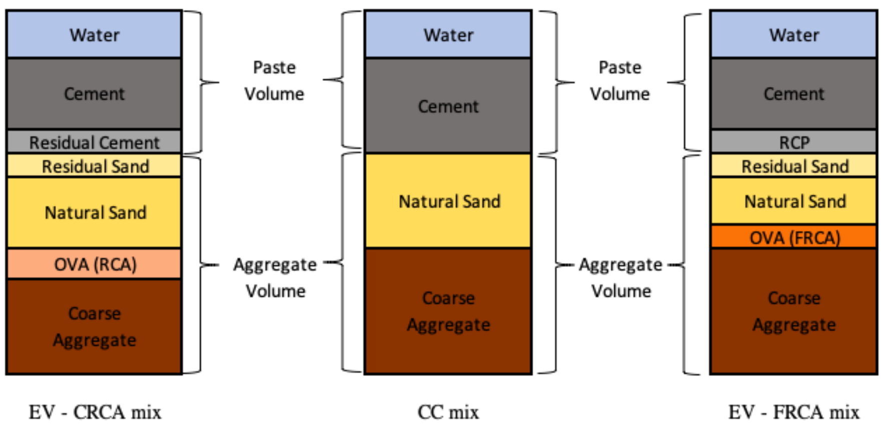

Figure 2 Volumetric comparison of CC with EV-CRCA [10] and EV-FRCA [12] mixture proportions.
Note: OVA: Original Virgin Aggregate; CC: Conventional Concrete; EV: Equivalent Volume mix-design method; CRCA: Coarse Recycled Concrete Aggregate; FRCA: Fine Recycled Concrete Aggregate; RCP: Residual Cement Paste.

2.3 Rheology of Recycled Concrete Mixtures

The fresh state behaviour of concrete can be evaluated and quantified through rheology. Factors such as the water-to-cement ratio, aggregate angularity, texture, gradation, etc. are known to influence the rheological profile of CC. However, the fresh state performance remains among the main challenges and concerns with regards to concrete made with RCA. Previous studies have mainly investigated the fresh state properties of RCA concrete mixtures through their consistency (i.e., slump test) [25, 33-36]. Meanwhile, self-compacting concrete (SCC) incorporating RCA requires the use of additional tests 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 entirely describe the fresh state behaviour of concrete mixtures. Therefore, recent studies have used rheometers to evaluate the fresh state properties of RCA concrete mixture and obtained a more comprehensive overview of its behaviour [38, 40, 41] yet, remains limited, especially regarding the influence of the distinct RCA type. Although advanced mix-design techniques have been shown to reduce the variability in hardened state properties of concrete made with various types of RCA, few works have evaluated their influence on the rheological behaviour of recycled mixtures [40, 41]. Nonetheless, a challenging aspect of concrete made with RCA remains that the RM/RCP acts as a sole aggregate in the fresh state while being incorporated as a mortar in the hardened state aspects which is more evident with high RCA replacement ratios.

3. Scope of Work

New mix-proportioning techniques accounting for the RM and RCP in recycled concrete mixtures have shown to improve their hardened state properties, however, few works have addressed and proposed solutions to improve the fresh state of such mixtures. This work, therefore, aims to appraise the fresh state properties (i.e., slump and rheological profile) of recycled concrete mixtures made with either CRCA or FRCA and proportioned using the EV method [10] while varying the distinct RCA features (i.e., mineralogy, texture, density, RM quality, manufacturing process, etc.). First, six types of CRCA were produced by varying the OVA (i.e., limestone and granite) and parent CC strength (i.e., 25 MPa, 35 MPa and 45 MPa) to vary the RM quality. In addition, the four FRCA mixtures were fabricated using either natural or manufactured sand and using two different crushed methods (i.e., Crusher Fines - the initial by-product of CRCA production or Fully Ground - consecutively crushed to obtain the targeted size). Six CRCA and four FRCA mixtures were designed using the EV-method and a selected w/c to achieve compressive strength of 35 MPa. Then, the fresh state and their rheological profile were quantified and compared to that of CC. Conclusions were drawn to propose suitable applications for the recycled mixtures used in this study.

4. Materials and Methods

4.1 Production and Properties of RCA

Before crushing the concrete cylinders to produce RCA, CC mixtures were produced using the dosage presented in Table 2. A total of 10 distinct types of RCA were produced, 6 CRCA and 4 FRCA mixtures. To the CRCA, CC mixtures, having various strengths (i.e., 25 MPa, 35 MPa and 45 MPa) to represent different qualities of RM, were designed as per the absolute volume method while incorporating either a coarse crushed limestone or granite sourced locally to vary the OVA within the RCA combined with a local natural sand. Meanwhile, the FRCA were produced using either a natural or manufactured sand combined with a crushed coarse limestone and proportioned to have a 35 MPa design strength. Concrete cylinders (i.e., 100 × 200 mm) were fabricated for each concrete mixture, moist cured at 20°C, demoulded after 24 hours and additionally moist cured at 20°C for a total of 28 days. To manufacture the CRCA particles, the concrete cylinders were jaw crushed using a 19 mm opening and then sieved to obtain aggregates sized from 4.75 mm to 19 mm. The FRCA on the other hand was obtained through two different crushing series to further produce two more types of FRCA by jaw crushing: a) the concrete cylinders and output twice, and b) the CRCA (i.e., greater than 4.75 mm) obtained from a first crushing and further crushing it twice. The material was then sieved to obtain particles smaller than 4.75 mm representing thus, crusher's fines (CF) and fully ground (FG) FRCA, respectively.

Table 2 CC mixture proportions to produce CRCA and FRCA.

	CRCA					
Aggregate type	**Crushed Limestone**			**Granite**		
Concrete strength (MPa)	**25**	**35**	**45**	**25**	**35**	**45**
Cement (kg/m^3)	314	370	424	314	370	424
Fine aggregate (kg/m^3)	840	840	840	806	806	806
Coarse aggregate (kg/m^3)	1050	1050	1050	1182	1182	1182
Water (kg/m^3)	192	174	157	192	174	157
Water/Cement ratio	0.61	0.47	0.37	0.61	0.47	0.37
	FRCA					
Aggregate type	**Natural sand**			**Manufactured sand**		
Concrete strength (MPa)	**35**			**35**		
Cement (kg/m^3)	370			370		
Fine aggregate (kg/m^3)	898			934		
Coarse aggregate (kg/m^3)	1032			1032		
Water (kg/m^3)	174			174		
Water/Cement ratio	0.47			0.47		

Note: CC: Conventional Concrete; CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates.

All the distinct types of RCA were characterized through their specific gravity, absorption capacity (%) and RM or RCP for the coarse and fine RCA, respectively and are presented in Table 3. The residual mortar content (RMC) of the CRCA was determined according to the method proposed by Abbas et. al. [21], where CRCA are exposed to freeze and thaw cycles while submerged in a sodium sulphate solution to induce mechanical and chemical degradation, respectively, and the bulk specific gravities and water absorption were determined as per ASTM C127-15 [42]. Meanwhile, the content of RCP in 2.5 g samples of FRCA was determined through the soluble silica sub-procedure as per ASTM C1084-15 [43] and ASTM C114-18 [44]. This method was preferred due to the use of the limestone coarse aggregate in the production of FRCA, which restricted using other methods such as maleic acid digestion. Moreover, the standard procedure for the specific gravity and water absorption provided used for the CRCA was not suitable for FRCA due to its cohesiveness and binding nature. Thus, the method proposed by Rodrigues et al. [45] was used for this study. Further details on those methods can be found in [12, 46].

Table 3 Detailed characterization of aggregates.

Aggregate type	Specific gravity (g/cm^3)	Absorption capacity (%)	Fineness modulus	RMC/RCP (%)
Granite (GR)	3.01	0.29	-	-
Limestone (LS)	2.78	0.42	-	-
Natural sand (NS)	2.67	0.86	2.59	-
Manufactured sand (MS)	2.74	0.65	2.85	-
25 MPa – GR - CRCA	2.63	5.63	-	45.6
35 MPa – GR - CRCA	2.65	5.32	-	48
45 MPa – GR - CRCA	2.67	5.2	-	50.2
25 MPa – LS - CRCA	2.4	5.4	-	40
35 MPa – LS - CRCA	2.41	5.09	-	45.6
45 MPa – LS - CRCA	2.43	4.88	-	52.1
NS-CF-FRCA	2.47	7.87	3.27	15.5
NS-FG-FRCA	2.56	6.38	2.53	11.5
MS-CF-FRCA	2.51	7.76	2.7	16.8
MS-FG-FRCA	2.58	6.16	2.85	11.4

Note: CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA); CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates.

4.2 Mixture Proportioning of Recycled Concrete

Six concrete mixtures were produced using the different types of RCA (i.e., with distinct strengths and OVA types) through the EV method with a companion CC having a w/c of 0.45 and using a replacement ratio of 100% and combined with a natural local sand. Moreover, four 100% FRCA (i.e., 35 MPa with distinct fine aggregate types) were also proportioned through the EV method with a companion CC having a w/c of 0.35 and combined with crushed coarse limestone. One may note the reduction in the w/c for the FRCA mixtures which was required to achieve the targeted strength of 35 MPa [12, 13]. Noticeably, the amount of cement is lower than that of CC to account for the RM/RCP in the new concrete. In addition, high range water reducing (HRWR) admixture was added to all mixtures as a percentage of the cement by mass 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 as a percentage of the cement by mass to design concrete under exposed conditions in North America (e.g., Class C1). The proportions of each recycled concrete mixture are presented in Table 4.

Table 4 Detailed CRCA mixture proportion using EV method for CRCA.

CRCA type	**Crushed Limestone**			**Granite**		
RCA strength (MPa)	**25**	**35**	**45**	**25**	**35**	**45**
Ingredient	**kg/m³**	**kg/m³**	**kg/m³**	**kg/m³**	**kg/m³**	**kg/m³**
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
w/c	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

FRCA type	**Natural Sand (NS)**		**Manufactured Sand (MS)**	
Crushed Type	**CF**	**FG**	**CF**	**FG**
Ingredient	**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
w/c	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

Note: CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA); CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates; HRWR: High Range Water Reducer; AEA: Air-Entrained Admixture.

4.3 Fresh State Assessment of Recycled Concrete Mixtures

The fresh state performance of the CC, CRCA, and FRCA concrete mixtures was appraised by consistency measurements (i.e., slump test) and rheological characterization using a planetary rheometer (IBB) as illustrated in Figure 3a. The H-shaped impeller (Figure 3b) has a height of 100 mm and length of 130 mm and covers an area of 4002.3 mm^2 whereas the bowl's diameter is 360 mm, and its height is 250 mm [47]. The targeted slump is 100 ± 20 mm which falls within the range of 40 mm to 300 mm thus, deeming this device suitable to evaluate the concrete mixtures [48].

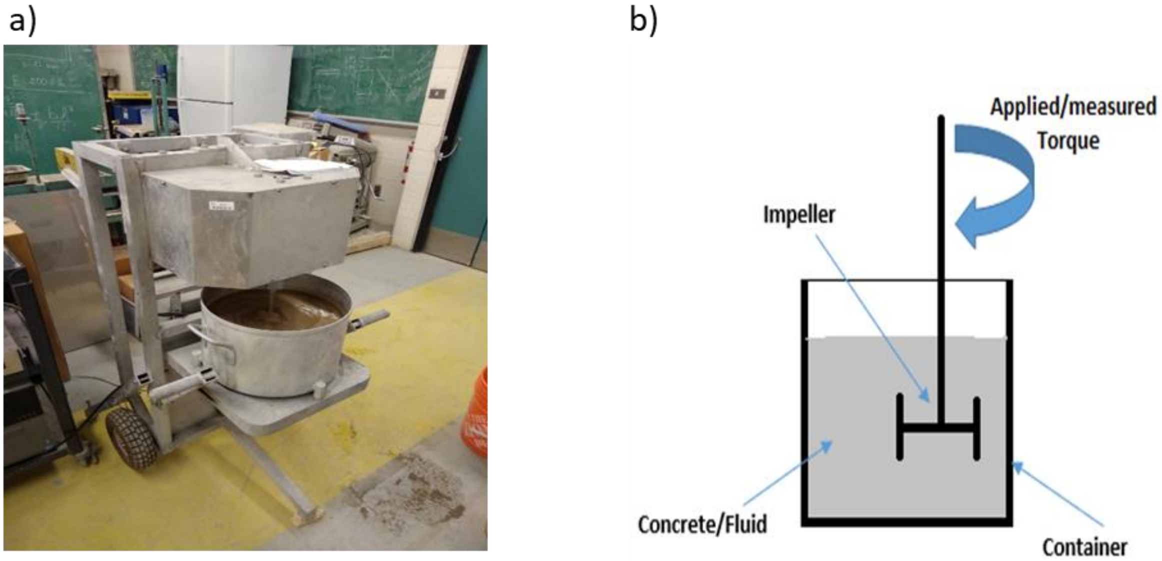

Figure 3 Illustration of the rheometer used: a) the IBB rheometer and b) schematics of a rotating impeller.

Despite the output of the IBB rheometer providing only two Bingham parameters (i.e., yield stress in N.m and plastic viscosity in N.m.s) which are not presented in fundamental units (Pa and Pa.s, respectively), similar trends can be found when analyzing rheological profile on other types of rheometers [47, 48]. The flow curves for the mixtures appraised in this study were therefore plotted using the output dataset from the IBB rheometer. Then, a comparison was made between the mixtures evaluated in this study as no direct comparison to the results of various rheometers can be made.

The rheological characterization (i.e., profile) was thus obtained by shearing the concrete sample placed in a 20-liters pan from 0 rpm to 43 rpm. The impeller rotates by increasing the rotational speed in a stepwise fashion (i.e., 10 seconds per step) during its ascending cycle (i.e., 90 seconds and up to a shear rate of 0.7 s^{-1}) followed by a descending cycle while measuring the torque applied at each stage of both cycles (Figure 4). This computer-controlled device, therefore, provides raw data of torque in relation to the rotational speed. To better quantify the rheological profile of the CC and recycled concrete mixtures, four key rheological parameters were measured: 1) apparent viscosity; 2) viscosity at 43 rpm; 3) yield stress defined as the minimum torque required; and 4) maximum applied torque. It is worth noting that the apparent viscosity is measured using the ratio of shear stress to the shear rate at the first deceleration point.

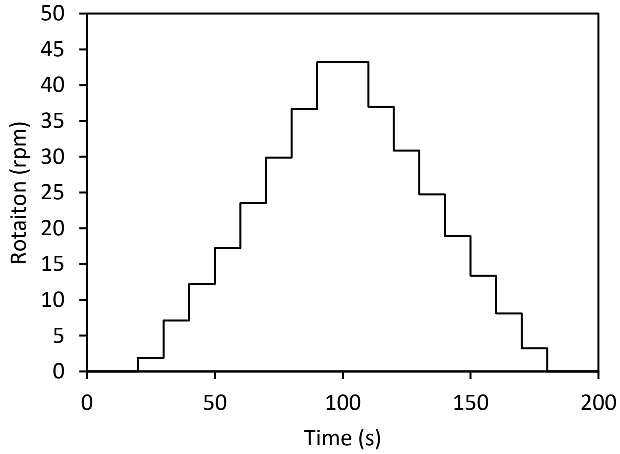

Figure 4 Diagram of the applied rotational speed per incremental time-step.

5. Results

5.1 Rheology of CC Mixtures

The rheological profiles of the CC used to produce the RCA were evaluated to further compare its behaviour to the recycled mixtures. Figure 5 shows the rheological profiles of all CC mixtures, all of which exhibit a shear-thinning behaviour; decrease in viscosity as a function of torque applied regardless of the water-to-cement ratio and aggregate type.

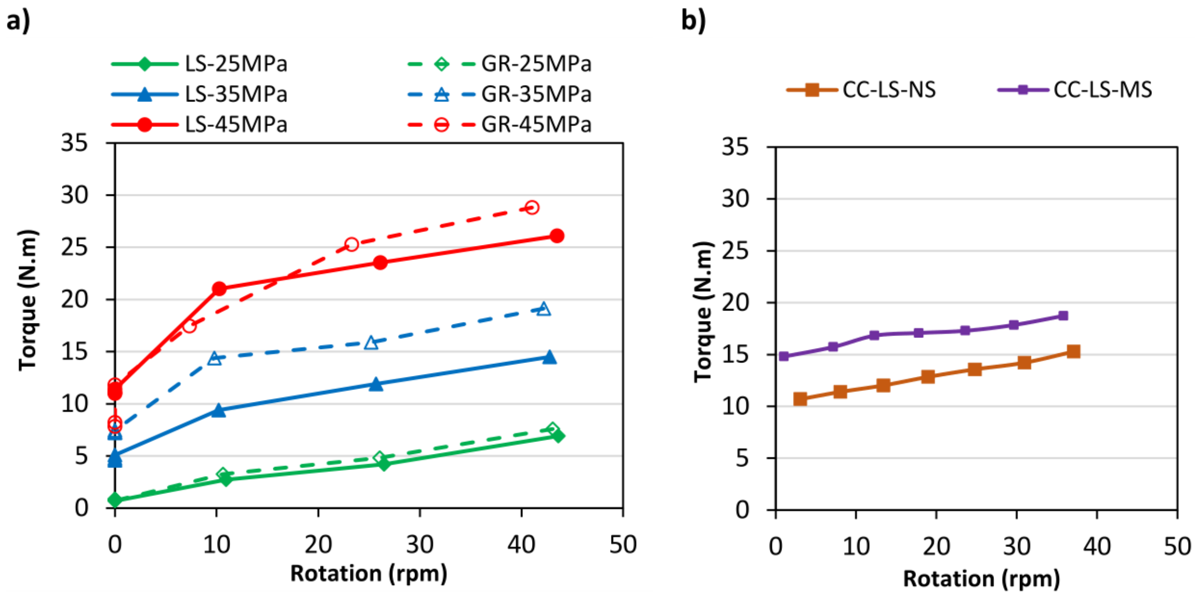

Figure 5 Rheological profile of CC mixtures used to produce: a) CRCA and b) FRCA.
Note: LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; CC: Conventional Concrete; NS: Natural Sand; MS: Manufactured Sand.

5.1.1 CC mixture manufactured to produce CRCA

Figure 5a highlights the rheological performance of six CC mixtures appraised before crushing and producing CRCA. In this analysis, one can notice the higher the concrete compressive strength, the higher the torque at higher rotation. Moreover, mixtures developed with limestone coarse aggregate (i.e., LS) yielded a slightly better rheological profile than mixtures developed with granite (i.e., GR). Yet, the distinction between the coarse aggregate types (i.e., granite versus limestone – green solid versus dashed lines) in 25 MPa CC mixtures is not as apparent, in which, the torque ranged from 0.71 N.m to 7.58 N.m. Torque values ranged from 5.08 N.m and 7.46 N.m to 14.50 N.m and 19.13 N.m for the 35 MPa limestone/granite CC, respectively, while for the 45 MPa CC the values ranged from 11.83 N.m for both to 26.09 N.m and 28.82 N.m for the limestone/granite, respectively.

5.1.2 CC mixture manufactured to produce FRCA

Two CC mixtures of 35 MPa were developed to produce FRCA, which contains natural and manufactured sand (i.e., NS and MS, respectively). The mixture made with NS (i.e., CC-LS-NS) yielded lower torque when compared to the mixture made with MS (i.e., CC-LS-MS), as displayed in Figure 5b, where values ranged from 10.70 N.m and 14.81 N.m to 15.28 N.m and 18.73 N.m for the natural/manufactured sand, respectively.

Noticeably, all 35 MPa CC mixtures (i.e., LS-35MPa, GR-35MPa, CC-LS-NS and CC-LS-MS) present similar rheological profiles, especially at the highest rotation (>30 rpm).

In addition, the slump measurements and three key rheological parameters measured were: 1) apparent viscosity (at highest rotation); 2) minimum torque or yield stress; and 3) maximum torque applied for all CC mixtures are presented in Table 5.

Table 5 Rheological parameters assessed for CC mixtures.

Mixture Name	**w/c**	**Apparent Viscosity (Nm/rpm)**	**Minimum Torque (Nm)**	**Maximum Torque (Nm)**	**Slump (mm)**
CC-LS-25MPa	0.61	0.16	0.69	11.65	150
CC-LS-35MPa	0.47	0.34	4.59	18.29	90
CC-LS-45MPa	0.37	0.60	10.98	29.87	40
CC-GR-25MPa	0.61	0.18	0.71	12.78	140
CC-GR-35MPa	0.47	0.45	7.21	23.30	95
CC-GR-45MPa	0.37	0.70	7.82	32.95	45
CC-LS-NS	0.47	0.37	10.70	16.11	110
CC-LS-MS	0.47	0.46	14.81	19.47	95

Note: LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; CC: Conventional Concrete; NS: Natural Sand; MS: Manufactured Sand.

5.1.3 Slump

The slump values are directly proportional to the w/c selected, where mixtures developed with w/c of 0.37 presented the lower slumps (e.g., 40-45 mm), while mixtures containing w/c of 0.61 yielded the higher slumps (e.g., 150-140 mm). Analyzing the aggregate type, no significant influence is noticed on mixtures developed with limestone or granite coarse aggregate (i.e., LS and GR, respectively) when similar w/c is selected, yet, the mixture made with manufactured sand (i.e., CC-

LS-MS) presents a lower slump than the mixture made with natural sand (i.e., CC-LS-NS). Therefore, one may notice that the fine aggregate type affects the slump in a higher proportion than the coarse aggregate type.

5.1.4 Apparent viscosity

It is worth noting that the apparent viscosity was measured using the ratio of shear stress to the shear rate at the first deceleration point. The results, therefore, show that the lower the water-to-cement ratio, the higher the apparent viscosity. Moreover, CC mixtures made of granite were slightly higher than the ones made of limestone, yet the higher the w/c the lower the influence of the aggregate type. A previous study [38] agrees that the rheological parameters of CRCA are highly affected when the w/c is lower. Although mixtures developed with manufactured sand and natural sand contain the same w/c, the former one presented higher apparent viscosity (0.46 Nm/rpm). Analyzing all 35 MPa mixtures (developed with w/c = 0.47), mixtures developed with natural sand (CC-LS-NS) or limestone coarse aggregate (CC-LS-35MPa) resulted in lower apparent viscosity (on average 0.35 Nm/rpm), whereas mixtures developed with manufactured sand (CC-LS-MS) or granite coarse aggregate (CC-GR-35MPa) yielded apparent viscosity of 0.45 Nm/rpm.

5.1.5 Minimum and maximum torque

The higher the yield stress (or minimum torque to enable flow), the higher the maximum torque achieved, and the lower the consistency measured. Similar to the apparent viscosity, the maximum torques obtained for CC mixtures made of granite were slightly higher than the ones made of limestone. Yet, an exception is seen in CC-GR-45MPa, where it obtained a lower minimum torque than CC-LS-45MPa. Analyzing all 35 MPa mixtures (developed with w/c = 0.47), mixtures developed to manufacture FRCA presented similar maximum torque to CC-LS-35MPa. Therefore, granite coarse aggregate is the main factor influencing maximum torque.

5.2 Rheology of EV-Designed RCA Concrete

The rheological profiles of all RCA concrete mixtures designed through the EV method are displayed in Figure 6 where all mixtures show a shear thinning behaviour yet, significantly higher torque is observed throughout for the FRCA mixtures, which may be explained by the lower w/c agreeing with a previous study [38].

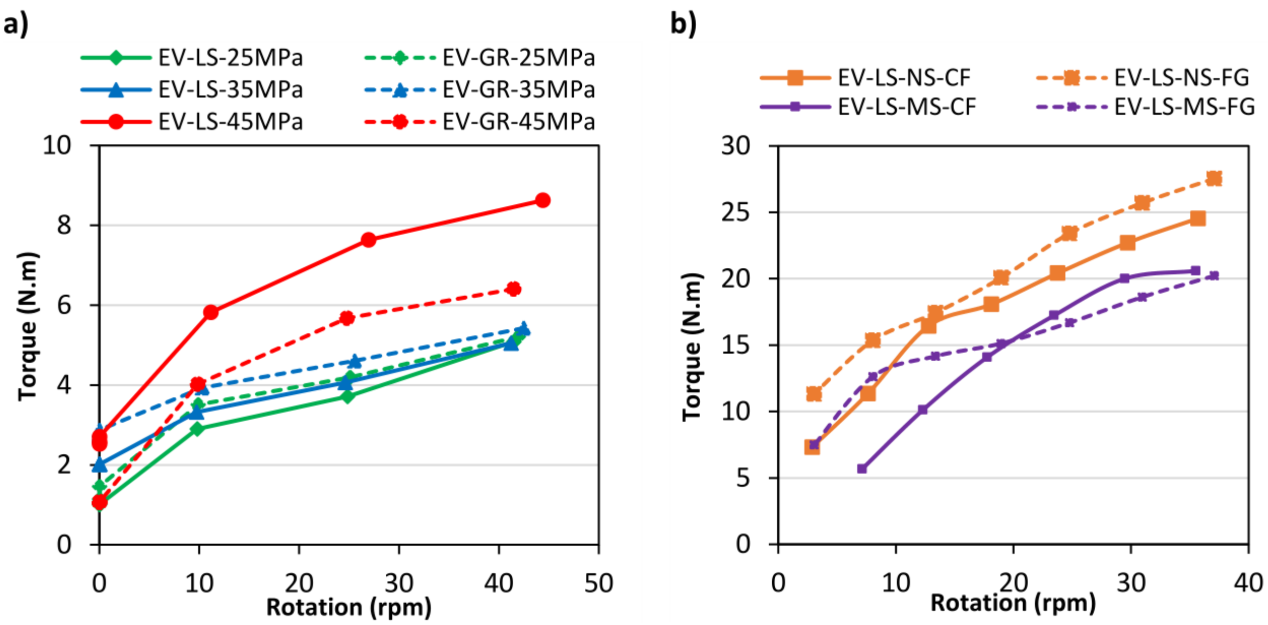

Figure 6 Rheological profile of CA concrete mixtures designed by EV method.
Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA).

5.2.1 CRCA analysis

Interestingly, the distinction between the CRCA strength (i.e., RM quality) is not as significantly evident as the CC strength presented in Figure 4a, yet only the 45 MPa-RCA mixtures (i.e., EV-LS-45MPa and EV-GR-45MPa – red solid and dashed lines) displayed a higher rheological profile. Based on Singh and Singh (2018), the yield stress of RCA mixtures increased with the better quality of CRCA (higher strength), which was mainly attributed to the use of SCMs [33]. However, in this study no different parameters (e.g., cement type or SCMs) were added to the mixtures thus, one can conclude that the CRCA quality does not affect the rheological profile.

5.2.2 FRCA analysis

Distinct from CRCA, the crushing method and the fine aggregate type used to produce the FRCA has a greater influence on the rheological parameters (Figure 6b). At lower rotation, mixtures manufactured with FRCA produced through crusher fines method (solid lines) result in lower torque. However, at higher rotation, mixtures produced with natural sand yielded higher torque, which is the opposite of the findings regarding CC (Figure 5b).

The rheological parameters measured for the EV-designed RCA concrete mixtures are shown in Table 6.

Table 6 Rheological parameters assessed for CRCA mixtures.

RCA type	Mixture Name	w/c	Apparent Viscosity (N.m/rpm)	Minimum Torque (N.m)	Maximum Torque (N.m)	Slump (mm)

CRCA	**EV-LS-25MPa**	0.45	0.12	1.08	6.72	110
	EV-LS-35MPa	0.45	0.12	1.64	6.83	100
	EV-LS-45MPa	0.45	0.19	1.91	10.12	90
	EV-GR-25MPa	0.45	0.12	1.27	6.88	120
	EV-GR-35MPa	0.45	0.13	1.51	7.32	100
	EV-GR-45MPa	0.45	0.15	1.83	8.54	85
FRCA	**EV-NS-CF**	0.35	0.69	7.33	28.97	115
	EV-NS-FG	0.35	0.73	11.33	31.97	120
	EV-MS-CF	0.35	0.58	10.12	24.78	105
	EV-MS-FG	0.35	0.63	7.48	21.88	115

Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA).

5.2.3 Slump

All recycled mixtures incorporate air-entraining and superplasticizer admixtures and were designed with a slump value of 100 ± 20 mm, since it is a common slump requirement for structural and non-structural concrete applications.

5.2.4 Apparent viscosity

Similar results are obtained for all CRCA concrete mixtures yet, significantly higher results are observed for the FRCA concrete mixtures. Both recycled mixtures display differences when compared to CC mixtures of 35 MPa in strength. Although CRCA concrete mixtures present a slight increase of apparent viscosity with higher RCA compressive strength (increasing from 0.12 to 0.19 Nm/rpm), lower values are obtained when compared to the CC mixtures (i.e., apparent viscosity >0.35 Nm/rpm). In contrast, FRCA yielded higher apparent viscosity (ranging from 0.58 N.m/rpm to 0.73 N.m/rpm) when compared to CRCA, where FRCA made of natural sand presents the highest values. (0.69 N.m/rpm to 0.73 N.m/rpm). Moreover, one may conclude that the method used to produce FRCA does not significantly affect the apparent viscosity.

5.2.5 Minimum and maximum torque

CRCA concrete mixtures present a trend of increasing apparent viscosity, minimum torque and maximum torque with higher strength of CRCA. However, a narrower range of values is obtained when compared to the CC mixtures. The minimum initial torque measured for all CRCA mixtures is in the range of 1.08 N.m to 1.91 N.m; while the maximum torque values ranged from 6.72 N.m to 10.12 N.m. Regarding FRCA mixtures, 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, the CF-FRCA made with natural sand has lower values compared to FG-FRCA yet, the parameters of FG-FRCA of manufactured sand have lower minimum and maximum torque values compared to CF-FRCA, clearly indicating that the FRCA quality (i.e., crusher fines-CF and fully ground-FG) and aggregate type used to produced FRCA affects the rheological parameters analyzed.

6. Discussion

6.1 Consistency (Slump Test)

It is a common misconception to utilize the slump test to evaluate concrete's fresh state performance and workability [49]. Although the slump test is the most commonly used procedure in-situ, it is merely a single-point test that can only describe an initial portion of the material's fresh state behaviour, the so-called consistency. Consistency is defined as the behaviour 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 [50].

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. 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 (slump - Table 6 and the rheological profile - Figure 6), although the slump values were similar, FRCA concrete mixtures presented the highest rheological parameters overall when compared to the CRCA mixtures. Therefore, it is evident that a single-point test such as slump cannot accurately describe the fresh state performance of cementitious materials.

6.2 Rheological Behaviour of Recycled Mixtures in Comparison to CC

The CC and recycled mixtures used in this study were designed to have a target slump of 100 ± 20 mm where the CC did not include any admixtures and the recycled mixtures were manufactured with HRWH and AEA admixtures to compensate for the reduction in fresh state properties when proportioning the recycled mixtures using the EV method and produce a concrete suitable for use in Canadian harsh climates (i.e., Class C1), respectively. Figure 7a) and Figure 7b) illustrate the descending curves for CC mixtures (used to manufacture the CRCA) and recycled mixtures (developed with w/c of 0.47 and 0.45), respectively. 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.

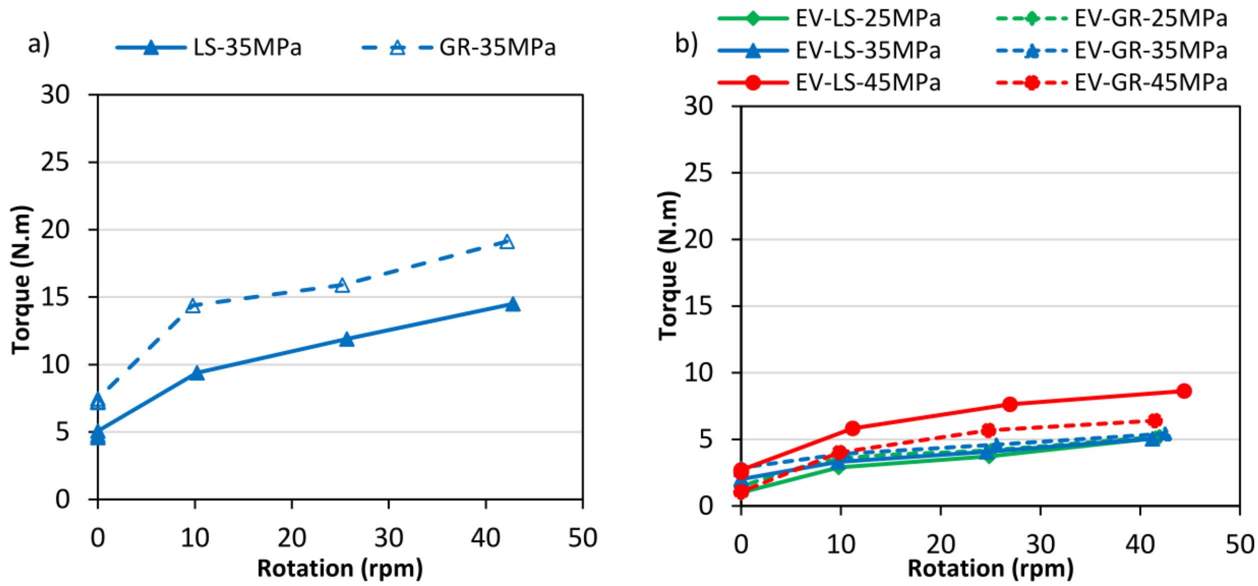

Figure 7 Descending curves of a) CC and b) CRCA concrete mixtures.
Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; CC: Conventional Concrete.

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 mixtures 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 (Table 3). Meanwhile, Figure 8a) displays the descending curve of the CC mixtures used to produce the FRCA (w/c of 0.47), while Figure 8b) presents the descending curve for FRCA recycled mixtures (w/c of 0.35). Both CC and FRCA mixtures were designed for 35 MPa, all of which display a shear-thinning behaviour (i.e., decrease in viscosity as a function of torque), but this behaviour is pronounced on FRCA mixtures. A previous study [33] that appraised self-compacting concrete also evaluated medium and high-strength RCA mixtures using the Herschel-Bulkley model and concluded that they both exhibit shear-thinning responses.

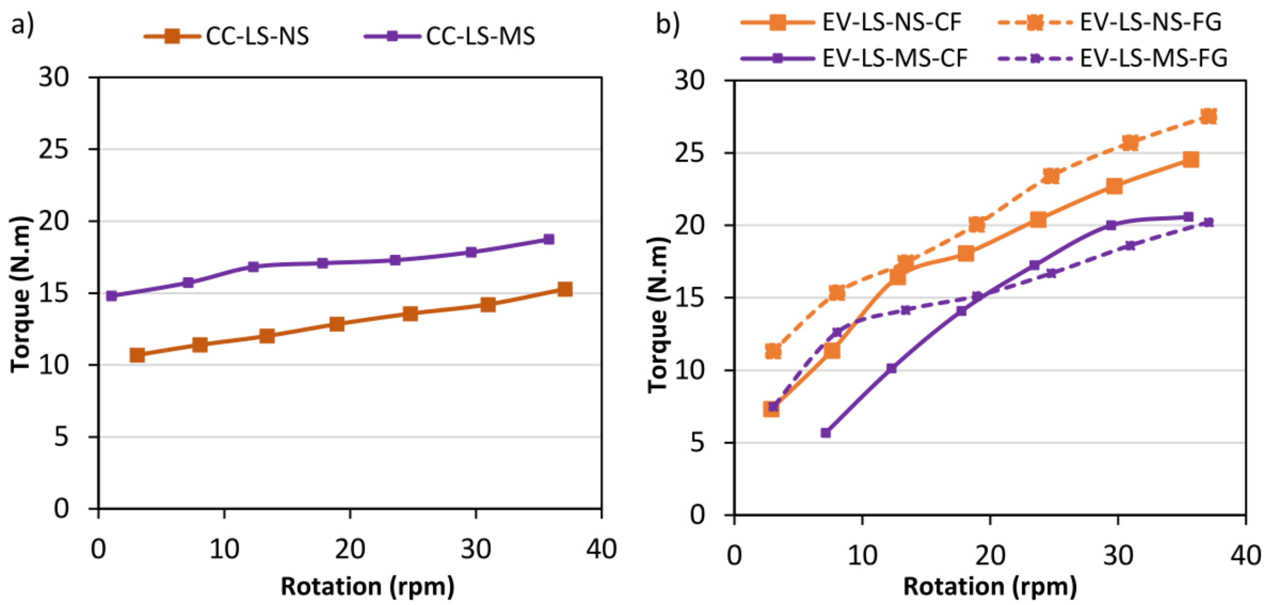

Figure 8 Descending curves of a) CC and b) FRCA concrete mixtures.
Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; CC: Conventional Concrete; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA).

In addition, Figure 8a) shows that the manufactured sand CC mixture (i.e., CC-LS-MS) reached a higher torque and apparent viscosity throughout the torque-rotation regime when compared to the natural sand mixture (i.e., CC-LS-NS). This can thus be explained by the angularity of the manufactured sand particles resulting in an adverse effect on the mixture's flow. On the other hand, the crushing procedure (i.e., crusher's fines – CF and fully ground – FG) did not present any noticeable trend as observed in Figure 8b) yet the two manufactured sand recycled mixtures exhibited slightly lower minimum torque and apparent viscosity. Although the RCP content of the natural and manufactured recycled mixtures produced with the same crushing process is quite similar (e.g., 11.4% and 11.5% respectively for the FG process), the rheological profile of the former is slightly shifted upward, which might only be an imprecision of the test.

6.3 Rheological Behaviour: CRCA Versus FRCA

The rheological behaviour presented through the descending curve of the CRCA (w/c = 0.45) and FRCA (w/c = 0.35) recycled mixtures are displayed in Figure 9a) and Figure 9b), 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 mixtures, 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].

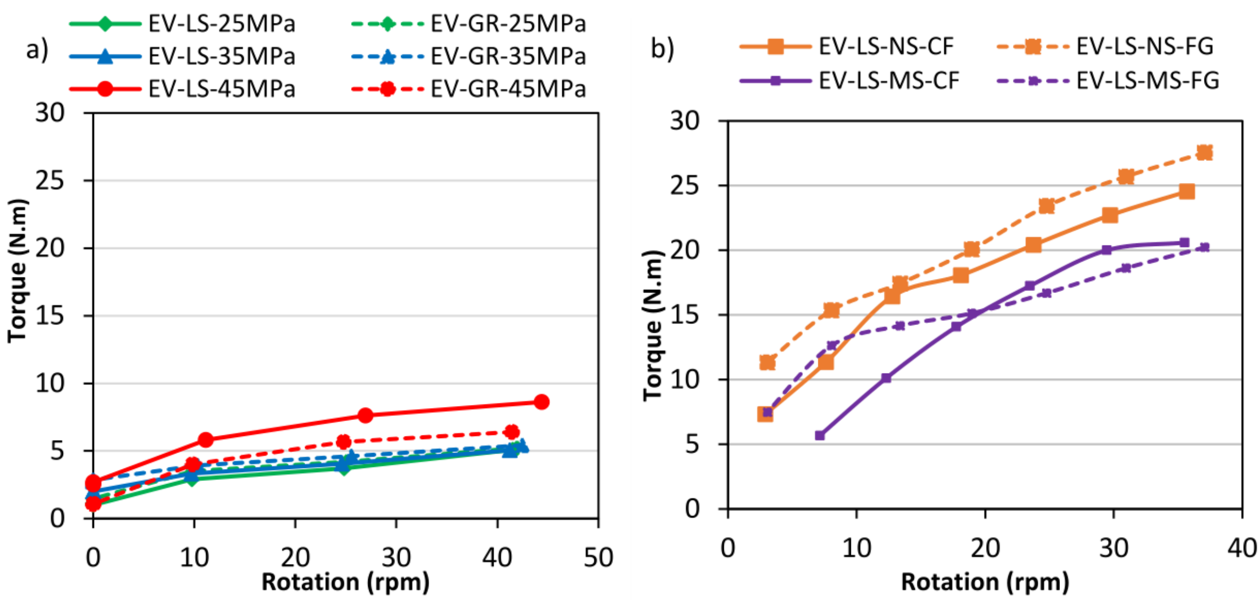

Figure 9 Descending curves of a) CRCA and b) FRCA concrete mixtures.
Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA).

Furthermore, analyzing the AV at 40 rpm from Table 6, the CRCA mixtures present lower AV than FRCA mixtures, 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 mixtures 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 while providing the targeted hardened state performance and eco-efficiency nature [10, 11].

6.4 Modelling the Rheological Behaviour of Recycled Concrete Made with CRCA and FRCA

The rheological behaviour of CC can sometimes (especially for fluid mixtures) be described by the Bingham model [40, 41, 51], which presents a linear relationship between shear stress and shear rate. Equation 1 expresses the aforementioned relationship.

$$\tau = \tau_0 + k_B \cdot \gamma \tag{1}$$

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 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, 52, 53] as per Equation 2.

$$\tau = \tau_0 + k_{HB} \cdot \gamma^n \tag{2}$$

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 the additional (compared to Bingham) flow parameter for concrete ($n < 1$ exhibits shear thinning behaviour and $n > 1$ exhibits shear thickening behaviour).

As such, the rheological profiles of all RCA mixtures including their models from the Bingham and Herschel-Bulkley approaches are presented in Figure 10. The concave shape of Herschel-Bulkley curves and flow parameter values lower than one (i.e., $n < 1$) therefore validate the shear thinning behaviour. Likewise, the rheological parameters of Bingham and Herschel-Bulkley models calculated for each CRCA and FRCA mixtures investigated in this study are presented in Table 7. Although RCA mixtures can also be evaluated with the Bingham Model as presented in [40], one can conclude that Herschel-Bulkley presents a better fit to CRCA and FRCA analyzed in this study. When 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. According to the Herschel-Bulkley model, the yield stress and apparent viscosity constant are lower for CRCA mixtures when compared to FRCA mixtures. 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 to CRCA made of granite. Similar results were also found for CF and FG types of FRCA.

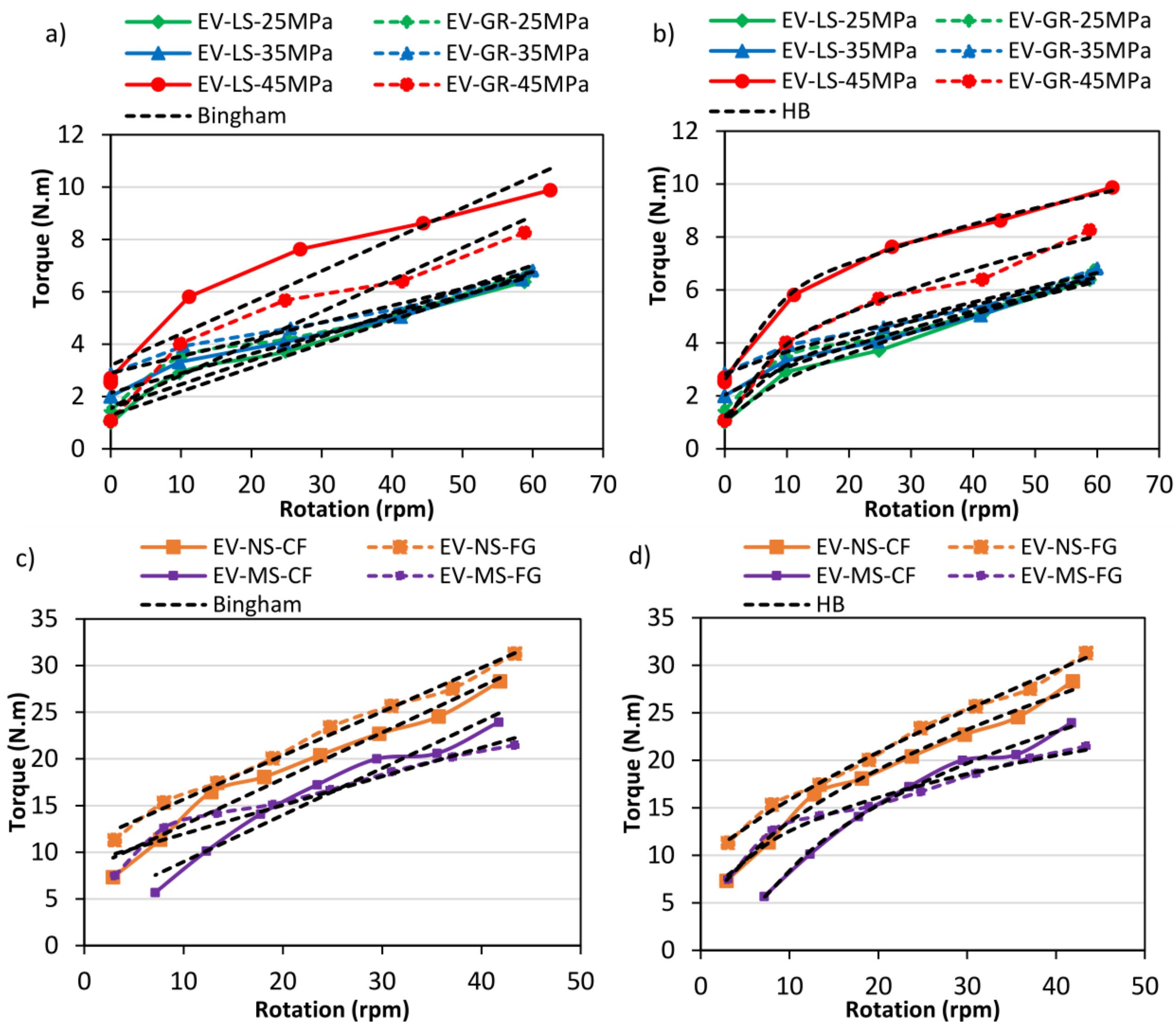

Figure 10 a) Bingham and b) Herschel-Bulkley model for rheological profiles of CRCA concrete mixtures, c) Bingham and d) Herschel-Bulkley model for rheological profiles of FRCA concrete mixtures.

Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA); CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates.

Table 7 Bingham and Herschel-Bulkley parameters for RCA concrete mixtures.

RCA type	RCA Mixture	Bingham			Herschel-Bulkley			
		Initial Torque (N.m)	τ_0	K_B	Initial Torque (N.m)	τ_0	K_{HB}	n
CRCA	**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

FRCA	**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
	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

Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA); CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates.

6.5 True Viscosity

The derivative of Herschel-Bulkley model was used to obtain the real viscosity equation (Table 8) using the Herschel-Bulkley parameters calculated and shown in Table 7. Figure 11a further shows that from 1 to 7 rpm, the recycled mixtures using the 45 MPa CRCA (i.e., EV-LS-45MPa and EV-GR-45MPa illustrated by the red lines with circle markers) present higher viscosity, followed by those using the 25 MPa CRCA (i.e., EV-LS-25MPa and EV-GR-25MPa illustrated by the green lines with diamond markers). On the other hand, the mixtures made with 35 MPa CRCA (i.e., EV-LS-35MPa and EV-GR-35MPa illustrated by the blue lines with triangle markers) resulted in a liner profile, with almost no change in the viscosity. Moreover, no significant difference is apparent in the viscosity profile of the CRCA with respect to the aggregate type (i.e., limestone-LS or granite-GR). Meanwhile, Figure 11b displays that the overall viscosity profile of mixtures developed with manufactured sand (MS) is slightly lower than mixtures with natural sand (NS). From Figure 11, one may notice that FRCA yielded higher viscosity than CRCA mixtures at low rotations (i.e., 1 rpm). As a result, at high rotation (42 rpm), FRCA mixtures have viscosities that range from 0.19 to 0.41 N.m/rpm, while CRCA mixtures had an average viscosity of 0.07 N.m/rpm. However, the 10 mixtures investigated present a shear-thinning behaviour, in which the viscosity decreases with the increase of the rotation. Regardless of the final viscosity, a concrete presenting a shear-thinning behaviour is recommended for vibrated and pumped application due to the viscosity reduction at higher rotations.

Table 8 True viscosity equations calculated through Herschel-Bulkley model.

CRCA Mixture	True Viscosity (N.m/rpm)	FRCA Mixture	True Viscosity (N.m/rpm)
LS-25MPa	$\gamma = 0.23*\gamma^{-0.33}$	**EV-NS-CF**	$\gamma = 2.09*\gamma^{-0.50}$
LS-35MPa	$\gamma = 0.14*\gamma^{-0.2}$	**EV-NS-FG**	$\gamma = 0.92*\gamma^{-0.22}$
LS-45MPa	$\gamma = 0.51*\gamma^{-0.56}$	**EV-MS-CF**	$\gamma = 1.21*\gamma^{-0.29}$
GR-25MPa	$\gamma = 0.3*\gamma^{-0.44}$	**EV-MS-FG**	$\gamma = 1.69*\gamma^{-0.58}$
GR-35MPa	$\gamma = 0.1*\gamma^{-0.15}$		
GR-45MPa	$\gamma = 0.46*\gamma^{-0.51}$		

Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA); CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates.

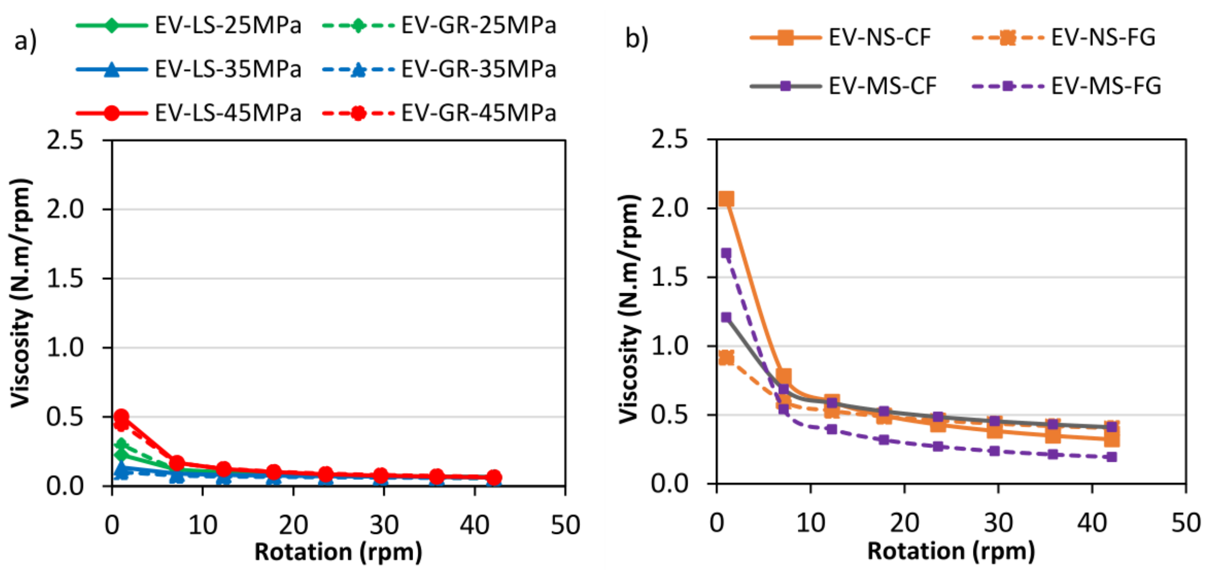

Figure 11 Herschel-Bulkley model's calculation of viscosity profile a) CRCA and b) FRCA. Note: EV: Equivalent Volume mix-design method; LS: Limestone Coarse Aggregate; GR: Granite Coarse Aggregate; NS: Natural Sand; MS: Manufactured Sand; CF: Crusher Fines (method to produce FRCA); FG: Fully Ground (method to produce FRCA); CRCA: Coarse Recycled Concrete Aggregates; FRCA: Fine Recycled Concrete Aggregates.

7. Conclusions

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

- The slump test is an unsuitable tool to appraise the fresh state performance of recycled concrete mixtures using coarse and fine RCA. Other tools such as the rheological behaviour present a more comprehensive assessment of the fresh state of such mixtures. As a result, four key rheological parameters were evaluated such as the apparent viscosity (AV), the minimum applique torque or yield stress, the torque at 43 rpm, and the maximum applied torque. Although some trends were observed between the slump and the rheological parameters, the slump showed to be inconsistent and thus, unreliable for recycled mixtures.
- All recycled mixtures presented 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 recycled mixtures designed through the EV proportioning technique are suitable for applications such as pumping and vibrating concrete. Nevertheless, the FRCA mixtures demonstrated higher yield stress and slightly higher apparent viscosity than CRCA mixtures. Yet, they are still considered suitable for vibrated and or pumped applications.

- The Herschel-Bulkley model provides an accurate estimation to predict the behaviour in the fresh state of the recycled concrete mixtures used in this study, regardless of RCA type. Such estimations are crucial to select a suitable concrete application method requiring the lowest amount of energy, thus further enhancing the eco-efficiency of the concrete. Yet, further studies using a wider range of mixtures are necessary.
- The type (fine vs coarse; natural versus manufactured), nature (mineralogy) and manufacturing process have an influence on the rheological profile of recycled concrete mixtures. However, only slight differences were observed between the various types of RCA while presenting more significant differences only with respect to the size of the RCA (i.e., coarse vs fine RCA) which was also observed through the true viscosity. Although the type of original coarse aggregate (i.e., coarse limestone or granite and natural or manufactured sand) present different rheological behaviours in CC mixtures, their influence on the RCA concrete was less evident.

Overall, the EV-proportioning method used in this study seems to be quite promising to proportion recycled mixtures with suitable fresh state performance. When compared to CC mixtures, CRCA mixtures exhibit less variability in their rheological behaviour. FRCA has nevertheless presented a shear-thinning behaviour and achieved the required slump, demonstrating their viability for application in the future. As a result, this study improved the eco-efficiency of RCA mixtures since natural aggregates can be completely replaced by CRCA and FRCA when employing the EV method, which accounts for the distinct multi-phase nature of RCA.

Acknowledgments

The authors would like to thank the National Research Council (NRC) of Canada for supplying the rheometer used in this study, André Demers at CANMET Energy with technical support during RCA production, and the team at Lafarge in St-Adèle, QC for the granite aggregate.

Author Contributions

Conceived and designed the experiments: Y.N. and L.F.M.S.; Acquired and analyzed data: M.D.G., Y.N., R.Z., H.F.M., L.F.M.S.; Drafted and revised manuscript: M.D.G., C.T., S.R.A.D., Y.N., R.Z., L.F.M.S.

Competing Interests

The authors have declared that no competing interests exist.

References

1. Abbas A, Fathifazl G, Isgor OB, Razaqpur AG, Fournier B, Foo S. Environmental benefits of green concrete. Proceedings of 2006 IEEE EIC Climate Change Conference; 2006 May 10-12; Ottawa, Canada. New York: IEEE.
2. Mehta KP. Reducing the environmental impact of concrete. Concr Int. 2001; 23: 61-66.
3. de Juan MS, Gutiérrez PA. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. Constr Build Mater. 2009; 23: 872-877.

4. Al-Bayati HKA, Das PK, Tighe SL, Baaj H. Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate. Constr Build Mater. 2016; 112: 284-298.
5. Leite MB, Monteiro PJM. Microstructural analysis of recycled concrete using X-ray microtomography. Cem Concr Res. 2016; 81: 38-48.
6. Fathifazl G, Abbas A, Razaqpur AG, Isgor OB, Fournier B, Foo S. New mixture proportioning method for concrete made with coarse recycled concrete aggregate. J Mater Civ Eng. 2009; 21: 601-611.
7. Fathifazl G, Ghani Razaqpur A, Burkan Isgor O, Abbas A, Fournier B, Foo S. Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate. Cem Concr Compos. 2011; 33: 1026-1037.
8. Fathifazl G, Razaqpur A, Isgor OB, Abbas A, Fournier B, Foo S. Shear strength of reinforced recycled concrete beams without stirrups. Mag Concr Res. 2009; 61: 477-490.
9. Hayles M, Sanchez LFM, Noël M. Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. Constr Build Mater. 2018; 169: 724-732.
10. Ahimoghadam F. Effect of recycled concrete aggregate properties on the behaviour of new concrete. Ottawa: University of Ottawa; 2018.
11. Ahimoghadam F, Sanchez LFM, De Souza DJ, Andrade GP, Noël M, Demers A. Influence of the recycled concrete aggregate features on the behavior of eco-efficient mixtures. J Mater Civ Eng. 2020; 32: 04020252.
12. De Freitas Macedo H. Concrete made with fine recycled concrete aggregate (FRCA): A feasibility study. Ottawa: University of Ottawa; 2019.
13. De Souza DJ, de Grazia MT, Macedo HF, Sanchez LFM, de Andrade GP, Naboka O, et al. Influence of the mix proportion and aggregate features on the performance of eco-efficient fine recycled concrete aggregate mixtures. Materials. 2022; 15: 1355.
14. Trottier C, de Grazia MT, Macedo HF, Sanchez LFM, de Andrade GP, de Souza DJ, et al. Freezing and thawing resistance of fine recycled concrete aggregate (FRCA) mixtures designed with distinct techniques. Materials. 2022; 15: 1342.
15. Olorunsogo FT, Padayachee N. Performance of recycled aggregate concrete monitored by durability indexes. Cem Concr Res. 2002; 32: 179-185.
16. Nagataki S, Gokce A, Saeki T, Hisada M. Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. Cem Concr Res. 2004; 34: 965-971.
17. Gómez-Soberón JMV. Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study. Cem Concr Res. 2002; 32: 1301-1311.
18. Katz A. Properties of concrete made with recycled aggregate from partially hydrated old concrete. Cem Concr Res. 2003; 33: 703-711.
19. Rao A, Jha KN, Misra S. Use of aggregates from recycled construction and demolition waste in concrete. Resour Conserv Recycl. 2007; 50: 71-81.
20. Pereira P, Evangelista L, De Brito J. The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates. Cem Concr Compos. 2012; 34: 1044-1052.
21. Abbas A, Fathifazl G, Isgor OB, Razaqpur AG, Fournier B, Foo S. Proposed method for determining the residual mortar content of recycled concrete aggregates. J ASTM Int. 2007; 5: 1-12.

22. Zhao Z, Remond S, Damidot D, Xu W. Influence of fine recycled concrete aggregates on the properties of mortars. Constr Build Mater. 2015; 81: 179-186.
23. Cartuxo F, de Brito J, Evangelista L, Jiménez JR, Ledesma EF. Rheological behaviour of concrete made with fine recycled concrete aggregates – Influence of the superplasticizer. Constr Build Mater. 2015; 89: 36-47.
24. Pedro D, de Brito J, Evangelista L. Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties. Constr Build Mater. 2017; 154: 294-309.
25. Khatib JM. Properties of concrete incorporating fine recycled aggregate. Cem Concr Res. 2005; 35: 763-769.
26. Vinay Kumar BM, Ananthan H, Balaji KVA. Experimental studies on utilization of recycled coarse and fine aggregates in high performance concrete mixes. Alexandria Eng J. 2018; 57: 1749-1759.
27. de Andrade GP, de Castro Polisseni G, Pepe M, Toledo Filho RD. Design of structural concrete mixtures containing fine recycled concrete aggregate using packing model. Constr Build Mater. 2020; 252: 119091.
28. Behera M, Bhattacharyya SK, Minocha AK, Deoliya R, Maiti S. Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review. Constr Build Mater. 2014; 68: 501-516.
29. Kou SC, Poon CS. Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. Constr Build Mater. 2009; 23: 2877-2886.
30. Safiuddin M, Alengaram UJ, Rahman MM, Salam MA, Jumaat MZ. Use of recycled concrete aggregate in concrete: A review. J Civ Eng Manag. 2013; 19: 796-810.
31. Fathifazl G, Razaqpur AG, Isgor OB, Abbas A, Fournier B, Foo S. Bond performance of deformed steel bars in concrete produced with coarse recycled concrete aggregate. Can J Civ Eng. 2012; 39: 128-139.
32. De Souza DJ, Sanchez L, Ahimoghadam F, Fathifazl G. Comparison among different mix-design procedures for RCA concrete. ACI Symp Publ. 2019; 334: 99-121.
33. Singh RB, Singh B. Rheological behaviour of different grades of self-compacting concrete containing recycled aggregates. Constr Build Mater. 2018; 161: 354-364.
34. Sagoe-Crentsil KK, Brown T, Taylor AH. Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cem Concr Res. 2001; 31: 707-712.
35. López-Gayarre F, Serna P, Domingo-Cabo A, Serrano-López MA, López-Colina C. Influence of recycled aggregate quality and proportioning criteria on recycled concrete properties. Waste Manag. 2009; 29: 3022-3028.
36. Evangelista L, de Brito J. Durability performance of concrete made with fine recycled concrete aggregates. Cem Concr Compos. 2010; 32: 9-14.
37. Güneyisi E, Gesoglu M, Algın Z, Yazıcı H. Rheological and fresh properties of self-compacting concretes containing coarse and fine recycled concrete aggregates. Constr Build Mater. 2016; 113: 622-630.
38. González-Taboada I, González-Fonteboa B, Martínez-Abella F, Seara-Paz S. Analysis of rheological behaviour of self-compacting concrete made with recycled aggregates. Constr Build Mater. 2017; 157: 18-25.
39. Saba M, Homsi F, Gerges N, Assaad J. Regression models to predict workability and strength of flowable concrete containing recycled aggregates. Mater Today Proc. 2020; 27: 68-71.

40. Faleschini F, Jiménez C, Barra M, Aponte D, Vázquez E, Pellegrino C. Rheology of fresh concretes with recycled aggregates. Constr Build Mater. 2014; 73: 407-416.
41. Barra Bizinotto M, Faleschini F, Jiménez Fernández CG, Aponte Hernández DF. Effects of chemical admixtures on the rheology of fresh recycled aggregate concretes. Constr Build Mater. 2017; 151: 353-362.
42. Standard test method for relative density (specific gravity) and absorption of coarse aggregate. West Conshohocken, PA: ASTM; 2015; ASTM C127-15.
43. Standard test method for Portland-cement content of hardened hydraulic-cement. West Conshohocken, PA: ASTM; 2015.
44. Standard test methods for chemical analysis of hydraulic cement. West Conshohocken, PA: ASTM; 2018; ASTM C114-18.
45. Rodrigues F, Evangelista L, de Brito J. A new method to determine the density and water absorption of fine recycled aggregates. Mater Res. 2013; 16: 1045-1051.
46. Nagaraju Y. Contribution to the understanding of the rheological behaviour of recycled concrete aggregate mixtures made of coarse and fine particles. Ottawa: University of Ottawa; 2020.
47. Banfill P, Beaupré D, Chapdelaine F, de Larrard F, Domone P, Nachbaur L, et al. Comparison of concrete rheometers: International tests at LCPC (Nantes, France) in October, 2000. Gaithersburg, MD: National Institute of Standards and Technology; 2001; NISTIR 6819.
48. Beaupré D, Chapdelaine F, Domone P, Koehler E, Shen L, Sonebi M, et al. Comparison of concrete rheometers: International tests at MB (Cleveland OH, USA) in May, 2003. NISTIR 7154.
49. Neville AM. Properties of concrete. 5th Ed. London: Pearson Education; 2011.
50. Struble LJ, Ji X. Rheology. In: Handbook of analytical techniques in concrete science and technology. Norwich, NY: William Andrew; 2001. pp.333-367.
51. Bao K, Lavrov A, Nilsen HM. Numerical modeling of non-Newtonian fluid flow in fractures and porous media. Comput Geosci. 2017; 21: 1313-1324.
52. De Grazia MT, Sanchez LFM, Romano RCO, Pileggi RG. Evaluation of the fresh and hardened state properties of low cement content systems. Mag Concr Res. 2020; 72: 232-245.
53. De Grazia MT, Sanchez LFM, Romano RCO, Pileggi RG. Investigation of the use of continuous particle packing models (PPMS) on the fresh and hardened properties of low-cement concrete (LCC) systems. Constr Build Mater. 2019; 195: 524-536.