

Effect of Recycled Concrete Aggregate Properties on the Behaviour of New Concrete

By

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To my beloved parents,

Amir Ahimoghadam & Masoomeh Haj Ali Arab

And

My lovely fiancée

Peyvand Moosavi

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Abstract

Application of recycled concrete aggregates (RCA) has increased recently as a sustainable alternative in concrete construction. Although application of RCA has substantially grown over the past decades, issues related to its structural performance and long-term behaviour still prevent its widespread application, especially in structural purposes. In this study, a new mixture proportioning method called the “Equivalent Volume (EV)” method is proposed for RCA concrete, which is developed on the assumption that the RCA mix is based on a companion conventional concrete mix having the same volume of “cement paste and aggregates” as the companion mixture. RCA mixes containing different aggregate types and mechanical properties were designed using the EV method. Chemical, mechanical and non-destructive tests were performed and their performance was investigated. Finally, a quality control protocol for evaluating the suitability of RCA sources for structural applications is proposed. Results show that the EV method seems a promising approach to mix-proportion eco-friendly recycled concrete mixes. Moreover, the RCA type and properties seem to influence in the behaviour of RCA concrete and thus should be accounted in the mix- design.

KEYWORDS: Recycled Concrete Aggregates (RCA), Mix- design methods, Equivalent volume (EV), Waste management, RCA quality control.

Table of Contents

Acknowledgement	iii
Abstract	iv
Table of Contents	v
List of Tables	ix
List of Figures	xi
Important Definitions and Acronyms	xiii
1. Introduction	1
1.1 General	1
1.2 Objectives and scope of the work	2
1.3 Overview of the thesis	3
1.4 References	4
2 Literature Review and Background	6
2.1 History of Recycled Concrete Aggregate (RCA)	6
2.2 Guidelines and Standards	8
2.3 Environmental and Economic Factors	11
2.4 Mechanical and Fresh State Properties of RCA Concrete	13
2.5 RCA Mix Design Proportioning	16
2.5.1 Equivalent Mortar Volume (EMV)	17
2.6 Techniques to evaluate the quality of RCA particles and mixes	21
2.7 Summary	24
2.8 References	26
3 The Use of the Equivalent Volume (EV) Method as a New Approach for Mix- Proportioning Recycled Concrete Aggregate (RCA) Mixtures	32
3.1 Abstract	32

3.2	Introduction.....	33
3.3	Background.....	33
3.4	Scope of the work	35
3.5	Materials and methods	35
3.5.1	Materials and CC mixture proportions	35
3.5.2	Residual mortar (RM) content and RCA characterization.....	37
3.5.3	Equivalent Volume (EV) Method.....	38
3.5.4	Methods for assessment and analysis	41
3.6	Results.....	43
3.6.1	Compressive strength tests.....	43
3.6.2	Stiffness damage test (SDT)	44
3.6.3	Ultrasonic pulse velocity (UPV) and Resistivity tests	46
3.6.4	Flexure test (third point test).....	47
3.7	Discussion.....	49
3.7.1	Properties of RCA designed through the EV method.....	49
3.8	Conclusion	52
3.9	References.....	53
4	Effect of the Quality of Recycled Concrete Aggregate (RCA) on the Behaviour of New Recycled Concrete Mixtures	56
4.1	Abstract.....	56
4.2	Introduction.....	57
4.3	Background	57
4.4	Tools for assessing quality in RCA concrete	59
4.4.1	Residual mortar (RM) content analysis	59
4.4.2	Stiffness damage test (SDT)	60
4.4.3	Non-destructive tests.....	61

4.4.4	Los-Angeles abrasion.....	61
4.4.5	Flexural test.....	62
4.5	Scope of the work	62
4.6	Materials and methods	63
4.6.1	Materials and RCA processing	63
4.6.2	Residual mortar (RM) content	64
4.6.3	RCA mix-design and testing.....	65
4.7	Results.....	66
4.7.1	Characterization of RCA and residual mortar (RM) content.....	66
4.7.2	Los Angeles abrasion.....	67
4.7.3	Compressive strength tests.....	68
4.7.4	Flexure test.....	69
4.7.5	Stiffness damage test (SDT)	70
4.7.6	Ultrasonic pulse velocity (UPV).....	72
4.7.7	Surface electrical resistivity (ER).....	73
4.8	Discussion.....	74
4.8.1	Residual mortar (RM) content	74
4.8.2	Mechanical properties of the RCA particles.....	74
4.8.3	Mechanical properties of the RCA concrete.....	75
4.8.4	Non-destructive evaluation	76
4.8.5	Quality control procedure for evaluating RCA mixtures.....	77
4.9	Conclusion	79
4.10	References.....	80
5	Summary and Conclusion	84
6	Recommendations for future research:	88
7	References.....	89

8 Appendix	96
8.1 Sample of calculation.....	96

List of Tables

Table 1.1. Construction and demolition waste and percentage of concrete recycled as RCA (Venta 2001)	2
Table 2.1 Specified limitations on RCA properties by different countries (Vázquez 2004).....	10
Table 3.1. Different materials used.....	36
Table 3.2. Detailed conventional concrete mixture proportions.....	36
Table 3.3. Different crushed recycled aggregates specifications.....	38
Table 3.4. RCA concrete mixture proportions.....	40
Table 3.5. Testing matrix present the amount of samples for each test developed in this research	41
Table 3.6. Compression strength results obtained on CC specimens	43
Table 4.1. Different materials used.....	63
Table 4.2. Detailed concrete mixture proportions.	64
Table 4.3. New RCA concrete mixture proportions.	65
Table 4.4. Testing matrix developed for this study	66
Table 4.5. Different crushed recycled aggregates specifications.....	67
Table 4.6. Compression strength results of the CC mixes.....	68
Table 4.7 - Modulus of Elasticity (ME) and Stiffness Damage Index (SDI) for the CC mixtures	71
Table 4.8. Quality control chart for assessing quality of the RCA in RCA mixtures.....	78
Table 8.1. 35 MPa conventional concrete proportions.	96
Table 8.2. Measured Residual Mortar Content (RMC), Residual Aggregate (RA).	96

Table 8.3. Calculated values of Recycled Material RA and Residual Mortar RM.....	97
Table 8.4. Calculated supplementary amount of sand and coarse aggregate.....	97
Table 8.5. Calculation of old and new values of sand and cement.	98
Table 8.6. New mix proportions.	98
Table 8.7. RCA final ingredients.	98

List of Figures

Figure 2.1. Binder intensity (bi_{cs}) vs. 28-day compressive strength for Brazilian (green dots) and international (red dots) data. The lines represent concretes with the same amount of total binder (Damineli et al. 2010)	13
Figure 2.2 - Features of conventional concrete mixture	18
Figure 2.3 – Features of RCA concrete mixture	18
Figure 2.4. Features of RCA concrete mixtures with A. R=0 and B. R=1	19
Figure 3.1. Volumetric material amounts of RCA mixtures designed with EMV and EV methods when compared to their initial CC mixes	40
Figure 3.2. The Stiffness Damage Test (SDT), A– Stiffness Damage Index, SDI & Modulus of Elasticity, ME, B – SDT Setup (Sanchez et al. 2016)	42
Figure 3.3. Compressive strength test results performed on the different RCA concrete mixtures designed with the EV method.	44
Figure 3.4. Modulus of elasticity (ME) results as a function of different mix proportions for 5 loading-unloading cycles: A: Conventional concrete .B: RCA concrete.	45
Figure 3.5. Stiffness Damage Index (SDI) results as a function of different mix proportions for five loading-unloading cycles: A: Conventional concrete .B: RCA concrete.	45
Figure 3.6. NDT test Setups performed on different RCA concrete mixtures presenting distinct qualities. A – UPV Setup, B – Surface ER Setup	46
Figure 3.7. NDT test results performed on different RCA concrete mixtures presenting distinct qualities. A – UPV results, B – surface ER results.	47
Figure 3.8. A- RCA concrete specimens tensile strength incorporating the different RCA strength and aggregate type, based on EV mix proportioning method, B- flexural test (third point bending) setup	48

Figure 3.9. Modulus of rupture (MOR) as a function of the concrete strength (25, 35, 45MPa) and aggregate type (CL and supplied).	48
Figure 3.10. Binder intensity ($b_{i_{cs}}$) vs. 28-day compressive strength for Brazilian (green dots) and international (red dots) data. The lines represent concrete mixtures with the same amount of total binder (Damineli et al. 2010).	52
Figure 4.1. Percent loss of Los Angeles abrasion test for recycled and reference aggregates.	67
Figure 4.2. Compressive strength test results performed on the 35 MPa RCA concrete mixtures incorporating different aggregate types (CL vs QG) and presenting distinct qualities (i.e. 25, 35, 45 MPa).....	69
Figure 4.3. Tensile strength results obtained on 35 MPa RCA concrete mixtures incorporating different aggregates (i.e. CL and QG) and distinct RCA qualities.	70
Figure 4.4. Modulus of rupture (MOR) as a function of the Aggregate strength (25, 35, 45MPa) and aggregate type (CL and QG) for 35 MPa RCA concrete mixtures.	70
Figure 4.5. Responses of selected SDT output parameters as a function of the aggregate strength (25, 35, 45MPa) and aggregate type (CL and QG) for 35 MPa RCA concrete mixtures: A: Modulus of elasticity (ME). B: Stiffness Damage Index (SDI).....	71
Figure 4.6. UPV test results performed on the 35 MPa RCA concretes incorporating CL and QG and presenting distinct RCA source qualities (25, 35 and 45 MPa).	72
Figure 4.7. Surface resistivity results performed on the 35 MPa RCA concretes with corporation of different aggregate strength (25, 35, 45MPa) and aggregate type (CL and QG).	73

Important Definitions and Acronyms

The following abbreviations and acronyms will be consistently used throughout this thesis to avoid confusion:

- CC (Conventional Concrete) = concrete produced using the ACI mix proportioning method.
- EMV (Equivalent Mortar Volume) = RCA mix-design proportioning method
- EV (Equivalent Volume) = RCA mix-design proportioning method
- FM (Fresh Mortar) = the mortar part made of sand, cement and water which is surrounding RCA particles in RCA concrete.
- FP (Fresh Paste) = the new paste (cement and water) used to make RCA concrete.
- ITZ (Interfacial Transition Zone) = the interface between the natural aggregate particles and the mortar in conventional concrete.
- NA (Natural Aggregate) = aggregate obtained from crushed stone or gravel.
- OC (Old Concrete) = concrete particles obtained from demolished concrete structures which can be used as raw material for the production of recycled aggregates. Old concrete is also referred to as original concrete or demolished concrete.
- OVA (Original Virgin Aggregate) = initial aggregate used in the manufacture of the original concrete.
- RCA (Recycled Concrete Aggregate) = aggregate obtained from crushing demolition concrete, normally comprising original virgin aggregate (OVA) coated with residual mortar (RM).
- RCA concrete = concrete produced with incorporation of RCA particles.
- RM (Residual Mortar) = the mortar that remains attached to original virgin aggregate in RCA after crushing, which includes sand and hydrated cement.
- RMC (Residual Mortar Content) = the proportion of RCA made up of residual mortar.

- RP (Residual Paste) = the hydrated cement part of RM attached to the original virgin aggregate in RCA
- TA (Total Aggregate) = the sum of OVA and NA volumes.
- TP (Total Paste) = the sum of RP and NP volumes.

1. Introduction

1.1 General

Concrete is by far the most important construction material and is used for all types of structures all around the world. Typically concrete comprises about 12% cement and 80% aggregate by mass in its fresh state (Neville 1995). In North America the total annual aggregate supply was around 350.5 million tons in 2003 (Panagapko 2003). The use of cement, which is by far the most important ingredient of concrete, has a negative impact towards sustainability. According to the IPCC (Intergovernmental Panel on Climate Change), every ton of cement produced releases 1.25 tons of CO₂ (Watson 1996). In addition, the global cement production in 2013 was 4.2 billion tons, which gives an eye watering 5.2 billion tons of CO₂ emitted from cement production (Van Oss 2013). It is worth noting that in the same year the total CO₂ emissions were about 36 billion tons. Therefore, carbon emission from cement production was just under 14.5% of all human emissions from all sources such as gas, coal, cement etc. which is even growing (Olivier (PBL) 2015).

One ton of cement production also requires about four giga-joules of energy. Mining large quantities of raw materials such as clay and crushed limestone, and fuel such as coal for the production of cement, often results in extensive deforestation or denudation and top-soil loss (Mehta 2001). Other negative environmental impacts caused by extraction of natural aggregates include destruction of the natural habitat and loss of groundwater storage capacity (Winfield 2005), as well as embodied energy and emissions associated with their mining, processing, and transportation (Abbas 2006).

The intended service life of concrete structures can be up to one hundred years or more. However, in reality, they may not actually last that long. Structures can become obsolete, experience extensive deterioration, zoning changes, or damage due to extreme events or other causes

(Fathifazl 2008). Therefore, a large amount of construction and demolition waste is produced annually, of which concrete comprises approximately one billion tons per year globally (Salem 1998), (Venta 2001). Annual construction and demolition waste in Canada has been estimated to be 11 million tons, approximately half of which is concrete (Venta 2001). Currently, about four million tons of concrete demolition waste is being recycled, mainly as backfill or road sub-base (George 2001). Recently, a greater societal emphasis has been placed on sustainability and so-called “green” practices. The amount of construction and demolition waste and percentage of concrete being recycled are shown in Table 1.1 for different countries.

Table 1.1. Construction and demolition waste and percentage of concrete recycled as RCA
(Venta 2001)

Country	Construction and demolition waste (million tons/year)	Concrete being recycled (%)
Canada	11	36
US	136	50-57
UK	30	45
France	24	15
EU-15	180	28
Australia	5	41
Sweden	2	21
Spain	13	<5
Belgium	7	87
Germany	59	17
Italy	20	9
Netherlands	11	90
Portugal	3	>5
Denmark	8	81
Greece	2	<5
Finland	1	41
Ireland	1	<5

1.2 Objectives and scope of the work

The research carried out in this thesis resulted in a number of original contributions related to the effect of the type and quality of RCA particles on the behaviour of new RCA concrete. These can be grouped in two categories:

1) To propose a new mix- design technique, the so-called Equivalent Volume (EV) method, able to produce RCA concrete mixtures with suitable performance in the fresh and hardened states towards a greener and more sustainable future in civil industry and;

2) To evaluate the influence of RCA types and qualities (i.e. mechanical properties) on the fresh and hardened state behaviours (chemical, mechanical and non-destructive) of concrete mixtures as well as proposing a quality control (QC) procedure for RCA concrete.

Application of recycled concrete aggregates (RCA) has increased in the past decades as a sustainable alternative in concrete construction. Despite environmental benefits of using RCA, the application of RCA concrete for structural applications has been limited to only a very small percentage, especially due to the current lack of guidelines, quality control and clear specifications from the process of RCA manufacturing to the mix-proportioning of RCA concrete mixtures.

Using the EV method, a large number of mixes were proportioned with the use of different sources (crushed limestone, quartzite gravel and supplied commercial aggregate) and qualities of recycled concrete aggregate (25, 35 and 45 MPa). For each mix, a number of chemical (i.e. residual mortar content), mechanical (i.e. Los Angeles abrasion, compressive strength, modulus of elasticity, bending flexure and stiffness damage test) and non-destructive (i.e. ultrasonic pulse velocity and surface electrical resistivity) techniques were performed to characterize the properties of RCA mixtures. Finally, analysis and recommendations on the use different RCA sources to produce RCA structural concrete were performed and a quality control procedure is suggested.

1.3 Overview of the thesis

This thesis consists of 5 Chapters, as indicated below. Chapters 3 and 4 are written in a paper format with their own separate literature reviews, which are in the process of submission for publication. These chapters consist of the reproduction of the papers. Because of the paper format adopted, some minor duplication of concepts/discussions/conclusions in various chapters could not be avoided.

- Chapter 1 introduces the research needs, objectives, and scope with highlighted original contributions.
- Chapter 2 provides a literature review of previous research projects that have been conducted, as well as an overall review of existing codes and standard development worldwide related to the use of RCA concrete.
- Chapter 3 presents the development of a mix design proportioning method for recycled concrete aggregates (RCA) in the format of a technical paper, which is cited below:

Ahimoghadam, Sanchez, Noël, Santos and Demers 2018. The Use of the Equivalent Volume (EV) Method as a New Approach for Mix- Proportioning Recycled Concrete Aggregate (RCA) Mixtures. Under review for publication in (Magazine of Concrete Research)

- Chapter 4 focuses on the development of a quality control procedure for RCA in the format of a technical paper, which is cited below:

Ahimoghadam, Sanchez, Noël, Santos and Demers 2018. Effect of the Source and Quality of Recycled Concrete Aggregate (RCA) on the Behaviour of New Recycled Concrete Mixtures. Under review for publication in (Construction and Building Materials)

- Chapter 5 provides a summary of the research contributions presented, the conclusions obtained through this study, and recommendations for future research.

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2 Literature Review and Background

2.1 History of Recycled Concrete Aggregate (RCA)

The use of recycled concrete aggregate (RCA) has been receiving increased attention in civil industry as a sustainable alternative to natural aggregates, not only with a low carbon footprint material but also to decrease the solid demolition waste. In addition, other concerns such as finishing natural aggregate resources with good quality (MOTH 1999), rising dumping fees (ECCO 1999) and increasing hauling price (Abbas 2006) provide additional motivation to use RCA materials. It is estimated that with the use of RCA material the total transportation distance for hauling aggregates can be reduced by as much as 80% (Abbas 2006).

After World War II, the use of demolished concrete as aggregate for new concrete started in Europe (Wainwright et al., 1994). However, at that period of time as soon as the demand for aggregate could be met by available natural aggregate, recycling was basically abandoned (Buck 1976). More recently, certain countries have developed standards and guidelines for RCA aggregate, albeit not for its use in RCA concrete. In the United States, the ASTM “Standard specification for concrete aggregates”, C33-82 has included “crushed hydraulic cement concrete” in its definition of coarse aggregate since 1982 (ASTM 33-82 (1982)). Moreover, “hydraulic-cement concrete” may also be considered as a type of manufactured sand according to ASTM 125-93a (ASTM 125-93 (1993)) “Standard definitions of terms relating to concrete and concrete aggregates”. The Building Contractors’ Society of Japan (BCSJ) developed a “Proposed standard for the use of recycled aggregate and recycled aggregate concrete” in 1977 (Hansen 1986), and recycling laws were established in 1991 to control the increase of waste and to promote recycling (Noguchi 2001).

In the Netherlands, the CUR (Commissie voor Uitvoering van Research ingesteld door de Betonvereniging) developed a standard to allow the use of RCA in concrete up to 20% by weight of the total coarse or fine aggregates (Hansen 1986). In the United Kingdom, the use of RCA

is permitted in both road construction and buildings according to the New British Standard Guide 6543, “Use of industrial by-products and waste materials in buildings and civil engineering”. In Russia, the use of coarse RCA is permitted in low-strength concrete (up to 20 MPa), including reinforced concrete, but not in prestressed concrete (Hansen 1986). Similarly, Denmark allows the use of RCA concrete for certain structural purposes under mild exposure conditions (Hansen 1992).

Although the use of RCA has grown, issues related to its structural performance, durability and long-term behaviour prevent its widespread application for structural members, especially when different material sources are used (i.e. presenting different features such as strength, aggregate type, etc.). Despite environmental benefits of using RCA in the construction industry (Abbas 2006), the use of RCA concrete for structural applications has been limited to only a very small percentage. Currently, in North America RCA is used mainly for non-structural applications, such as backfill, base or fill for drainage systems, pavement base and sub-base, lean-concrete bases, concrete blocks, sound barrier walls along highways, partition walls, embankments, etc. (Fathifazl 2008). In Canada, use of RCA is permitted for road or parking lot base and sub-base as well as sewer bedding and backfills (Wilson 1993).

Although the use of RCA in structural grade concrete is limited, RCA has been used successfully for road construction in Canada, the United States, France, Netherlands, Denmark, Germany, Japan, Belgium, and United Kingdom. Some of the barriers to adoption of RCA concrete for structural grade concrete, as reported by Fathifazl (2008) include: (1) reluctance on the part of designers and owners to use RCA due to concerns related to quality control, clear specifications, and lack of technical data or guidelines both for RCA materials as well as the production and proportioning of concrete mixes made with RCA, thus necessitating further investigation; and (2) insufficient demand and lack of economic motivations to use RCA. Therefore, there is a need for new technical specifications, quality control and quality assurance methodologies for producing structural grade RCA concrete.

2.2 Guidelines and Standards

Currently, the application of RCA in structural-grade concrete has not been standardized in North America. The most common standard accepted internationally for recycled aggregates has been developed by RILEM (RILEM 1994). In North America, ACI 555R-01 provides some guidelines about hardened concrete removal and its reuse as new aggregate in RCA concrete according to the report on “Removal and Reuse of Hardened Concrete” (Lamond et al. 2002).

In the United Kingdom, since the publication of BS EN 12620:2002 “Aggregates for Concrete” the permission of the use of recycled aggregates is granted; however, no specific compositional limits are suggested in this document. Also, the Specification for Constituent Materials and Concrete permits the use of RCA in designated concrete types, subject to certain restrictions on concrete strength and exposure environment as presented in BS EN 8500-2:2002, Concrete-Complementary British Standard to BS EN 206-1.

In the UK, a default value of 0.075% for concrete drying shrinkage must be met for the combination of RCA and NA. With respect to BS 8500-2, RCA can be used in a range of exposure conditions and up to strength class C40/50. Also, commonly the use of RCA concrete is not allowed in concrete exposed to sea water, de-icing salts or severe freezing and thawing. It is recommended that concrete with incorporation of RCA particles be restricted to use in non-aggressive soils. The amount of RCA is limited to 20% by mass of the total coarse aggregate in concrete (Research Information Digest 1 .2005).

A National C&D (construction and demolition) Waste Plan (PNRCD) was published by the Ministry of the Environment of Spain in 2001 (Vázquez 2004). This five year plan aimed for 25% recycling and 10% reduction of C&D waste by 2006. In November 2002, with respect to achieve these objectives, particularly in the area of structural concrete, a task force was formed to draft the technical regulations governing structural concrete. The draft regulation specified definite restrictions on the use of recycled aggregate for structural concrete, including (Vázquez 2004).:

- Allowing RCA in mass and reinforced concrete but not in prestressed concrete.

- Excluding RCA made from lightweight and fiber-reinforced concrete, or made with aluminous cement.
- Reliant on the effect of old concrete quality on new RCA concrete, specification of minimum strength for old concrete and identification of the reasons for demolition (to avoid using concrete affected and damaged by causes such as alkali-aggregate reaction, sulphate attack, etc.).
- Limiting the replacement of coarse aggregate with RCA at 20%,
- Providing restrictions on the use of RCA concrete in aggressive environments.

In Germany, the national standard “DIN 4226-1000, 2002” which is about aggregates for concrete and mortar, imposed the guideline for recycled aggregate concrete. In the Netherlands, the Dutch standard NEN 6720:1995 “Construction Requirements and Calculating Methods”, permits the use of recycled concrete aggregate up to the limit of 20% for the replacement percentage of natural aggregate, or up to 10% for masonry aggregates (Corinaldesi 2002). In Japan, a “proposed standard for the use of recycled aggregate and recycled aggregate concrete” was issued by the Building Contractors’ Society of Japan (BCSJ) in 1977. Table 2.1 presents some limitations on use of RCA established by different countries (Vázquez 2004).

In Canada, the C-2000 Green Building Standards aims for a target of 75% recyclable materials in structures, including all building materials (Mishulovich 2003), but this program does not require any processing of concrete other than its separation from other demolition waste (Taschereau 2001). Use of RCA is permitted according to the Ontario Provincial Standard Specification (OPSS) for road or parking lot base and sub-base aggregate as well as sewer bedding and backfills (Wilson 1993).

Table 2.1 Specified limitations on RCA properties by different countries (Vázquez 2004).

Country	Compressive Strength (MPa)		Max. Fines Content (<0.063 mm) %	Elastic Modulus*		Creep*		Shrinkage*		Maximum Impurities Content (%)				
	100% Coarse RCA	20% Coarse RCA		100% Coarse RCA	20% Coarse RCA	100% Coarse RCA	20% Coarse RCA	100% Coarse RCA	20% Coarse RCA	Ceramic	Light Weight Particles	Asphalt	Other Materials	
RILEM	50	No Limit	2	0.8	-	1.25	1	1.5	1	20	1			
Belgium	30	-	3	0.8	1	1.25	1	1.5	1					
Hong Kong	20	25-30	4	-	-	-	-	-	-					
Holland	45 ⁽⁴⁾	No Limit	-	-	-	1.25 - 1.45	1	1.35 - 1.55	1	-	-	-	-	
Germany	-	-	4	-	-	-	-	-	-	-	-	-	-	
Japan ²	24	-	-	-	-	-	-	-	-	-	-	-	-	
UK	40	No Limit	5(3)	-	-	-	-	-	-	5	0.5	5	1	
Australia ¹	40	-	6	-	-	-	-	-	-	2 (Total Amount)				

* The modification factors given in the table should be applied to the conventional equations for normal concrete

¹ Non Structural application

² Civil works

³ BS-EN-206-1

⁴ Cubic strength

2.3 Environmental and Economic Factors

Due to both economic and environmental considerations, the global demand for regulating, recycling and reusing construction and demolition waste has amplified in the last few decades. From the economical perspective, the cost of conventional aggregates will continue to increase while that of recycled aggregates is expected to decrease. The following reasons, adapted from Fathifazl (2008) can be considered for this economic scenario:

- 1) Good quality natural aggregate resources used for concrete, which vary from river gravel to crushed stone for coarse aggregate, are associated with expensive extraction and processing fees, resulting in higher overall cost.
- 2) Transportation of high quality aggregates, which may need to be hauled over long distances, increases their overall cost. Based on the Environmental Council of Concrete Organization (ECCO 1999) information sheet, contractors often need to haul Natural Aggregate (NA) more than 100 km on different projects. Using RCA can be considered as a cost effective method for savings in hauling, which can reduce the total transportation distance by up to 80% in some cases (Abbas 2006).
- 3) Decreasing the number of available landfills due to the increase in quantity of construction waste and demolition structures; therefore, the dumping fees are expected to rise (ECCO 1999). For example, the dumping fee within only a few years has raised from almost \$20 to \$112-120 per ton in the Netherlands (De Vries 1996).
- 4) Distant transportation of construction and demolition waste to dumping facilities can be averted by using mobile recycling equipment.
- 5) According to the growth in global demand for RCA, the number of recycling plants is increasing. Consequently, decrease in cost of RCA production is expected.

From an environmental perspective, the extraction of new natural aggregates presents the following drawbacks (Fathifazl 2008):

- Destruction of natural habitat (Winfield 2005).

- Influence on the quality and level of the surface and groundwater resources due to changes in water drainage patterns (Winfield 2005).
- Effect on the groundwater storage capacity (Winfield 2005).
- Increase in the emissions of greenhouse gas (GHG) due to the energy consumption required for mining, processing, and transportation of natural aggregates.

As a result, in the construction industry an increase in the use of recycled concrete aggregates will decrease the demand for fresh natural aggregate and the associated energy and GHG emissions required to produce fresh aggregates.

The concept of sustainable development includes 1) the cautious consumption of natural resources, which are being rapidly depleted, and reducing waste by using industrial by-products; and 2) the need of decreasing energy usage that is linked to CO₂ emissions, which is the major cause for the “greenhouse effect” leading to climate change (Nations 1992). It is well established that the Portland cement (PC) industry is one of the main contributors regarding the carbon footprint of civil construction (Gartner 2015). In this context, to improve cement efficiency is one of the most important strategies for reducing CO₂ emissions. Damineli et al (Damineli et al. 2010) suggested the development of a performance indicator to better understand and quickly estimate PC efficiency in concrete. The authors proposed an index, the so-called *Binder Intensity Index* (*bi*), which is defined as the amount of PC required to obtain 1 desired unit of a given concrete; e.g. the amount of PC in kg/m³ to obtain 1 MPa of compressive strength at a given time (i.e., 28 days).

$$bi = \frac{B}{CS} \quad 2.1$$

Where, B is the amount of binder (in kg/m³), and CS is the compressive strength in MPa. Damineli et al (Damineli et al. 2010) benchmarked the *bi* indices in Brazil and around the globe and noticed that the higher the compressive strength, the lower the *bi* factor (Figure 2.1). However, conventional concrete mixtures with compressive strengths between 25 to 45 MPa generally present *bi* factors between 10-20 kg·m³/MPa, which highlights the need for further optimization of eco-efficiency for regular concrete applications.

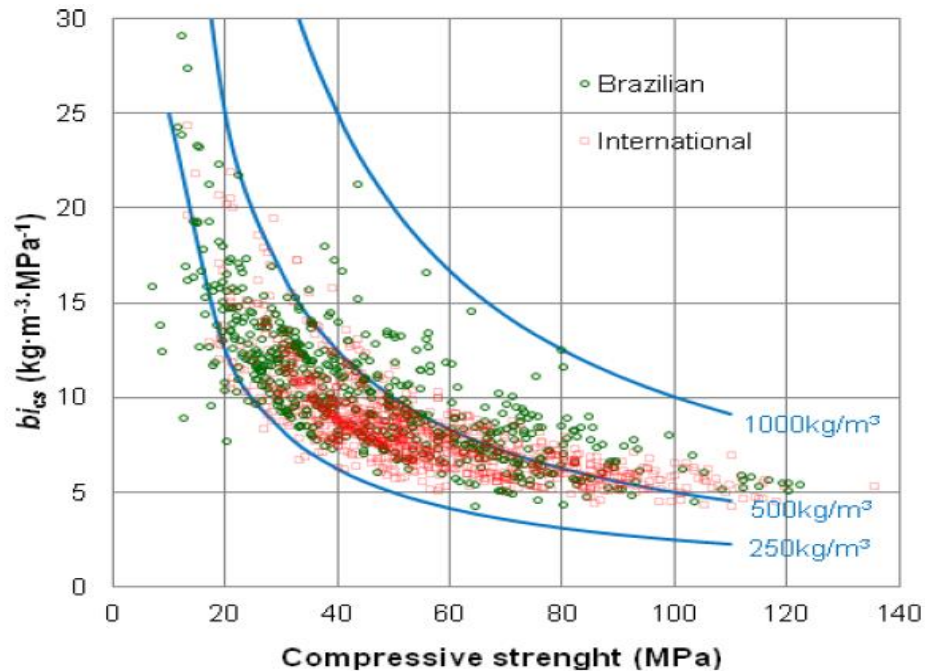


Figure 2.1. Binder intensity (bi_{cs}) vs. 28-day compressive strength for Brazilian (green dots) and international (red dots) data. The lines represent concretes with the same amount of total binder (Damineli et al. 2010)

2.4 Mechanical and Fresh State Properties of RCA Concrete

RCA is normally described as a two-phase material made by original virgin aggregates (OVA) embedded into residual mortar (RM), and thus presents a significantly different microstructure when compared to conventional concrete (CC).

The vast majority of RCA works previously performed treated recycled aggregates as a homogenous material similar to natural aggregates (NA) and adopted direct replacement techniques (mass or volume) for mix- proportioning RCA concrete (Mandal 2002; Gómez Soberón 2002; Gómez-Soberón 2002b; Limbachiya 2000; Dhir 1999). Concrete made with RCA particles, if proportioned based on conventional methods, would have larger total mortar (TM) volume (i.e., fresh and residual mortar) in comparison with concrete made with an equal volume of NA. As a result, RCA mixes have always resulted in inferior mechanical and physical properties when

compared to CC and thus RCA has always been seen as a low-quality material (Ray 1991; Topcu 2004). Otherwise, it has been found that RCA mixtures with at least similar performance to CC (i.e. compressive strength) might be achieved whether the differences in the microstructure are accounted for in the recycled mixtures such as modifying the w/c ratio (i.e. porosity) and fresh paste content (accounting for the RM) of the RCA concrete (Dhir 1999; Topcu 2004).

In addition, according to existing literature, the properties of concrete at the fresh and hardened states for a given w/c ratio and identical mix proportions become inferior compared to CC as the coarse RCA content is increased (Ray 1991; Topcu 2004; Limbachiya 2000). Moreover, the compressive strength of RCA concrete is lower compared to CC (Nixon 1978; Hansen 1986; Hansen 1992; De Vries 1996; Topcu 2004; Kiuchi 2003; Sogo et al. 2004). However, 20-30% coarse NA replacement by RCA does not considerably change the compressive strength, creep, and shrinkage of RCA concrete (De Vries 1996; Dhir 1999; Gómez Soberón 2002; Gómez-Soberón 2002b; Gómez-Soberón 2002a). Microstructural studies (Nagataki 2004) showed that coarse aggregate could originally present defects in the form of voids and cracks. Further processing of the recycled coarse aggregate changed the microstructural profile of the material and enhanced their properties. The splitting tensile and compressive strengths of the concretes incorporating coarse RCA were higher than those of companion natural aggregate concrete NAC. The unusual results of the performance tests carried out on the recycled aggregate concretes could be explained with the findings of microscopic level investigations.

However, similar or even higher compressive strength in RCA concrete is achievable by adjusting the w/c ratio (either by reducing water content or increasing cement content) as a function of the RCA content (Dhir 1999; Limbachiya 2000). One of the common consequences is a lower elastic modulus and higher drying shrinkage and creep of RCA concrete due to the large amount of attached residual mortar compared to CC (Hansen 1992; Hansen 1986; de Oliveira 1996; Yamasaki 1999; Limbachiya 2000; Kiuchi 2001, 2003; Gomez-Soberon 2003; Sogo et al. 2004; Sakata 2000). (Ray 1991) conducted an experiment to investigate the compressive, tensile, and bearing strengths of RCA concrete by using different w/c ratios (0.45, 0.55, 0.65, and 0.70), with incorporation of either 100% RCA replacement or with mixed coarse RCA and NA (60% RCA and 40% NA). According to their results, the compressive strength of RCA concrete was significantly lower than that of CC.

Microstructural changes introduced by the recycling process to each constituent of the RCA have been investigated in the past (Nagataki 2004). The recycling process generally includes crushing the source concrete with a combination of jaw, gyratory and crushers and processing the crushed material twice with a mechanical grinding apparatus to minimize the residual mortar (RM) (Nagataki 2004).

(Katz 1999) investigated the effect of partially hydrated waste concrete on the properties of both RCA and RCA concrete. According to their results, regardless of the crushing age of the old concrete, a 25% reduction in the compressive strength of RCA concrete compared to CC was observed. Furthermore, similar trends were found for other properties, such as flexural and splitting strengths and drying shrinkage. The authors also pointed out that using RCA produced similar effects as lightweight aggregate on the new concrete properties in terms of strength and stiffness.

Despite several researchers achieving RCA concrete with compressive strength equal to the associated original concrete by adjusting the w/c ratio (Dhir 1999; Topcu 2004), the elastic modulus for RCA concrete made by direct replacement method, has typically been lower than for similar conventional concrete mixes (Fathifazl et al. 2009; Hansen 1992; Hansen 1986; Kiuchi 2003; Sogo et al. 2004; de Oliveira 1996; Sakata 2000). This is easily explained by the fact that generally the concrete compressive strength is dependent on the strength of the mortar (water-to-cement ratio) and the interfacial transition zone (ITZ), while the elastic modulus is a function of the volume fractions and the elastic moduli of the aggregate and the mortar (Lydon 1982; Neville 1995; Mindess 1981). In general, the lower RCA elastic modulus is related to the presence of the residual mortar (RM) in RCA (Mindess 1981), (Fathifazl et al. 2009), the properties of which have not been thoroughly investigated. In RCA concrete, the higher the RM content (and the lower its quality), the inferior the mechanical response of the material. Hence, the properties of RCA concrete depend on the composition and quality of the RCA (Fathifazl et al. 2009). In fact, in the majority of previous studies, the RCA residual mortar (RM) content has not been stated and apparently not determined (Fathifazl et al. 2009).

According to this reason, the observed inferior properties of RCA concrete are not inherent but are the consequence of its material composition and by selecting an appropriate method of mix

proportioning this inferiority behaviour may be avoided (Fathifazl et al. 2009). One of the methods recently introduced for RCA concrete, which is capable of accounting for RM is the so-called EMV (Equivalent Mortar Volume) method. This approach allows one to determine the proper amount of RCA and other mix ingredients to achieve certain specified fresh and hardened state properties (Fathifazl et al. 2009). In the EMV method, the quantity of each phase is used to adjust both the coarse aggregate and fresh paste content of the mix accordingly to achieve the same total mortar volume as a companion mix with the same specified properties but made entirely with natural coarse aggregates (Fathifazl et al. 2009).

Accounting for the residual mortar (RM) in the design of RCA concrete has showed significant improvements in its hardened state behaviour. Although using the EMV method gives good mechanical and likely long-term properties in the hardened state, it can result in poor performance of RCA mixes in the fresh state, especially when sustainable RCA mixtures using low amounts of cement are designed. Furthermore, higher RM results in less new paste added which affects negatively on the fresh state properties. Moreover, the EMV performed quite well overall with the use of moderate to high amounts of cement and superplasticizer, which somewhat offsets the environmental benefits of using RCA.

2.5 RCA Mix Design Proportioning

Using conventional mix design methodologies (e.g. ACI method), the main parameters which require some adjustments while using RCA are its lower specific gravity and higher water absorption compared with NA, which are a result of the RMC. To evaluate the properties of RCA concrete, the majority of investigations present in the literature have incorporated RCA as a direct replacement of NA (either by volume or by mass) in mix design proportioning.

Besides the EMV method which has been proposed recently (Fathifazl et al. 2009), the majority of research studies have made use of conventional concrete mix design procedures for RCA concrete (Dhir 1999; Limbachiya 2000; Mandal 2002; Gómez Soberón 2002; Gómez-Soberón 2002b; Gómez-Soberón 2002a; Gomez-Soberon 2003). Moreover, pre-soaking of RCA aggregates has been recommended by some researchers to compensate for the higher absorption

of RCA (Ray 1991; Merlet 1993; Yanagi 1993; Ramamurthy 1998; Nagataki 2000; Sagoe-Crentsil 2001; Buyle-Bodin 2002; Gómez Soberón 2002; Gómez-Soberón 2002b; Gómez-Soberón 2002a; Gomez-Soberon 2003; Topcu 2004; Xiao 2005).

Most of the research studies available in reported literature have used the absolute volume method (i.e. ACI method) of conventional mix design proportioning with consideration of the lower specific gravity of RCA particles (Salem 1998; Yamasaki 1999; Buyle-Bodin 2002; Salem 2003; Gómez Soberón 2002; Gómez-Soberón 2002b; Gómez-Soberón 2002a; Gomez-Soberon 2003; Poon et al. 2004; Dos Santos 2004). Any reduction in the strength of RCA concrete is generally compensated by adjusting its w/c ratio. Basically, by increasing cement content or decreasing water content, concrete strength increases (Dhir 1999; Limbachiya 2000; Sagoe-Crentsil 2001). (Lin et al. 2004) conducted some investigations by optimizing the mix design procedure via adjustable inputs and measurable outputs to decrease the number of costly mix trials.

2.5.1 Equivalent Mortar Volume (EMV)

According to (Fathifazl et al. 2009) the main assumption of the EMV method which is capable of accounting for RM is that “the quantity of each phase is used to adjust both the coarse aggregate and fresh paste content of the mix accordingly to achieve the same total mortar volume as a companion mix with the same specified properties but made entirely with natural coarse aggregates”. Therefore, the RM needs to be quantified and is considered as part of the mortar volume instead of the aggregate volume as most previous studies have done.

According to the EMV method, an appropriate proportion of RCA and other mix ingredients can be determined to achieve certain specified fresh and hardened properties (Fathifazl et al. 2009). In the EMV method, an RCA concrete mix has the same total mortar (TM) volume as a companion CC mix with the same specified properties. It should be mentioned that coarse NA in the control mix must be from the same source or have similar properties to the coarse NA contained in RCA (Figure 2.2). The TM volume of RCA concrete is composed of the sum of its fresh (NM) and residual mortar (RM) volumes (Fathifazl et al. 2009) (Figure 2.3).

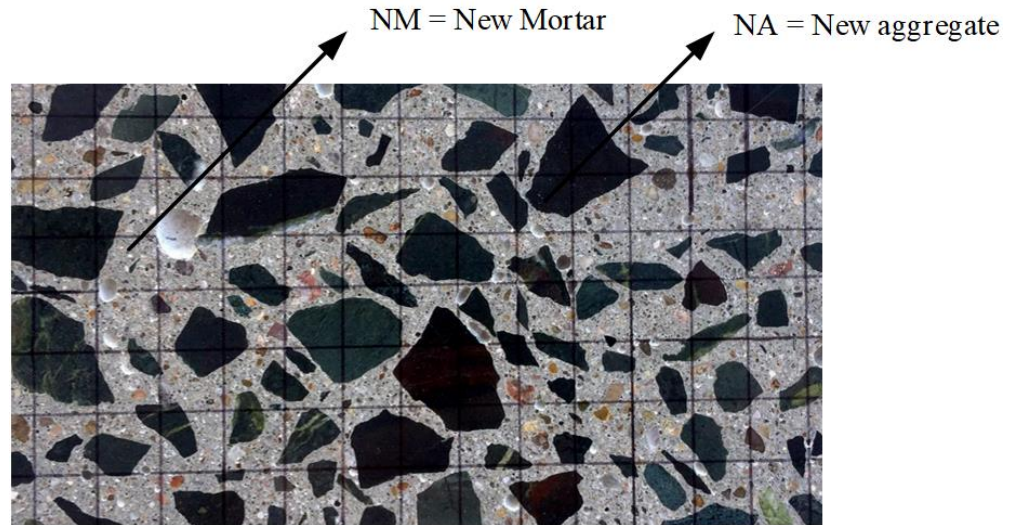


Figure 2.2 - Features of conventional concrete mixture

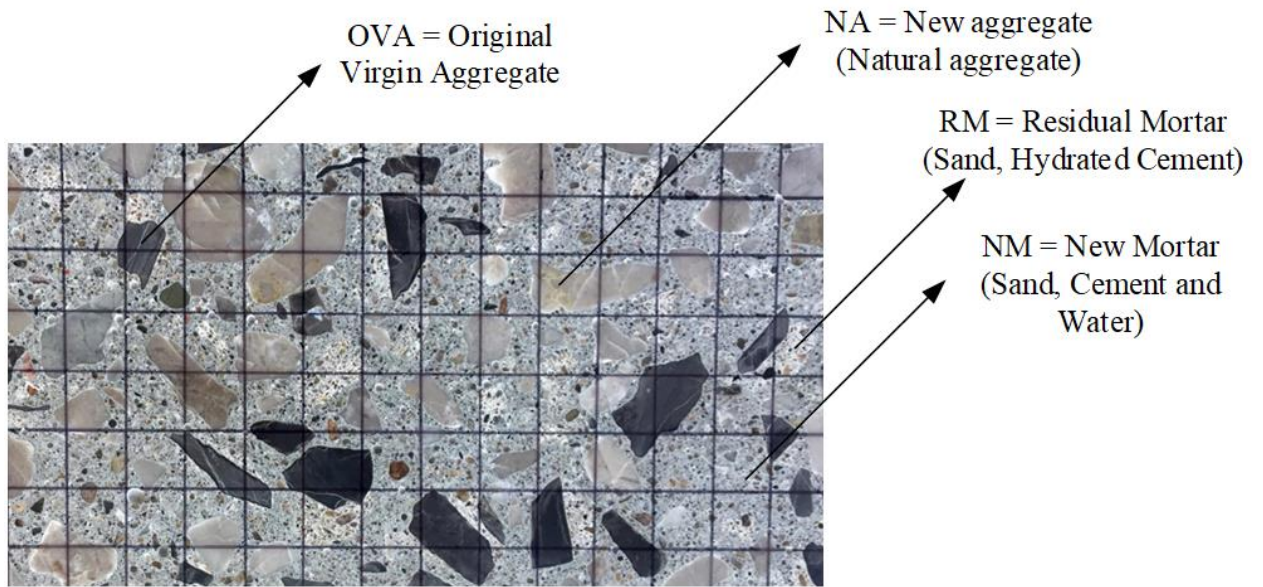


Figure 2.3 – Features of RCA concrete mixture

Assumptions for EMV method (Fathifazl et al. 2009):

The volume of total mortar in RCA and mortar in natural aggregate concrete should be equal.

$$V_{TM}^{RCA-concrete} = V_M^{NAC} \quad 2.2$$

The volume of total natural aggregate in RCA and natural aggregate in natural aggregate concrete should be equal.

$$V_{TNA}^{RCA-concrete} = V_{NA}^{NAC} \quad 2.3$$

Natural aggregate content can be obtained from formula below:

$$V_{NA}^{RCA-concrete} = R \times V_{NA}^{NAC} \quad 2.4$$

Where:

$V_{TM}^{RCA-concrete}$ = volume of total mortar in RCA concrete

V_M^{NAC} = volume of mortar in natural aggregate concrete

$V_{TNA}^{RCA-concrete}$ = volume total natural aggregate in RCA concrete

V_{NA}^{NAC} = volume natural aggregate in natural aggregate concrete

$V_{NA}^{RCA-concrete}$ = volume natural aggregate in RCA concrete

In the condition that R is equal to zero, all the coarse aggregates are 100% RCA and if R=1, all coarse aggregates are fresh natural aggregates (Figure 2.4).

(A) R=0

(B) R=1



Figure 2.4. Features of RCA concrete mixtures with A. R=0 and B. R=1

Hence, it can be concluded that (Fathifazl et al. 2009):

$$V_{TM}^{RCA-concrete} = V_{RM}^{RCA-concrete} + V_{NM}^{RCA-concrete} \quad 2.5$$

$$V_{TNA}^{RCA-concrete} = V_{OVA}^{RCA-concrete} + V_{NA}^{RCA-concrete} \quad 2.6$$

Where also:

$V_{RM}^{RCA-concrete}$ = volume of residual mortar in RCA concrete

$V_{NM}^{RCA-concrete}$ = volume of new mortar in RCA concrete

$V_{OVA}^{RCA-concrete}$ = volume of original virgin aggregate in RCA concrete

The magnitude of $V_{OVA}^{RCA-concrete}$ can be calculated with the formula below:

$$V_{RCA}^{RCA-concrete} = \frac{V_{NA}^{NAC} \times (1 - R)}{(1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}} \quad 2.7$$

Where:

RMC = residual mortar content,

SG = bulk specific gravities of RCA and OVA,

$V_{RCA}^{RCA-concrete}$ = volume of old RCA particles in new RCA concrete

In addition, the weights of RCA in the RCA concrete can be found as follows:

$$W_{OD-RCA}^{RCA-concrete} = V_{RCA}^{RCA-concrete} \times SG_b^{RCA} \times 1000 \quad 2.8$$

Where:

$W_{OD-RCA}^{RCA-concrete}$ is the oven-dry weight of RCA in RCA concrete.

The quantity of water, cement and coarse aggregate can be found using the following equations:

$$W_W^{\text{RCA-concrete}} = W_W^{\text{NAC}} \times \frac{V_{\text{NM}}^{\text{RCA-concrete}}}{V_M^{\text{NAC}}} \quad 2.9$$

$$W_C^{\text{RCA-concrete}} = W_C^{\text{NAC}} \times \frac{V_{\text{NM}}^{\text{RCA-concrete}}}{V_M^{\text{NAC}}} \quad 2.10$$

$$W_{\text{OD-FA}}^{\text{RCA-concrete}} = W_{\text{OD-FA}}^{\text{NAC}} \times \frac{V_{\text{NM}}^{\text{RCA-concrete}}}{V_M^{\text{NAC}}} \quad 2.11$$

Where $W_W^{\text{RCA-concrete}}$ and W_W^{NAC} are the weight of water in RCA and companion natural aggregate concrete respectively. $W_C^{\text{RCA-concrete}}$ and $W_{\text{OD-FA}}^{\text{RCA-concrete}}$ are the weight of cement and oven dried fine aggregate in RCA respectively. W_C^{NAC} and $W_{\text{OD-FA}}^{\text{NAC}}$ are the weight of cement and oven dried fine aggregate in natural aggregate concrete respectively.

2.6 Techniques to evaluate the quality of RCA particles and mixes

RCA is a material that is widely known to have inferior mechanical properties compared to NA, containing high porosity and flaws such as pre-existing inner cracks (due to crushing processes) and can greatly vary in terms of RM and OVA amount, type and quality. Hence, the technical community currently presents a non-negligible reluctance on its use, especially for important applications such as structural concrete.

A number of chemical, mechanical and non-destructive techniques were developed in the past to assess the inner quality and damage of RCA particles and CC mixtures and some of them may be of interest for evaluating the overall quality of RCA mixtures.

2.6.1 Residual mortar (RM) content method

The majority of studies on RCA concrete reported in the literature make use of conventional mix proportioning methods through direct replacement of the NA by RCA. Often, additional

adjustments are then needed to meet performance criteria in the fresh and/or hardened states, such as a significant increase in cement content and/or use of non-negligible amounts of superplasticizers if the existing residual mortar of the RCA is not accounted for. In fact, the quality and amount of RM distinguishes RCA from NA. As previously stated, RCA consists of two distinct phases: the original virgin aggregate (OVA) and the attached RM. Due to the inferior physical properties of mortar compared to NAs, higher RM amounts generally leads to lower RCA quality and thus lower RCA concrete performance. Common consequences are lower modulus of elasticity and higher drying shrinkage and creep of RCA concrete (Hansen 1992; Hansen 1986; de Oliveira 1996; Yamasaki 1999; Limbachiya 2000; Kiuchi 2001, 2003; Gomez-Soberon 2003; Sogo et al. 2004; Sakata 2000).

The quantity of RM in an RCA source may be determined by soaking the RCA particles into a sodium sulphate solution (26% by weight) and subjecting them to five freezing and thawing cycles after which the samples are sieved, oven dried and weighed. The weight loss over the process is considered to be the RM of the RCA in percentage (Abbas et al. 2007).

According to the literature, in order to achieve the maximum strength in RCA concrete, the w/c ratio in new mortar (NM) should be equal to or smaller than the w/c ratio in RM. In other words, the strength of NM should be higher than that of RM (Hansen 1992; Hansen 1986; Yamasaki 1999). While the previously developed EMV and EV mix design methods allow the designer to account for the *quantity* of RM in a RCA source, they do not explicitly consider its *quality*. Nevertheless, these approaches present the distinct advantage of allowing one to determine the proper amount of RCA and other mix ingredients to achieve certain specified fresh and hardened properties (Fathifazl et al. 2009).

2.6.2 Los Angeles (LA) abrasion method

Los Angeles (LA) abrasion test is generally conducted to measure the toughness of coarse aggregate particles or, in other words, to evaluate their resistance to degradation (micro-deval is actually the test procedure currently used to measure abrasion of aggregates) (Reza Fathi-Fazl et al. 2017). According to the European Standard EN-12620, LA abrasion test is able to give a measure of the RCA quality since distinct toughness results might be measured from RCA presenting different RM contents (De Juan 2009). Furthermore, it has been found that a correlation

exists between LA test results and the compressive strength of concrete made by RCA (Topcu 1997). However, quantitative LA results, especially in correlation to chemical, mechanical and NDT tests are still missing in literature and should be further researched.

2.6.3. Stiffness damage test (SDT) method

Recently, Sanchez et al. proposed the use of the Stiffness Damage Test (SDT) to quantify the degree of damage in concrete affected by a number of distress mechanisms such as alkali-aggregate reaction (AAR), freezing and thawing (FT) and delayed ettringite formation (DEF) (Sanchez et al. 2016; Sanchez et al. 2017; Sanchez et al. 2014; Sanchez 2015). The SDT is a cyclic test procedure in compression usually performed at 40% of the design (28-day) concrete strength of the sample under analysis at a controlled loading rate of 0.10 MPa/s (Sanchez et al. 2016; Sanchez et al. 2017; Sanchez et al. 2014; Sanchez 2015). The main outcomes of the test are: 1) the modulus of elasticity (calculated as the average of the modulus obtained in the cycles 2 and 3) as well as the 2) Stiffness Damage Index (SDI) and 3) Plastic Deformation Index (PDI) which are respectively the relationship between the dissipated energy or plastic deformation during the five loading/unloading cycles and the total energy/total deformation placed in the system over five cycles (Sanchez et al. 2016; Sanchez et al. 2017; Sanchez et al. 2014; Sanchez 2015).

The SDT's use is based on the assumption that the use of low-quality RCA is analogous to internal "damage" in the concrete due to weaknesses in the microstructure and presence of microcracks which will result in more energy dissipation/plastic deformation during loading/unloading cycles compared to CC. Although the SDT has never been used thus far to evaluate the condition of RCA concrete, it is expected that this tool might be able to evaluate the inner quality of the RCA mix and thus appraise the influence of the RCA source on the behaviour of RCA concrete mixtures (Crouch 1987; Sanchez et al. 2014; Sanchez 2015; Sanchez 2014; Bérubé 2005a; Bérubé 2005b; Smaoui et al. 2004; Sanchez et al. 2016; Alexander 1995; Chrisp 1993).

2.6.4. Non-Destructive (NDT) techniques

Non-destructive test (NDT) procedures enable a fast assessment of the inner quality of concrete mixtures. It has been found that a number of non-destructive techniques, such as ultrasonic pulse velocity (UPV), surface electrical resistivity (ER), Schmidt hammer etc., (Topcu 1997) may be

able to appraise the influence of RCA amount on the mechanical properties of RCA concrete. According to (Topcu 1997), the higher the RCA content, the lower the Schmidt hardness values and the lower the UPV results. Otherwise, it is expected that different NDT techniques might be able to distinguish not only the RCA amount but rather its inner overall quality (i.e. cracking extent and porosity). Furthermore, to the knowledge of the authors, NDT has never been used to assess the quality of RCA and thus should be further studied.

2.6.5. Flexural test

One of the most commonly used tests for estimating “indirectly” the tensile strength of concrete is through ASTM C 78- third-point flexural loading test (ASTM 1999). Although not a “direct” nor “pure” measure of the tensile strength (i.e. modulus of rupture), the third point flexural test provides an indication of the behaviour of cementitious materials under bending which could be directly correlated to their practical response in the field. Moreover, a number of studies have investigated the modulus of rupture of RCA concrete. Although no significant difference in modulus of rupture of CC when compared to RCA concrete is reported in literature in some works, there is still some doubts on the ability of this test to distinguish different RCA qualities and sources due to their damaged and more porous nature when compared to CC (Sri Ravindrarajah and Tam 1985; Tavakoli 1996; O.O. 2008). Finally, the modulus of rupture measures also the ability of a mixture to control first cracking, which may change in concrete designed with different RCA qualities and sources.

2.7 Summary

In order to use concrete made with RCA in structural members, appropriate mechanical, durability and physical properties must be satisfied. According to the detailed literature review, while many research studies have been conducted in this area, there is a lack of a comprehensive and systematic approach in the process of making RCA aggregate and RCA concrete; moreover, concerns over quality and issues related to its structural performance and properties at fresh and hardened states

have prevented its widespread adoption. According to these studies, three main gaps in the current literature on using concrete with RCA are listed as follows:

1) The effects of using different RCA sources on the properties of concrete

In the previous research studies, it was common to use more laboratory-produced RCA in comparison with commercially-produced RCA (Fathifazl 2008), so that to the author's best knowledge few attempts have been made to investigate the effect of the RCA source. Difficulty related to producing RCA with uniform quality in large amounts even when the same procedure is used can be considered as a major reason for this selection, because demolition concrete from different sources and quality are used. On the other hand, the effect of the variability in the properties of RCA on the fresh and hardened properties of RCA concrete is not clear.

2) No specific standard or guideline for the procedure of producing RCA concrete

Currently, to the author's best knowledge, besides the Equivalent Mortar Volume (EMV) method recently proposed, which may result in some problems in the fresh state properties, there is no specific standard or mix design proportioning method as a guideline available for structural-grade RCA concrete. The majority of studies on the topic of RCA concrete make the use of a conventional mix proportioning methods (such as the absolute volume method) by direct replacement of the NA with RCA. Often, additional adjustments are needed to meet performance criteria in the fresh or hardened states, such as increases in cement content or addition of superplasticizers, without accounting for the existing RM content of the RCA. In fact, the amount and quality of RM distinguishes RCA from NA. Although some previous investigations have successfully attained equal or even superior compressive strength, sustainability, economical factors and workability in RCA concrete when compared to CC by modifying the concrete mix ingredient proportions, these adjustments have always resulted in poor creep and shrinkage results and lower elastic modulus for RCA concrete compared to CC.

3) Lack of quality control in the procedure of making RCA concrete

To the author's best knowledge, there is no consensus on the quality control procedures and the influence of the RCA amount and quality on the fresh and hardened state behaviours of recycled mixtures. Also, in terms of quality control, there is a lack of clear specifications, technical data,

and guidelines related not only to the production of RCA materials but also in the proportioning of concrete mixes made with RCA, thus needing further investigation.

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3 The Use of the Equivalent Volume (EV) Method as a New Approach for Mix- Proportioning Recycled Concrete Aggregate (RCA) Mixtures

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3.1 Abstract

Recycled concrete aggregates (RCA) have been widely researched in the past decades as a sustainable alternative in civil construction. Accounting for the residual mortar (RM) in the mix-design of RCA concrete has previously been shown to improve RCA hardened state properties. However, most of the successful results in the literature reported challenges in the fresh state along with the use of moderate to high amount of binders and chemical admixtures, which offsets the environmental benefits of RCA use. This work proposes a new mix-design approach, the so-called Equivalent Volume (EV) method, aiming to improve the fresh and hardened states of eco-friendly RCA concrete. RCA mixes containing different aggregates sources and mechanical properties were designed using this method, and various chemical, mechanical and non-destructive methods were used to evaluate their behaviour. Results show that the EV method seems to be a promising approach to mix- proportion eco-friendly recycled mixes. Further research is still needed to prove EV's efficiency in a wider range of RCA mixes.

KEY WORDS: Recycled Concrete Aggregates (RCA); Mix- design techniques, eco-friendly materials, waste management

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3.2 Introduction

Cement is by far the most important ingredient of concrete; however, its use has an extremely negative impact towards sustainability since according to the Intergovernmental Panel on Climate Change (IPCC) every tonne of cement produced releases 1.25 tonnes of CO₂ (Watson 1996). According to (Mehta 2001), the annual cement production of 1.6 billion tons in the world accounts for about 7% of the global carbon dioxide (CO₂) emission. Moreover, the global cement production in 2013 was about 4.2 billion tonnes, which gives an eye watering 5.2 billion tonnes of CO₂ emitted from cement production (Van Oss 2013). In 2015, the total CO₂ emissions were about 36 billion tonnes. Hence, carbon emissions from cement production was just under 14.5% of all human emissions, which is even growing over time (Olivier (PBL) 2015). In this context, improving cement efficiency is one of the most important strategies for reducing CO₂ emissions. Damireli et al (Damireli et al. 2010) suggested the development of a performance indicator to better understand and quickly estimate PC efficiency in concrete. Furthermore, concrete constitutes a large part of the millions of tons of annual solid demolition waste. Using Recycled Concrete Aggregate (RCA) is one of the methods which has been receiving increased attention in civil industry as a sustainable alternative to natural aggregates not only with a low carbon footprint but also to decrease the solid demolition waste.

3.3 Background

RCA is normally described as a two-phase material made by original virgin aggregates (OVA) embedded into residual mortar (RM), and thus presents a significantly different microstructure when compared to conventional concrete (CC). Although some documents such as ACI-555R (Lamond et al. 2002) provide basic guidelines and criteria on how to deal with and use RCA for proportioning RCA concrete, the vast majority of RCA works previously performed have treated recycled aggregates as a homogenous material similar to natural aggregates (NA) and adopted direct replacement techniques (mass or volume) for mix- proportioning RCA concrete (Mandal 2002; Gómez Soberón 2002; Gómez-Soberón 2002b; Limbachiya 2000; Dhir 1999). As a result, RCA mixes have always resulted in inferior mechanical and physical properties when compared

to CC and thus RCA has always been seen as a low-quality material (Ray 1991; Topcu 2004). Otherwise, it has been found that RCA mixtures with at least similar performance to CC (in compressive strength) might be achieved whenever the differences in the microstructure were accounted for in the recycled mixtures such as modifying the w/c ratio (i.e. porosity) and fresh paste content (accounting for the RM) of the RCA concrete (Dhir 1999; Topcu 2004).

In RCA concrete, the higher the RM content (and the lower its quality), the inferior the mechanical response of the material. Hence, the properties of RCA concrete are directly dependent on the amount, composition and quality of the RCA (Fathifazl et al. 2009). One of the mix-design procedures that has recently been introduced in the literature, which is able to account for the different microstructure of RCA by quantifying the amount of RM, is the so-called Equivalent Mortar Volume (EMV) method (Fathifazl et al. 2009). In the EMV approach, the amount of each phase of the RCA (i.e. OVA and RM) is quantified and used to adjust both the amount of coarse aggregate and fresh paste of the RCA mix, so that the recycled mixture presents at the end the same amount of mortar and aggregates as a companion CC (Fathifazl et al. 2009). The use of the EMV method has been shown to provide recycled mixtures with quite interesting hardened state properties, yet this procedure may display some challenges in the fresh state (i.e. consistency, rheological behaviour, etc.), especially when eco-friendly RCA mixtures using low cement contents are designed. Moreover, previous successful RCA mixtures with the use of EMV indicated the need of using moderate to high amounts of cement and chemical admixtures, which somewhat offsets the environmental benefits of the RCA (Fathifazl et al. 2010; Fathifazl et al. 2009). Therefore, there is a need of developing new mix- proportioning procedures able to capture the benefits of EMV while improving the fresh state behaviour and eco-efficiency of RCA mixes. Moreover, Damineli et al. proposed an index accounting for PC efficiency in CC, the so-called *Binder Intensity Index* (bi), which is defined as the amount of PC required to obtain 1 desired unit of a given concrete (e.g. the amount of PC in kg/m³ to obtain 1 MPa of compressive strength at 28 days). The authors benchmarked the relationships between the binder intensity index (bi) and the compressive strength of CC used in Brazil and around the globe, yet this concept has never been used to benchmark the use of cement in RCA concrete (Damineli et al. 2010).

3.4 Scope of the work

The previous sections clearly showed the lack of mix-design approaches to design RCA concrete with performance in the fresh and hardened states similar to CC. Moreover, although the EMV might be considered a breakthrough in the area of RCA, it is clear that RCA mixes designed through this method may present poor performance in the fresh state, especially when eco-friendly RCA mixtures using reduced amounts of cement are targeted. In this work, a new mix-design proportioning approach, the so-called Equivalent Volume (EV) method is proposed in order to overcome the challenges presented in the prior sections. The EV method is based on a similar concept than the EMV (i.e., accounting for the RM of the RCA). It is designed with the following assumption: the RCA mix is based on a companion CC mix having the same amount (in volume) of *cement paste and aggregates* as opposed to having the same amount of *coarse aggregates and mortar* as stated in the EMV.

In this study, concrete mixtures containing different RCA mechanical properties (i.e., 25, 35 and 45 MPa) are mix- designed using the EV method and evaluated through chemical (i.e., residual mortar test), mechanical (i.e., compression strength test, tensile strength test and stiffness damage test) and non-destructive (i.e., ultrasonic pulse velocity- UPV and surface electrical resistivity - ER) procedures. Discussion on the overall performance of the distinct mixtures are performed and proposals on the use of EV to mix- design RCA concrete are established.

3.5 Materials and methods

3.5.1 Materials and CC mixture proportions

Three different conventional concrete (CC) mixtures with three distinct compressive strengths (i.e., 25, 35 and 45 MPa) and incorporating a crushed limestone as coarse aggregate were selected for the research. The coarse aggregate particles used in this study ranged from 5 to 20 mm in size. A natural sand was selected as fine aggregate presenting a fineness modulus of 2.6. Furthermore,

a general use (GU) cement was used in all mixes of the project. Table 3.1 provides information on the different materials used.

Table 3.1. Different materials used

Material identification			Specific gravity (g/cm ³)	Absorption capacity (%)
Type	Feature	Specification		
Cement	-	GU	3.125	-
Fine	Natural	-	2.602	0.91
Coarse	Crushed stone	Limestone	2.680	0.58

Nine 100 by 200 mm concrete cylinders were fabricated for each of the three different concrete mixtures, using a conventional mix- design procedure (i.e. ACI method – Table 3.2). After 24 h, the specimens were demolded and moist cured for 28 days after which mechanical test procedures (i.e., Stiffness Damage Test as per (Sanchez et al. 2016; Sanchez et al. 2014; Sanchez 2015), followed by compressive strength tests) were performed on three random specimens per mix, for characterizing the conventional control samples. Then, the remaining cylinders were jaw crushed into coarse recycled concrete aggregate particles ranging from 5 to 20 mm. Table 3.2 gives the detailed CC mixture proportions before crushing.

Table 3.2. Detailed conventional concrete mixture proportions

Aggregate type	Crushed Limestone					
	25		35		45	
Concrete strength (MPa)	L/m ³	kg/m ³	L/m ³	kg/m ³	L/m ³	kg/m ³
Cement	101	314	118	370	136	424
Fine aggregate	300	782	300	782	301	783
Coarse aggregate	382	1024	382	1024	382	1024
Water addition	205	205	187	187	169	169
Slump (mm)	200		130		50	
Water/ Cement	0.61		0.47		0.37	
bi (kg m⁻³ MPa⁻¹)	12.58		10.58		9.42	

3.5.2 Residual mortar (RM) content and RCA characterization

After crushing and sifting the recycled particles, the residual mortar (RM) content was determined for each of the three mixtures as by (Abbas 2007). Six samples (one per concrete type) were then selected to determine the RM in each individual size fraction (i.e. 4.75- 9.5mm; 9.5-12.5mm and 12.5- 19mm) and an average RM value was adopted to represent the overall RM of each RCA concrete.

RM evaluation was performed according to the following process: representative samples of the three different RCA mixtures were obtained using a quartering process similar to the one used for NA (Charles 1981). The sample sizes were approximately 1000 g for the 4.75–9.5 mm fraction and 2000 g for the larger size fractions. After drying the samples for 24 h at 105°C, the oven-dried samples were immersed in a 26% sodium sulphate solution (by weight) over 24h (similar concentration to the one used in the ASTM C88 soundness test). The RCA samples, while still immersed in the sodium sulphate solution, were subjected to five cycles of freezing and thawing (i.e., overnight 16h at –17°C, the same freezer conditions used for the ASTM C 672 scaling test, and 8h in an oven at 80°C). After the last freezing-and-thawing cycle, the solution was drained from the sample and the aggregate was washed with tap water over a No. 4 (4.75 mm) sieve. The washed aggregate was then placed in the oven for 24 h at 105°C, and its oven-dried mass was measured. The residual mortar (RM) content was then obtained using the following equation:

$$\mathbf{RMC\% = \left(\frac{W_{RCA} - W_{OVA}}{W_{RCA}} \right) \times 100} \quad 3.1$$

Where W_{RCA} = initial oven-dry mass of RCA sample before test (g) and W_{OVA} = final oven-dry mass of the OVA after full removal of the RM (g) (Fathifazl et al. 2009). It is worth noting that this procedure is not significantly more complicated nor time consuming than the aggregate soundness test procedure as per ASTM C88. Furthermore, some basic properties of the different RCA were also measured such as specific gravity, absorption capacity and moisture content. Finally, in order to compared the results from well-controlled RCA produced at the laboratory and

RCA materials currently used in the market, RCA made from returned concrete (incorporating a crushed limestone as OVA) was obtained from an industrial supplier and its RM was also measured. Table 3.3 displays the characterization results of the different RCA fabricated and obtained.

Table 3.3. Different crushed recycled aggregates specifications.

Crushed material identification		Shape	RMC (%)	Specific gravity (g/cm ³)	Absorption capacity (%)	Moisture (%)
Strength (MPa)	OVA Type					
25	Crushed limestone	Crushed stone	40.0	2.40	5.40	0.97
35	Crushed limestone	Crushed stone	45.6	2.41	5.09	1.10
45	Crushed limestone	Crushed stone	52.1	2.43	4.88	1.30
Unknown	RCA Supplier	Crushed stone	27.0	2.45	5.01	1.05

3.5.3 Equivalent Volume (EV) Method

The Equivalent Volume (EV) method was developed due to the fact that RCA mixtures designed through the EMV method might present poor performance in the fresh state, especially when eco-friendly RCA mixtures using low amounts of cement are targeted. Based on the EMV, the EV approach accounts for the residual mortar in the design of RCA mixtures. The EV is designed with the assumption that the RCA mix is based on a companion CC mixture having the same amount (in volume) of *cement paste and aggregates* as opposed of having the same amount of *coarse aggregates and mortar* as stated in the EMV. Practically, the EV method treats the RM in the RCA as a combination of residual paste (RP) and residual fine aggregate. In this context, the total cement paste (CP) of a given RCA mixture is then considered as the sum of its RP and fresh paste (FP) volumes.

In the EV, the RCA concrete mixture is proportioned to have the same total CP and aggregate volumes (i.e., summation of coarse and fine aggregates) as a companion CC mix made entirely with fresh NA, with the companion mix made with the same type of fine and coarse aggregates as in the RCA. Mix- proportioning based on the proposed method essentially involves proper

determination of the amounts of OVA and RM from the RCA. Then, the following conditions must be satisfied:

$$V_{CP}^{RCA-Concrete} = V_{CP}^{CC} \quad 3.2$$

$$V_{Ag}^{RCA-Concrete} = V_{Ag}^{CC} \quad 3.3$$

Where $V_{CP}^{RCA-Concrete}$ is total paste volume in RCA concrete. V_{CP}^{CC} and V_{Ag}^{CC} are respectively cement paste and aggregate volumes (i.e. coarse and fine) in the CC mixture. $V_{Ag}^{RCA-Concrete}$ is the total volume of coarse and fine aggregates in the RCA concrete, which is the sum of the volumes of new aggregate (NA: coarse and fine) and the original virgin aggregate (OVA: coarse and fine) contained in RCA.

Therefore:

$$V_{CP}^{RCA-Concrete} = V_{RP}^{RCA-Concrete} + V_{FP}^{RCA-Concrete} \quad 3.4$$

$$V_{TA}^{RCA-Concrete} = V_{OVA}^{RCA-Concrete} + V_{NA}^{RCA-Concrete} \quad 3.5$$

Where $V_{RP}^{RCA-Concrete}$ is the RP volume in RCA concrete; $V_{FP}^{RCA-Concrete}$ is the volume of the fresh paste (FP) in the RCA concrete; $V_{OVA}^{RCA-Concrete}$ is the OVA (coarse and fine) volume in the RCA concrete; and $V_{NA}^{RCA-Concrete}$ is the new aggregate (NA) (coarse and fine) volume in the RCA concrete. Figure 3.1 illustrates the volumetric material volumes of RCA mixtures designed with EMV (i.e. same volumetric amount of mortar and coarse aggregates) and EV (i.e. same volumetric amount of cement paste and aggregates) methods when compared to their initial CC mixes.

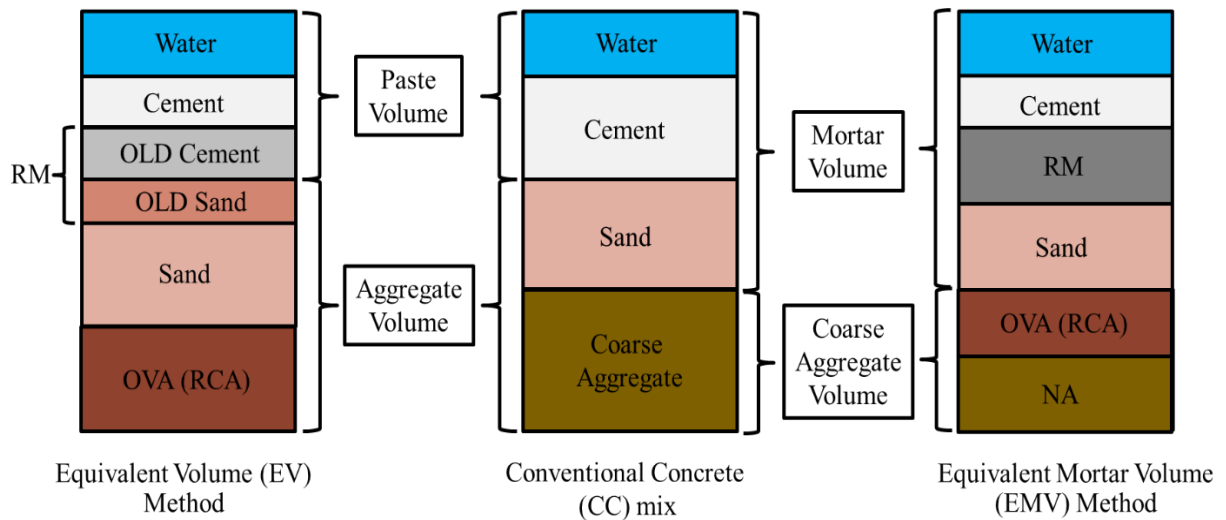


Figure 3.1. Volumetric material amounts of RCA mixtures designed with EMV and EV methods when compared to their initial CC mixes

Using the proposed EV approach, RCA concrete mixtures presenting different strengths (i.e., 25, 35 and 45 MPa) were mix- proportioned based on the CC mixes presented in Table 3.2 and the RCA characterization illustrated in Table 3.3. Similar strengths were targeted in this project regarding the initial quality of the RCA and the final RCA mix (e.g., 25 MPa RCA was used to generate 25 MPa RCA concrete; similar concepts were adopted for 35 and 45 MPa mixes). Furthermore, the RCA gathered from a commercial supplier was used to provide a 35 MPa RCA concrete for comparison purposes. Table 3.4 gives the detailed RCA concrete mixture proportions used in this work.

Table 3.4. RCA concrete mixture proportions.

RCA Conc. Strength (MPa)	25		35		45		35	
	25 CL		35 CL		45 CL		Supplier	
Agg. Type (MPa)	Kg/m ³	Ratio*	Kg/m ³	Ratio	Kg/m ³	Ratio	Kg/m ³	Ratio
Cement (kg/m ³)	261	1.0	321	1.0	335	1.0	354	1.0
Fine Agg. (kg/m ³)	712	2.7	686	2.1	707	2.1	682	1.9
RCA (kg/m ³)	1186	4.5	1223	3.8	1223	3.7	1165	3.3
Water (L/m ³)	169	0.65	145	0.45	133	0.40	160	0.45
RMC (%)	40		46		52		27	
bi (kg m ⁻³ MPa ⁻¹)	10.43		9.17		7.43		10.13	

*: The mix- design is presented in ratios here; i.e. all the ingredients of each mix are divided by the cement content of the respective mixture.

3.5.4 Methods for assessment and analysis

A total of 66 specimens, including 54 cylinders (i.e., 100 by 200 mm in size) and 12 prisms (i.e., 100 x 100 x 400 mm), were cast from the three RCA concrete mixtures manufactured in the laboratory. The RCA specimens were demolded 24 hours after casting and moist cured over 28 days. Table 3.5 highlights the testing matrix performed in this research. The investigation program conducted on RCA concrete specimens with different properties includes fresh state (i.e., slump test), hardened state (i.e. compressive strength, bending flexure, modulus of elasticity and SDT) and non-destructive measurements (i.e. UPV and surface resistivity). It is worth noting that in this study, supplementary cementing materials (SCMs) and chemical admixtures were intentionally *not considered* in order to benchmark the results from EV mix- designed RCA concrete without including new variables to the system.

Table 3.5. Testing matrix present the amount of samples for each test developed in this research

Test methods (number of samples)	Time (days)				
	Fresh state	3	7	14	28
1) Compressive strength	x	3	3	x	3
2) Tensile strength (flexure)	x	x	x	x	2
3) Modulus of elasticity/SDT	x	x	x	x	3
4) Slump test	✓	x	x	x	x
5) Resistivity	x	3	3	3	3
6) UPV	x	3	3	3	3

All the fresh state (slump test) and mechanical test procedures (compressive strength and bending flexure), except the SDT, are conventional and well-known standardized approaches currently used in concrete laboratories worldwide. For those tests, ASTM C143 – 78, ASTM C C39 / C39M, ASTM C78 / C78M – 16 were used respectively.

The Stiffness Damage Test (SDT), was performed as by (Sanchez et al. 2016; Sanchez et al. 2014; Sanchez 2015) Figure 3.2.B. The RCA specimens were subjected to five loading/unloading cycles at a controlled loading rate of 0.10 MPa/s with loading levels of 40% of the compressive strength measured at 28 days. The analysis of the outcomes were also performed as by (Sanchez et al. 2016; Sanchez et al. 2014; Sanchez 2015); i.e. *Stiffness Damage Index*, *SDI* – which indicates the dissipated energy over the five loading/unloading cycles Figure 3.2.A; the *Plastic Deformation Index*, *PDI* – which gives the plastic deformation which occurs due to the closure of cracks during the five loading/unloading cycles and; the *Modulus of Elasticity*, *ME* – which indicates the stiffness of the material (assumed as an average of the second and third cycles). All these parameters are quantitative measures of the “damage” and/or “inner quality” of a given material. The results presented in this work are the average of three concrete specimens from the same mix at a given age.

A) Stiffness Damage Index (SDI, Plastic Deformation Index (PDI) and Modulus of Elasticity (E)

B) SDT setup

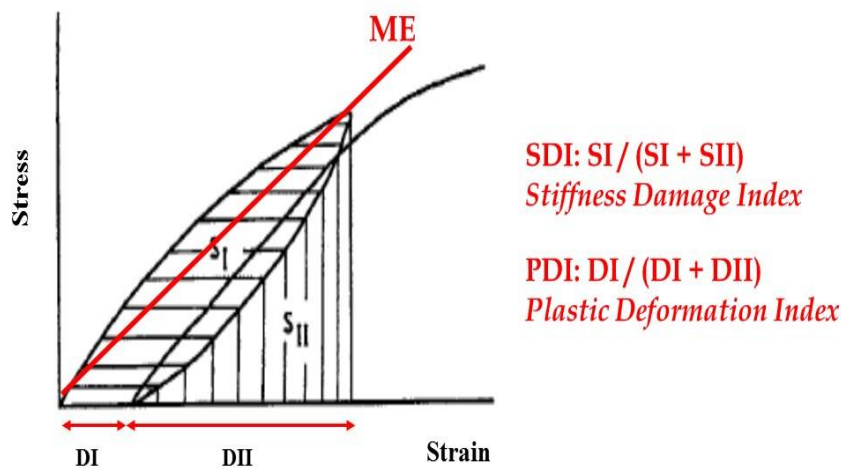


Figure 3.2. The Stiffness Damage Test (SDT), A– Stiffness Damage Index, SDI & Modulus of Elasticity, ME, B – SDT Setup (Sanchez et al. 2016)

Two non-destructive techniques (NDT) ultrasonic pulse velocity (UPV) and surface electrical resistivity (ER) were used to assess the inner quality of RCA concrete. UPV is one of the oldest NDT procedures used for determining the inner quality and distress in concrete. UPV captures the time that ultrasonic pulse waves are transmitted through a particular medium (i.e. such as concrete)

with a known length (Davis et al. 1998). It has been established that the faster the UPV waves propagate through a medium, the sounder (i.e. less damaged and porous) the medium should be. Thus, UPV might be seen as an interesting technique to measure the microstructure quality of RCA concrete. Likewise, surface ER is one of the most recent and promising NDT techniques used to appraise quality and damage in concrete. It measures the resistance of a material to electrical current transmission. Conventional surface ER devices use the setup called “4-probe array” and thus measure the electrical current over 4 channels (located at 90° from each other). The results presented in this work on the two above NDT techniques are the average of three concrete specimens from the same mix at a given age.

3.6 Results

3.6.1 Compressive strength tests

Compressive strength tests were initially performed on the CC mixtures at 28 days to confirm their targeted strength (25, 35, 45 MPa). Table 3.6 shows the results obtained on CC specimens. Then, compressive tests were carried out over time (i.e., 3, 7, 14 and 28 days) on the four RCA mixtures designed with the EV method (three from laboratory samples and one from a commercial supplier). Figure 3.3 illustrates the values obtained at 28 days.

Table 3.6. Compression strength results obtained on CC specimens

Designed strength (MPa)	25.0	35.0	45.0
Measured strength (MPa)	25.1	35.4	46.5

According to the results, each of the different RCA concrete mixtures reached the intended target compressive strength at 28 days (dashed lines). Moreover comparing to the CC mixes, all RCA concrete mixtures reached similar or slightly greater compressive strength values.

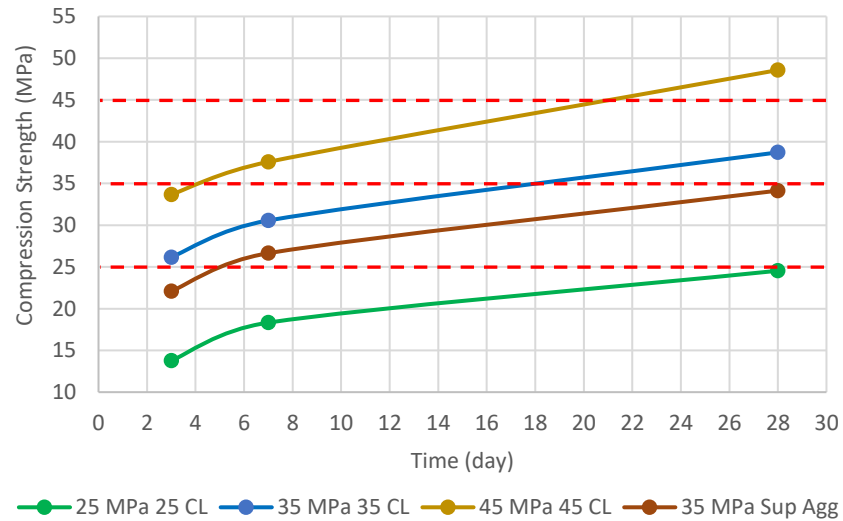


Figure 3.3. Compressive strength test results performed on the different RCA concrete mixtures designed with the EV method.

3.6.2 Stiffness damage test (SDT)

The SDT was performed on both the distinct CC mixes and different RCA concrete incorporating different RCA qualities and sources. Figure 3.4 illustrates the modulus of elasticity results obtained. Analyzing the data, one notices that the greater the compressive strength of the CC mixes, the higher the modulus of elasticity (i.e. higher stiffness), as expected. ME values ranged from 26.7 GPa to 46.0 GPa for 25 and 45 MPa, respectively. Furthermore, RCA mixtures presented ME values similar to CC. All the RCA mixtures presented ME slightly lower than CC at about 2 GPa with the exception of 45 MPa RCA mix, which showed higher results than CC (about 5 GPa). Finally, the RCA concrete made with the material gathered from a market supplier presented results very similar ME (slightly lower – 1 GPa) than the 35 MPa RCA concrete.

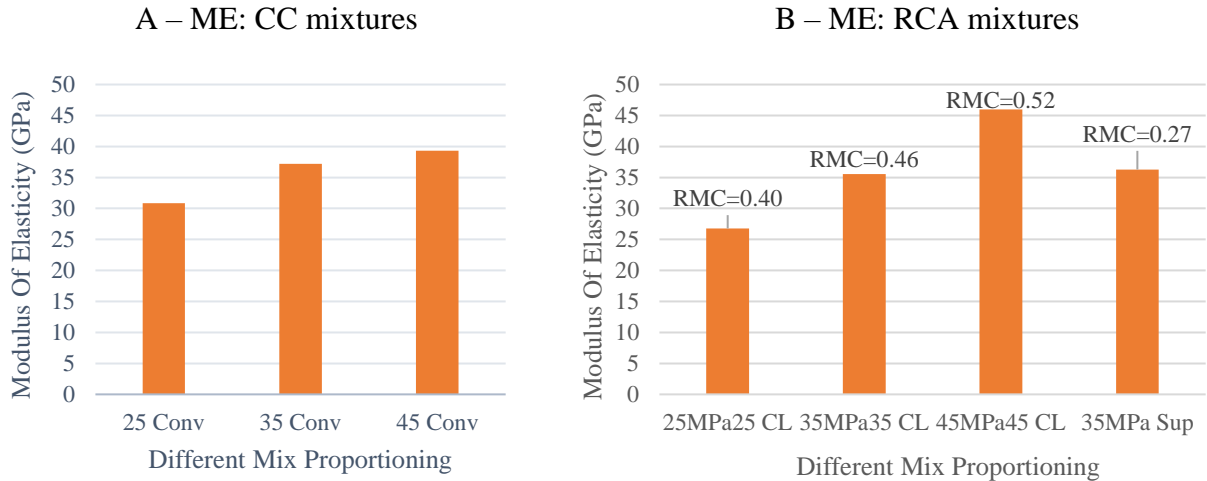


Figure 3.4. Modulus of elasticity (ME) results as a function of different mix proportions for 5 loading-unloading cycles: A: Conventional concrete .B: RCA concrete.

Figure 3.5 illustrated the Stiffness Damage Index (SDI) results for both conventional and RCA concrete. Analyzing the data, one notices that the greater the compressive strength of the CC mixes, the lower the SDI (i.e. higher inner quality), as expected. SDI results varied from 0.12 to 0.05 for 25 and 45 MPa respectively. Moreover, RCA mixtures presented SDI results fairly similar to CC. All the RCA mixtures presented SDI slightly lower than CC (about 0.01-0.02) with the exception of 45 MPa RCA mix, which showed considerably lower SDI result than CC (about 0.04). In addition, the RCA concrete made with the material gathered from a market supplier presented SDI results similar (i.e. slightly lower – 0.01) than the 35 MPa RCA concrete.

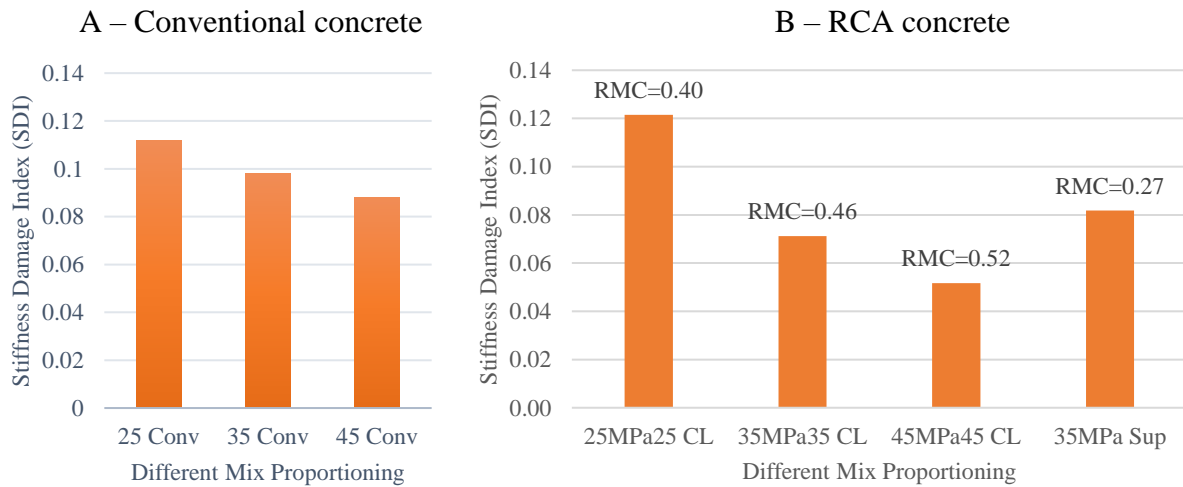


Figure 3.5. Stiffness Damage Index (SDI) results as a function of different mix proportions for five loading-unloading cycles: A: Conventional concrete .B: RCA concrete.

3.6.3 Ultrasonic pulse velocity (UPV) and Resistivity tests

Figure 3.6 illustrates the UPV and surface ER test setup and results performed on the different RCA concrete mixes can be seen in figure 3.7. The results are the average values obtained on three specimens from a specific mix at a given age. Analysing the data below, one sees that for all the RCA concrete mixtures, the greater the material's strength, the greater the UPV and ER results. Moreover, the RCA concrete made with the material gathered from a market supplier presented results higher than 25 MPa RCA concrete or close to 35 MPa RCA concrete, especially in ER's case. Finally, based on ASTM C597-16 all the concrete mixtures designed with the EV method presented "very good to excellent concrete quality results with low amount of porosity" since the values ranged from 4.43 to 4.87 km/s for 25 and 45 MPa respectively, despite very likely presenting significant microcracking due to crushing processes.

A – Ultrasonic pulse velocity (UPV)



B – Surface electrical Resistivity (ER)



Figure 3.6. NDT test Setups performed on different RCA concrete mixtures presenting distinct qualities. A – UPV Setup, B – Surface ER Setup.

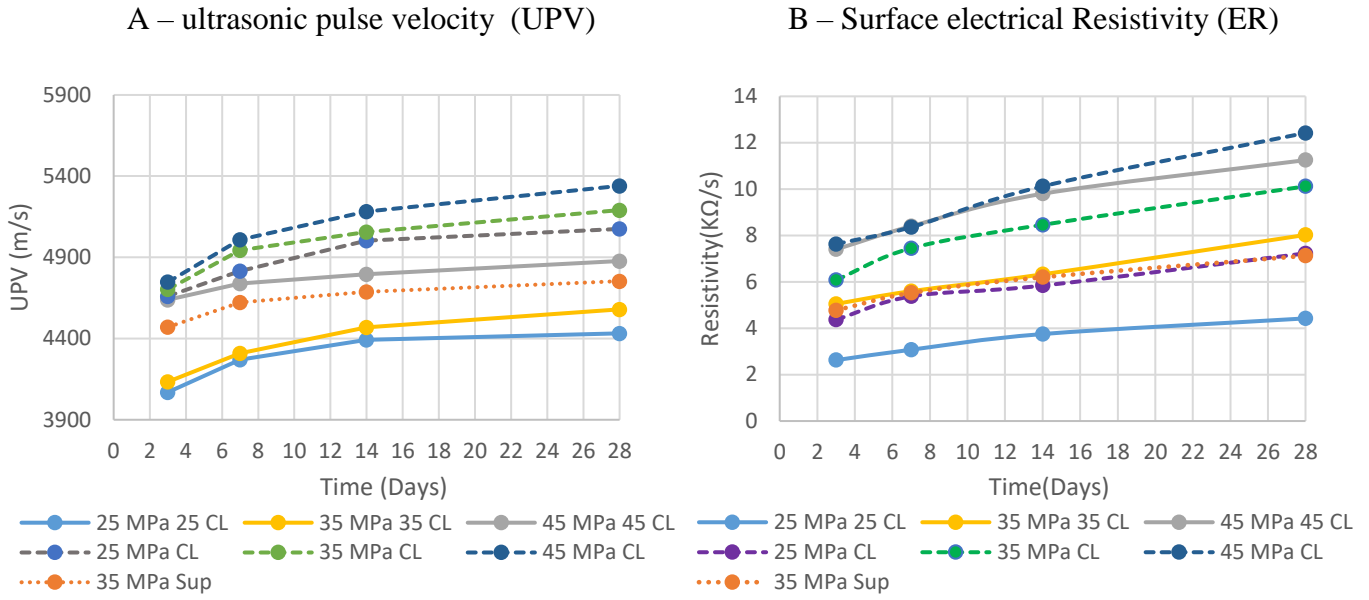


Figure 3.7. NDT test results performed on different RCA concrete mixtures presenting distinct qualities. A – UPV results, B – surface ER results.

3.6.4 Flexure test (third point test)

Figure 3.8.A presents the results of the flexural test (third point bending) performed on the RCA mixtures evaluated in this work figure 3.8.B. It is possible to see that the greater the concrete strength, the greater is the flexure capacity. Moreover, the RCA concrete made with the material gathered from a market supplier presented results slightly lower than the 35 MPa RCA concrete. Figure 3.9 presents the results of modulus of rupture (MOR) performed on the RCA mixtures assessed in this work. It is possible to see that the greater the concrete strength, the greater the MOR. Moreover, the RCA concrete made with the material gathered from a market supplier presented results slightly lower than the 35 MPa RCA concrete,

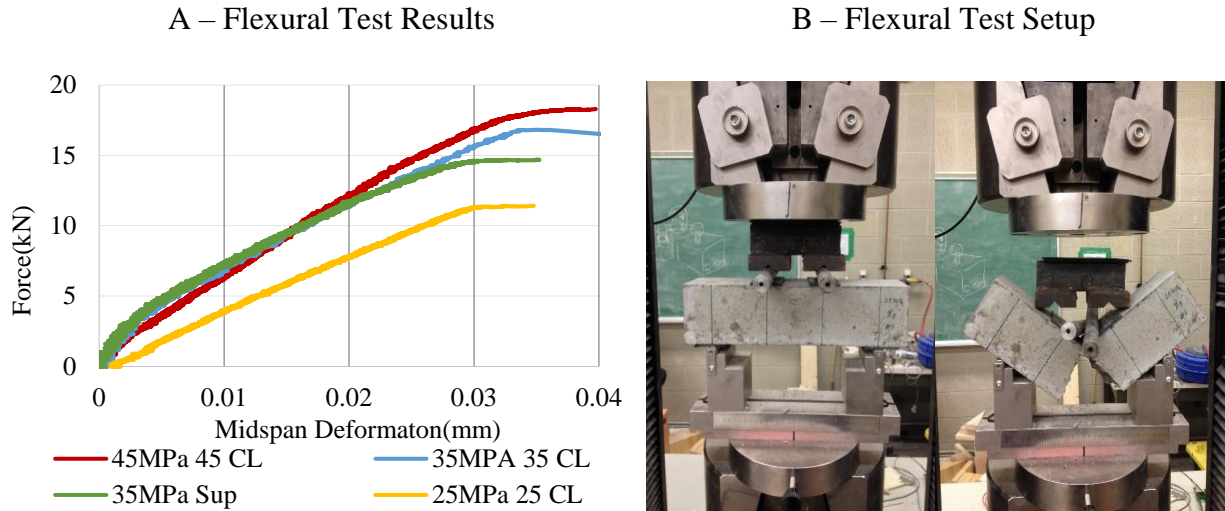


Figure 3.8. A- RCA concrete specimens tensile strength incorporating the different RCA strength and aggregate type, based on EV mix proportioning method, B- flexural test (third point bending) setup.

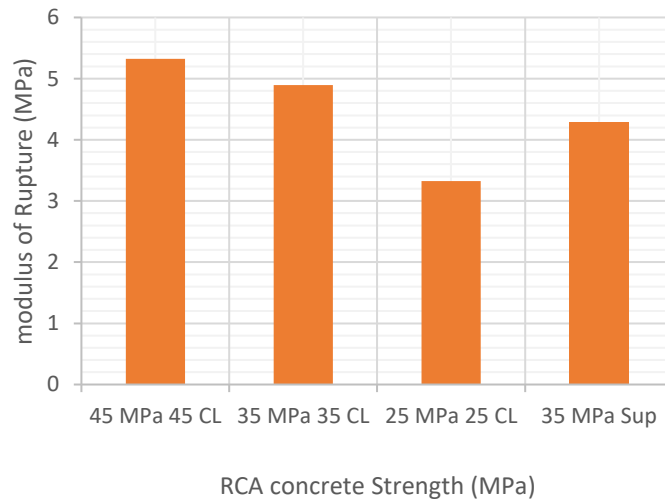


Figure 3.9. Modulus of rupture (MOR) as a function of the concrete strength (25, 35, 45MPa) and aggregate type (CL and supplied).

3.7 Discussion

3.7.1 Properties of RCA designed through the EV method

3.7.1.1 Fresh state properties

A number of mix- design procedures were developed in the past to mix- proportion RCA concrete. Most of those procedures used direct aggregates replacement and thus did not account for RM in RCA. Although several works reported similar fresh state properties compared to CC, those mixes did not behave properly in the hardened state, which actually attributed to the perception of RCA as a “low quality material”. The EMV was then developed with a different concept and proved that if an RCA concrete mixture is properly designed (i.e. RM is accounted for in the RCA mix), the hardened state properties of RCA mixes may be similar to CC. However, some challenges were faced in the fresh state due to the low amount of cement paste in the design of the recycled mix. The major fresh state problem of RCA mixes in the EMV method lies in the fact that the RM acts as an aggregate in the fresh state, although is a mortar (i.e. cement paste + sand + water) in the hardened state. If one takes that into account and is required to match the amount of mortar and coarse aggregates in the recycled mix with a companion CC, the amount of new cement paste to be added in the mix may be too low and thus will result in stiff behaviour in the fresh state.

In order to avoid the above problem, the EV method is proposed in this work. The EV takes advantage of the interesting concepts of the EMV (such as RM), yet it incorporates in its design a higher amount of fine aggregates (and lower amount of coarse) which helps to decrease the viscosity and consistency of the recycled mix.

The EV mix- designed mixtures in this work demonstrated interesting behaviour in the fresh state in comparison to the EMV method. Their consistency was still quite high (i.e. around 50 mm or slightly less) depending on the RM of the RCA, but all mixtures were easily vibrated, presenting very likely a shear thinning rheological behaviour (i.e. decrease of viscosity as a function of the torque applied). It is worth mentioning that in this work no chemical admixtures and SCMs were used to not introduce a new variable to the system. Therefore, one might think that there is still

room for improving the behaviour of EV mix- designed RCA mixtures, without causing issues to their hardened and long-term performance.

3.7.1.2 Hardened state and durability related properties

The EV mix- designed RCA mixtures studied in this work presented quite interesting mechanical performance. All the recycled mixtures met the strength criteria (i.e. compressive strength requirements). Moreover, similar values of modulus of elasticity compared to the reference CC mixtures were found throughout this work, which seems promising for use in structural applications. Most of the previous works found in literature showed a significant decrease of E in RCA mixes, very likely due to the multi-phase character of the material (i.e. OVA + RM; RM being much more porous than NA). Conversely, in this work the modulus of elasticity of the recycled mixes seems to be kept due to a better packing of the granular skeleton (i.e. introduction of more fine particles in the system) of the recycled material. Furthermore, durability-related tests such as UPV and surface ER highlighted their good behaviour and quality to be used in harsh climates, being acceptable according to guidelines and standards. Finally, the RCA mix made with the use of the commercial RCA also performed quite satisfactorily, which gives to the new method a great potential. However, the EV still needs to prove its efficiency for the design of a much wider range of RCA with different qualities and incorporating distinct aggregate types.

3.7.1.3 Eco-efficiency of EV mix- designed RCA mixtures

It is well established that the Portland cement (PC) industry is one of the main contributors regarding the carbon footprint of civil construction (Gartner 2015). Thus, Damineli et al [5] proposed an index, the so-called *Binder Intensity* (bi), which is defined as the amount of PC required to obtain 1 desired unit of a given performance indicator; e.g., the amount of PC in kg/m³ to obtain 1 MPa of compressive strength at a given time (i.e., 28 days). (Equation 3.6).

$$bi = \frac{B}{CS} \quad 3.6$$

Where, B is the amount of binder (in kg/m³), and CS is the compressive strength in MPa. Damineli et al (Damineli et al. 2010) benchmarked the bi indices in Brazil and around the globe and noticed that the higher the compressive strength, the lower the bi factor. In other words, high strength concrete mixtures implicitly have low bi indices and thus lower carbon footprint (Figure 3.10). However, high bi factors are currently used in CC for civil infrastructure (i.e. from 20 to 40 MPa). As illustrated in Table 3.4, the cement contents of the CC mixes designed through conventional methods were 314, 370 and 424 kg/m³ for 25, 35 and 45 MPa mixtures respectively. Otherwise, the EV mix- designed RCA mixtures presented a much lower binder content of 261, 321 and 335 kg/m³ for 25, 35 and 45 MPa RCA mixes, respectively. This increase in binder efficiency made the high bi factors of the CC mixes (i.e. 12.6, 10.6 and 9.4 ($kg\ m^{-3}MPa^{-1}$)) to drop significantly to 10.4, 9.2 and 7.4 ($kg\ m^{-3}MPa^{-1}$) (black points). The latter indicates that besides being efficient for improving fresh and hardened states of RCA concrete mixtures, the EV method might also be an alternative towards a greener future in civil engineering. Furthermore, whether one only accounts for the new cement added to make the RCA concrete, the new bi factors (red points) obtained are even lower (i.e. 8.34, 7.13 and 5.2 $kg\ m^{-3}MPa^{-1}$) and are located by the line with the lowest cement content (i.e. 250 kg/m³) which may be considered a very eco-efficient material for structural purposes.

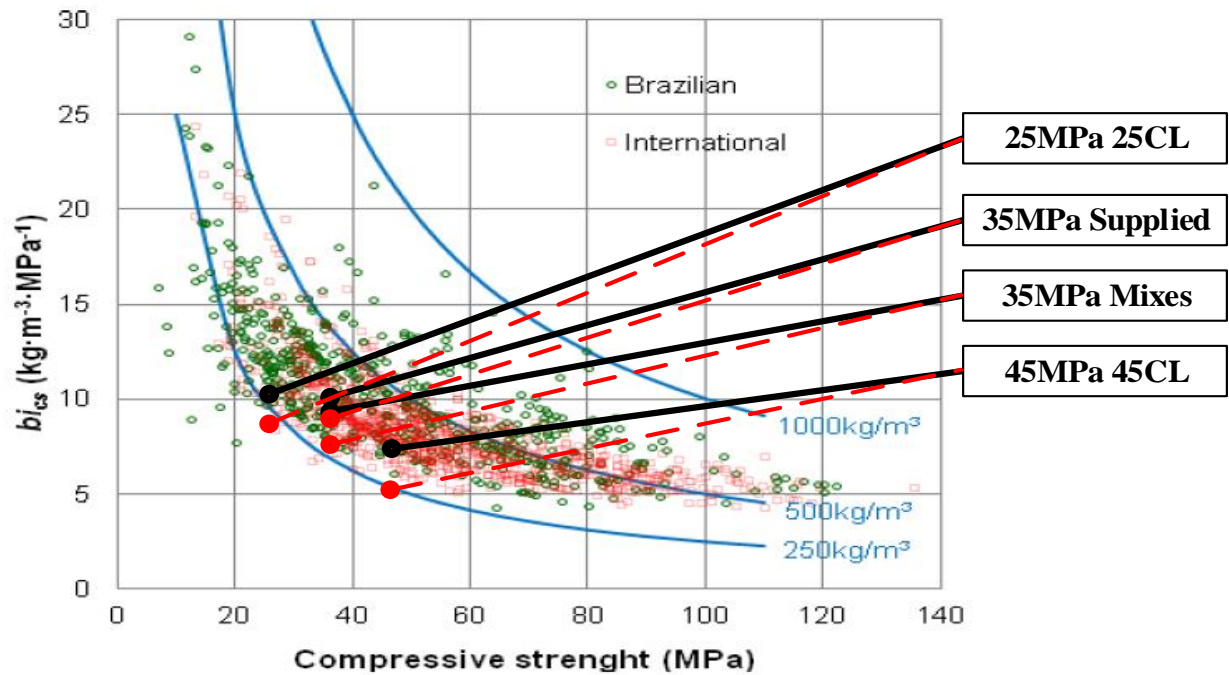


Figure 3.10. Binder intensity (bi_{cs}) vs. 28-day compressive strength for Brazilian (green dots) and international (red dots) data. The lines represent concrete mixtures with the same amount of total binder (Damineli et al. 2010).

3.8 Conclusion

In this study, a new mix- design procedure, the so-called Equivalent Volume (EV) method was developed to mix- proportion RCA concrete with suitable properties in the fresh and hardened states. A number of EV mix- designed RCA concrete specimens were fabricated presenting different qualities (i.e. 25, 35 and 45 MPa) and were evaluated through chemical (i.e., residual mortar test), mechanical (i.e., compression strength test, flexure and stiffness damage test) and non-destructive (i.e. UPV and surface ER) procedures. The main findings of the current study are presented hereafter:

- The EV method was capable of efficiently improve the fresh state behaviour of RCA concrete without the need of chemical admixtures. This happened very likely due to the

use of higher amount of fine aggregates (and lower amount of coarse particles) when compared to the EMV method, which helps to decrease the viscosity and consistency of the recycled mix;

- All the EV mix- designed concrete mixtures presented excellent behaviour in the hardened state. The specimens showed similar to slightly higher compressive strength than the required values. Moreover the ME results were quite similar to CC;
- The long-term behaviour of RCA concrete designed through the EV method seems promising since interesting UPV, SDI and surface ER were found. However, the latter are only an indication and further research is still needed accounting for different damage mechanisms such as freezing and thawing, alkali-aggregate reaction, sulfate attack, etc.;
- Besides being efficient for improving fresh and hardened state performance of RCA concrete mixtures, the EV method might also be an alternative towards a greener future in concrete construction since low bi factors are obtained through the method;
- Finally, although the EV seems to have a great potential in designing RCA concrete with interesting fresh and hardened state behaviours, further research accounting for a wider range of aggregates and RCA & RCA concrete mechanical properties is still needed to prove the method.

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4 Effect of the Quality of Recycled Concrete Aggregate (RCA) on the Behaviour of New Recycled Concrete Mixtures

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4.1 Abstract

Although the use of recycled concrete aggregate (RCA) as coarse aggregate in concrete mixtures has substantially grown over the past decades, concerns related to its structural performance and long-term behaviour still prevent its widespread application, especially for structural purposes. Considering that RCA is a composite material comprised of original virgin aggregates (OVA) and residual mortar (RM), it has been found that accounting for RM as part of the total mortar volume in the design of RCA concrete can improve its mechanical and durability properties. However, there is a lack of information on the influence of the RCA source/quality on the fresh and hardened states of RCA concrete. This work presents an experimental (i.e. chemical, mechanical and non-destructive) characterization of RCA mixes from distinct sources. Results indicate that RCA concrete may be considered for structural applications since they can meet performance targets in the fresh and hardened states. Finally, a quality control protocol for evaluating the suitability of RCA sources for structural applications is proposed.

Keywords: RCA concrete, RCA source and quality, RCA quality control, Waste management

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4.2 Introduction

Demolished concrete constitutes a large part of the millions of tons of annual solid demolition waste. Using recycled concrete aggregate (RCA) is one of the methods which has been receiving increased attention in the civil industry as a sustainable alternative to natural aggregates with a low carbon footprint and also to decrease the solid demolition waste. Although the use of RCA in concrete has grown over the past decades, issues related to its structural performance, durability and long-term behaviour prevent its widespread application for structural purposes, especially when different raw material sources are used (i.e. presenting different features such as mechanical properties, aggregates type/nature, etc.). Despite environmental benefits of using RCA in the construction industry (Abbas 2006), the use of RCA concrete for structural applications has been limited to only a very small percentage, especially due to the current lack of guidelines, quality control and clear specifications from the process of RCA manufacturing to the mix- proportioning of RCA concrete mixtures.

4.3 Background

RCA is normally described as a two-phase material made by original virgin aggregates (OVA) embedded into residual mortar (RM), and thus presents a significantly different microstructure when compared to conventional concrete (CC). Although some documents such as ACI-555R (Lamond et al. 2002) provide basic guidelines and criteria on how to deal with and use RCA for proportioning RCA concrete, the vast majority of previous research works on the topic of RCA concrete have treated recycled aggregates as a homogenous material similar to natural aggregates (NA) and adopted direct replacement techniques for mix- proportioning RCA concrete (Mandal 2002; Gómez Soberón 2002; Gómez-Soberón 2002b; Limbachiya 2000; Dhir 1999). As a result, RCA mixes have always resulted in inferior mechanical and physical properties when compared to CC and thus RCA has always been seen as a low-quality material (Ray 1991; Topcu 2004). Conversely, it has been found that RCA mixtures with at least similar performance to CC (at least in terms of compressive strength) might be achieved whenever the differences in the microstructure were accounted for in the recycled mixtures such as modifying the w/c ratio (i.e.

porosity) and fresh paste content (accounting for the RM) of the RCA concrete (Dhir 1999; Topcu 2004).

In RCA concrete, the higher the RM content (and the lower its quality), the inferior the mechanical response of the material. Hence, the properties of RCA concrete are directly dependent on the amount, composition, and quality of the RCA (Fathifazl et al. 2009). One of the methods recently introduced in the literature which is able to account for the different microstructure of RCA by quantifying the amount of the RM is the so-called *Equivalent Mortar Volume* (EMV) method (Fathifazl et al. 2009). In the EMV approach, the amount of each phase of the RCA (i.e. OVA and RM) is quantified and used to adjust both the amount of coarse aggregate and fresh paste of the RCA mix, so that the recycled mixture presents at the end the same amount of mortar and aggregates as a companion CC (Fathifazl et al. 2009). The use of the EMV method has been shown to provide recycled mixtures with satisfactory hardened state properties, yet this procedure may display some challenges in the fresh state (i.e. consistency, rheological behaviour, etc.), especially when sustainable RCA mixtures using low cement contents are designed. Moreover, previous successful RCA mixtures with the use of the EMV method have utilized moderate to high amounts of cement and superplasticizer, which somewhat offsets the environmental benefits of the RCA. Therefore, a new mix-design proportioning approach, the so-called *Equivalent Volume* (EV) method was recently proposed to overcome those issues. The EV method is based on a similar concept than the EMV (i.e. accounting for the RM of the RCA). It was designed with the following assumption: the RCA mix is based on a companion CC mix having the same amount (in volume) of *cement paste and aggregates* as opposed to having the same amount of *coarse aggregates and mortar* as stated in the EMV. The EV approach seems very promising and has demonstrated great potential since it partially solves some of the challenges encountered with the use of the EMV in the fresh state (especially for RCA mixes with moderate to low cement content) while keeping the same benefits of the EMV in the hardened state.

Several previous research studies on RCA concrete (especially the ones employing the EMV method) have reported similar or even superior values of compressive strength in RCA concrete when compared to CC. However, it can be challenging to achieve the same trend for other hardened state properties such as tensile strength and modulus of elasticity (Fathifazl et al. 2009; Hansen 1992; Hansen 1986; Kiuchi 2003; Sogo et al. 2004; de Oliveira 1996; Sakata 2000). It is well

established that the compressive/tensile strength of concrete is dependent on the cement paste/interfacial transition zone (ITZ) quality, which is directly linked to the porosity (or w/c ratio) of the mix, while the modulus of elasticity is a function of the volume fractions and elastic moduli of the coarse aggregates and mortar (Lydon 1982; Neville 1995; Mindess 1981). In general, the lower RCA modulus of elasticity is likely related to the “more porous/cracked” nature of the RCA as well as to its non-negligible amount of RM adhered to the OVA (Mindess 1981). Moreover, differently from CC, RCA might present important initial inner “damage” such as microcracks and flaws generated during the crushing process of the material. The latter might even vary according to the quality/type of the RCA source (i.e. quality of the RM and type/nature of the aggregate) which could impact the performance of the RCA concrete. In other words, the quality of a RCA mix might not only be limited by the mix- proportioning method used but also by the quality of the RCA source in the RCA mix. However, there is currently no quality control protocol to evaluate this impact on the performance of RCA mixtures in the fresh and hardened states. In this context, some chemical (i.e. residual mortar test- RM), mechanical (i.e. stiffness damage test- SDT) and non-destructive techniques (i.e. ultrasonic pulse velocity- UPV and surface electrical resistivity- ER) were seen to be suitable to evaluate the inner damage and/or quality of CC microstructure and thus might also be considered to RCA evaluation.

4.4 Tools for assessing quality in RCA concrete

4.4.1 Residual mortar (RM) content analysis

The majority of studies on RCA concrete reported in the literature make use of conventional mix proportioning methods through direct replacement of the NA by RCA. Often, additional adjustments are then needed to meet performance criteria in the fresh and/or hardened states, such as a significant increase in cement content and/or use of non-negligible amounts of superplasticizers if the existing residual mortar of the RCA is not accounted for. In fact, the quality and amount of RM distinguishes RCA from NA. As previously stated, RCA consists of two distinct phases: the original virgin aggregate (OVA) and the attached RM. Due to the inferior physical properties of mortar compared to NAs, higher RM amounts generally lead to lower RCA

quality and thus lower RCA concrete performance. Common consequences are lower modulus of elasticity and higher drying shrinkage and creep of RCA concrete (Hansen 1992; Hansen 1986; de Oliveira 1996; Yamasaki 1999; Limbachiya 2000; Kiuchi 2001, 2003; Gomez-Soberon 2003; Sogo et al. 2004; Sakata 2000). Hence, the quantity of RM is a critical design parameter; unfortunately, in the majority of previous studies, the RCA residual mortar content (RMC) has not been stated and apparently not determined (Fathifazl et al. 2009).

The quantity of RM in an RCA source may be determined by soaking the RCA particles in a sodium sulphate solution (26% by weight) and subjecting them to five freezing and thawing cycles after which the samples are sieved, oven dried and weighed. The weight loss over the process is considered to be the RM of the RCA in percentage (Abbas et al. 2007).

According to the literature, in order to achieve the maximum strength in RCA concrete, the w/c ratio in new mortar (NM) should be equal to or smaller than the w/c ratio in RM. In other words, the strength of NM should be higher than that of RM (Hansen 1992; Hansen 1986; Yamasaki 1999). While the previously developed EMV and EV mix design methods allow the designer to account for the *quantity* of RM in a RCA source, they do not explicitly consider its *quality*. Nevertheless, these approaches present the distinct advantage of allowing one to determine the proper amount of RCA and other mix ingredients to achieve certain specified fresh and hardened properties (Fathifazl et al. 2009).

4.4.2 Stiffness damage test (SDT)

Recently, Sanchez et al. proposed the use of the Stiffness Damage Test (SDT) to quantify the degree of damage in concrete affected by a number of distress mechanisms such as alkali-aggregate reaction (AAR), freezing and thawing (FT) and delayed ettringite formation (DEF) (Sanchez et al. 2016; Sanchez et al. 2017; Sanchez et al. 2014; Sanchez 2015). The SDT is a cyclic test procedure in compression usually performed at 40% of the design (28-day) concrete strength of the sample under analysis at a controlled loading rate of 0.10 MPa/s (Sanchez et al. 2016; Sanchez et al. 2017; Sanchez et al. 2014; Sanchez 2015). The main outcomes of the test are: 1) the modulus of elasticity (calculated as the average of the modulus obtained in the cycles 2 and 3) as well as the 2) Stiffness

Damage Index (SDI) and 3) Plastic Deformation Index (PDI) which are respectively the relationship between the dissipated energy or plastic deformation during the five loading/unloading cycles and the total energy/total deformation placed in the system over five cycles (Sanchez et al. 2016; Sanchez et al. 2017; Sanchez et al. 2014; Sanchez 2015).

The SDT's use is based on the assumption that the use of low-quality RCA is analogous to internal "damage" in the concrete due to weaknesses in the microstructure and presence of microcracks which will result in more energy dissipation/plastic deformation during loading/unloading cycles compared to CC. Although the SDT has never been used thus far to evaluate the condition of RCA concrete, it is expected that this tool might be able to evaluate the inner quality of the RCA mix and thus appraise the influence of the RCA source on the behaviour of RCA concrete mixtures (Crouch 1987; Sanchez et al. 2014; Sanchez 2015; Sanchez 2014; Bérubé 2005a; Bérubé 2005b; Smaoui et al. 2004; Sanchez et al. 2016; Alexander 1995; Chrisp 1993).

4.4.3 Non-destructive tests

Non-destructive test (NDT) procedures enable a fast assessment of the inner quality of concrete mixtures. It has been found that a number of non-destructive techniques, such as ultrasonic pulse velocity (UPV), surface electrical resistivity (ER), Schmidt hammer etc., (Topcu 1997) may be able to appraise the influence of RCA amount on the mechanical properties of RCA concrete. According to (Topcu 1997), by using conventional mix proportioning methods, the higher the RCA content, the lower the Schmidt hardness and UPV results. Otherwise, it is expected that different NDT techniques might be able to distinguish not only the RCA amount but rather its inner overall quality (i.e. cracking extent and porosity). Furthermore, to the knowledge of the authors, NDT has never been used to assess the quality of RCA and thus should be further studied.

4.4.4 Los-Angeles abrasion

Los Angeles (LA) abrasion test is generally conducted to measure the toughness of coarse aggregate particles or, in other words, to evaluate their resistance to degradation (micro-deval is

actually the test procedure currently used to measure abrasion of aggregates) (Reza Fathi-Fazl et al. 2017). According to the European Standard EN-12620, LA abrasion test is able to give a measure of the RCA quality since distinct toughness results might be measured from RCA presenting different RM contents (De Juan 2009). Furthermore, it has been found that a correlation exists between LA test results and the compressive strength of concrete made by RCA (Topcu 1997). However, quantitative LA results, especially in correlation to chemical, mechanical and NDT tests are still missing in literature and should be further researched.

4.4.5 Flexural test

One of the most commonly used tests for estimating “indirectly” the tensile strength of concrete is through ASTM C 78- third-point flexural loading test (ASTM 1999). Although not a “direct” nor “pure” measure of the tensile strength (i.e. modulus of rupture), the third point flexural test provides an indication of the behaviour of cementitious materials under bending which could be directly correlated to their practical response in the field. Moreover, a number of studies have investigated the modulus of rupture of RCA concrete. Although no significant difference in modulus of rupture of CC when compared to RCA concrete is reported in literature in some works, there is still some doubts on the ability of this test to distinguish different RCA qualities and sources due to their damaged and more porous nature when compared to CC (Sri Ravindrarajah and Tam 1985; Tavakoli 1996; O.O. 2008). Finally, the modulus of rupture measures also the ability of a mixture to control first cracking, which may change in concrete designed with different RCA qualities and sources.

4.5 Scope of the work

The previous sections clearly showed the lack of guidelines, specifications and quality control procedures for RCA concrete mixtures for structural purposes. Thus, this work aims to: 1) understand the influence of the quality of the RCA source (i.e. different mechanical properties and aggregate types) on the fresh and hardened state properties of RCA mixes and; 2) propose a quality

control protocol for evaluating the suitability of different RCA sources for structural applications in civil engineering through the use of laboratory test procedures (chemical, mechanical and NDT).

4.6 Materials and methods

4.6.1 Materials and RCA processing

Six different types of concrete mixtures with three distinct specified compressive strengths (i.e. 25, 35 and 45 MPa) and two types of aggregates (i.e. crushed limestone (CL) and quartzite gravel (QG)) were selected for this study. The coarse aggregates ranged from 5 to 20 mm in size. Table 4.1 provides information on the different materials used in this study.

Table 4.1. Different materials used

Material identification		Specification	Specific gravity (g/cm ³)	Absorption capacity (%)
Type	Description			
Cement	-	GU	3.125	-
Fine	Natural sand	-	2.602	0.91
Coarse	Crushed Limestone	CL	2.680	0.58
Coarse	Quartzite gravel	QG	2.560	1.09

Nine 100 by 200 mm concrete cylinders were fabricated for each of the 6 different concrete mixtures, using a conventional mix- design procedure (i.e. ACI method – Table 4.2). After 24 h, the specimens were demoulded and moist cured for 28 days after which the *Stiffness Damage Test* (SDT) followed by compressive strength tests were performed on three random specimens per mix to characterize the control samples. Then, the remaining cylinders were crushed into coarse RCA particles ranging from 5 to 20 mm.

Table 4.2. Detailed concrete mixture proportions.

Aggregate type	Crushed Limestone			Quartzite Gravel		
Concrete strength (MPa)	25	35	45	25	35	45
	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³
Cement	314	370	424	314	370	424
Fine aggregate	782	782	783	730	730	730
Coarse aggregate	1024	1024	1024	1024	1024	1024
Water addition	205	187	169	210	192	175
Water/ Cement	0.61	0.47	0.37	0.61	0.47	0.37

4.6.2 Residual mortar (RM) content

After crushing and sifting the RCA particles, the residual mortar (RM) content measurements were performed on all six mixtures as per (Fathifazl et al. 2009). Six samples (one per concrete type) were selected to determine the RM in each individual size fraction (i.e. 4.75- 9.5mm; 9.5-12.5mm and 12.5- 19mm) and an average RM value was adopted to represent the overall RM of each RCA concrete.

Representative samples of the six different RCA mixtures were obtained using a quartering process similar to the one used for NA (Charles 1981). The sample sizes were approximately 1000 g for the 4.75–9.5 mm fraction and 2000 g for the larger size fractions. After drying the samples for 24 h at 105°C, the oven-dried samples were immersed in a 26% sodium sulphate solution (by weight) over 24h (similar concentration to the one used in the ASTM C88 soundness test). The RCA samples, while still immersed in the sodium sulphate solution, were subjected to five cycles of freezing and thawing (i.e. overnight 16h at -17°C, same freezer/conditions used for ASTM C 672 scaling test and 8h in an oven at 80°C). After the last freezing-and-thawing cycle, the solution was drained from the sample and the aggregate was washed with tap water over a No. 4 (4.75 mm) sieve. The washed aggregate was then placed in an oven for 24 h at 105°C, and its oven-dried mass was measured. The RMC was then obtained using the following equation:

$$\text{RMC}\% = \left(\frac{W_{\text{RCA}} - W_{\text{OVA}}}{W_{\text{RCA}}} \right) \times 100 \quad 4.1$$

Where W_{RCA} = initial oven-dry mass of RCA sample before test (g) and W_{OVA} = final oven-dry mass of the OVA after full removal of the RM (g) (Fathifazl et al. 2009). It is worth noting that this procedure is not significantly more complicated nor time consuming than the aggregate soundness test procedure as per ASTM C88.

4.6.3 RCA mix-design and testing

In order to evaluate the influence of the RCA source on the fresh and hardened states of RCA concrete mixtures, six 35 MPa RCA concrete mixtures were fabricated with the use of the six different RCA aggregates prior discussed. The EV method was effectively used to mix- design the RCA mixes accounting for their respective RM contents. All of the coarse aggregates used in the RCA mixtures were obtained from the crushed concrete produced in the laboratory (i.e. 100% replacement of NA). Table 4.3 gives the detailed RCA concrete mixture proportions.

Table 4.3. New RCA concrete mixture proportions.

New concrete strength (MPa)	35 MPa RCA Concrete											
	25(MPa)		35(MPa)		45(MPa)		25(MPa)		35(MPa)		45(MPa)	
Crushed aggregate properties	Crushed Limestone						Quartzsite Gravel					
	kg/m ³	Ratio*	kg/m ³	Ratio	kg/m ³	Ratio	kg/m ³	Ratio	kg/m ³	Ratio	kg/m ³	Ratio
Cement	330	1	321	1	309	1	341	1	332	1	336	1
Fine aggregate	693	2.1	686	2.14	685	2.22	695	2.04	691	2.08	693	2.06
RCA	1200	3.64	1223	3.81	1247	4.04	1179	3.46	1200	3.61	1189	3.54
Water	149	0.45	145	0.45	139	0.45	153	0.45	149	0.45	151	0.45
RMC (%)	40		46		52		34		40		37	
Water/Cement	0.45		0.45		0.45		0.45		0.45		0.45	

*: The mix- design is presented in ratios here; i.e. all the ingredients of each mix are divided by the cement content of the respective mixture.

A total of 66 samples, which contain 54 cylinders (100 by 200 mm in size) and 12 cubic prisms (100 x 100 x 400 mm), were cast from the six RCA concrete mixtures manufactured in the laboratory. The specimens were demolded 24 hours after casting and moist cured over 28 days.

Mechanical (i.e. compressive strength, bending flexure, SDT) and non- destructive (i.e. UPV, electrical resistivity) testing were performed on the RCA samples according to Table 4.4.

Table 4.4. Testing matrix developed for this study

Test methods (number of samples)	Time (days)				
	Fresh state	3	7	14	28
1) Compressive strength	x	3	3	x	3
2) Bending flexure (3 point test)	x	x	x	x	2
3) Modulus of elasticity/SDT	x	x	x	x	3
4) Slump test	✓	x	x	x	x
5) Resistivity	x	3	3	3	3
6) UPV	x	3	3	3	3

The compressive strength test was performed according to ASTM C C39 / C39M and the flexural test through the third point test as per ASTM C78 / C78M - 16. To carry out the SDT, the RCA specimens were subjected to five loading/unloading cycles at a controlled loading rate of 0.10 MPa/s with loading levels of 40% of the 28-day concrete compressive strength. Moreover, ultrasonic pulse velocity (UPV) measurements and surface electrical resistivity (ER) were performed at 3,7,14 and 28 days on the RCA concrete samples.

4.7 Results

4.7.1 Characterization of RCA and residual mortar (RM) content

Table 4.5 displays the different characterization results obtained for the different RCA materials produced. The results show that the RM content values on the RCA samples ranged from 34.3% to 51.2%. The RCA concrete mixtures made with the use of CL presented higher residual mortar content (angular particles) compared to the mixtures fabricated with QG (rounded shape). Moreover, for the two aggregate types, and especially for the RCA concrete made by CL, the higher the RCA quality (i.e. less porosity and higher compressive strength), the higher the RM content, with the exception of 45 MPa concrete made with QG. Moreover, CL source presented slightly less specific gravity and slightly higher absorption capacity than QG, on average.

Table 4.5. Different crushed recycled aggregates specifications.

Crushed material strength (MPa)	Crushed material identification OVA Type	RMC (%)	Specific gravity (g/cm ³)	Absorption capacity (%)	Moisture (%)
25	Quartzite Gravel	34.3	2.45	4.45	0.85
35	Quartzite Gravel	39.6	2.42	5.17	1.20
45	Quartzite Gravel	36.9	2.47	4.23	1.00
25	Crushed Limestone	40.0	2.40	5.40	0.97
35	Crushed Limestone	45.6	2.41	5.09	1.10
45	Crushed Limestone	52.1	2.43	4.88	1.30

4.7.2 Los Angeles abrasion

LA abrasion test was performed on all RCA sources used in this research project. Figure 4.1 presents the results gathered in the test. Evaluating the data obtained, one may see that all the RCA lost more mass than the NA, as expected. The difference between NA and RCA was greater for RCA made with CL. However, comparing the RCA materials, quite similar mass losses were found for the RCAs made with QG (from 30% to 33% loss) and CL (from 29.5 to 31%). Moreover, all the RCA mixtures tested met the criterion according to *Canadian Standards Association* (CSA.A.23.2-16A) where aggregates are considered suitable for use in concrete when their losses are lower than 50%.

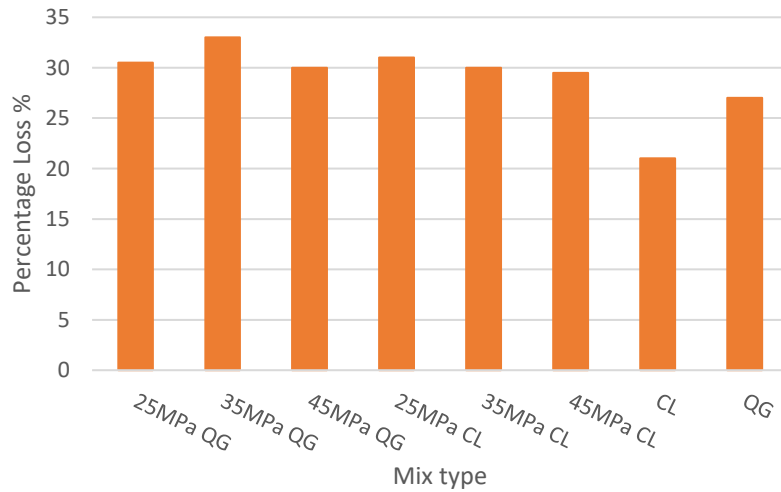


Figure 4.1. Percent loss of Los Angeles abrasion test for recycled and reference aggregates.

4.7.3 Compressive strength tests

The compressive strength tests were performed in two steps. First compressive strength was conducted on cylinders of each of the six conventional concrete mixtures to evaluate their actual strength and make sure they reached the anticipated strength. Table 4.6 displays the results obtained on the CC mixes designed based on ACI method. All the specimens reached the targeted 28-day compressive strengths and the variability of the results were within $\pm 5\%$.

Table 4.6. Compression strength results of the CC mixes

Design strength (MPa)	25.00	35.00	45.00
Actual strength CL (MPa)	25.08	36.23	47.48
Actual strength QG (MPa)	25.17	35.48	48.12

Second, to appraise the influence of the aggregate type and RCA quality on the compressive strength of recycled mixes, the test was also carried out on the 35 MPa RCA specimens designed through the EV mix proportioning method (Figure 4.2). The data in Figure 4.2 clearly shows that all the concrete mixes designed with the use of the EV method presented 28-day compressive strengths superior than the targeted design value (i.e. 35 MPa). Moreover, it is possible to notice that the better the RCA quality, the higher the compressive strength of the recycled mixtures (i.e. $45 > 35 > 25$). Finally, the aggregate type (CL vs QG) did not show significant influence in the tests outcomes.

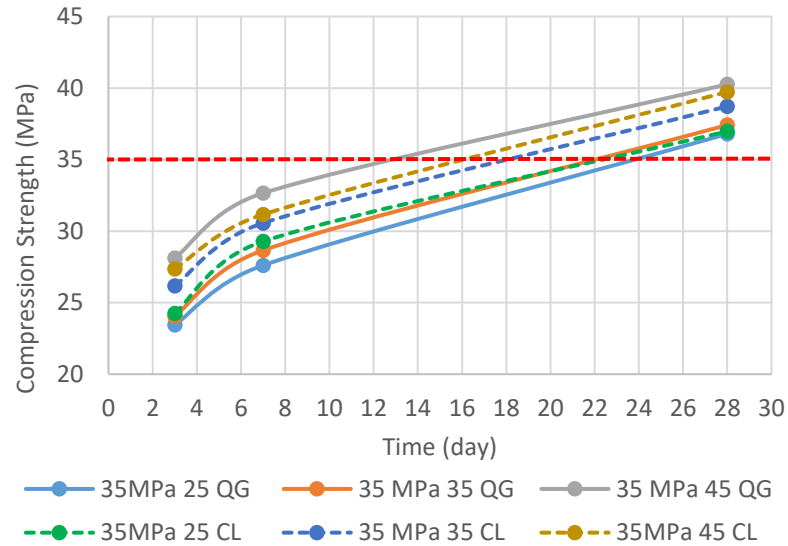


Figure 4.2. Compressive strength test results performed on the 35 MPa RCA concrete mixtures incorporating different aggregate types (CL vs QG) and presenting distinct qualities (i.e. 25, 35, 45 MPa).

4.7.4 Flexure test

Figure 4.3 illustrates the force vs. displacement plot for the different 35 MPa RCA mixes evaluated through the flexural test. Figure 4.4 shows the modulus of rupture (MOR) values for the RCA concrete mixtures. Analyzing the results, one may see that the behaviour found in flexure is quite different from the outcomes obtained in compression. First, all the RCA concrete mixes made with the QG presented lower flexural strength compared to the CL RCA mixes. Furthermore, for the QG mixtures, the greater the RCA quality (i.e. compressive strength), the higher the flexural capacity. However, distinct results were found on the RCA mixes made by CL. For those mixtures, the previous quality of the RCA did not significantly influence the ultimate flexural capacity of the RCA mixtures. Finally, the MOR results obtained on the RCA mixes seemed very similar to the one obtained on 35 MPa CC mixes made with CL and QG aggregates.

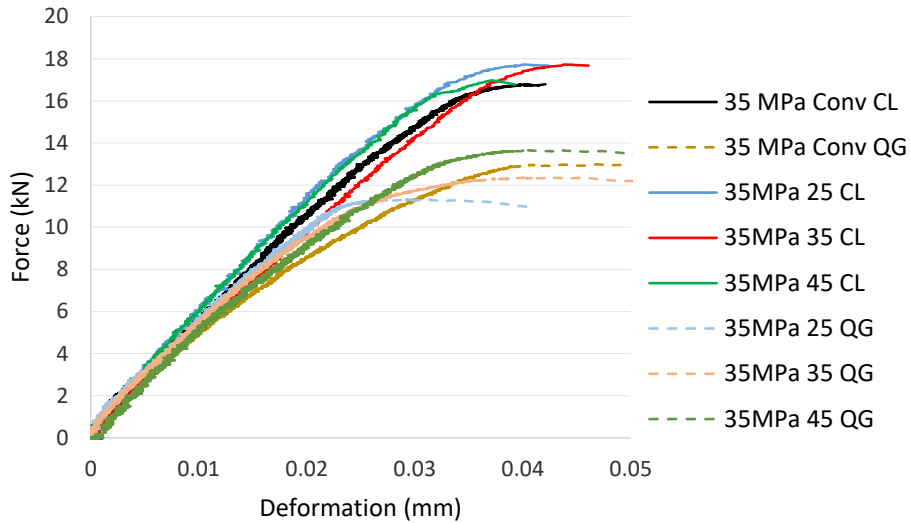


Figure 4.3. Tensile strength results obtained on 35 MPa RCA concrete mixtures incorporating different aggregates (i.e. CL and QG) and distinct RCA qualities.

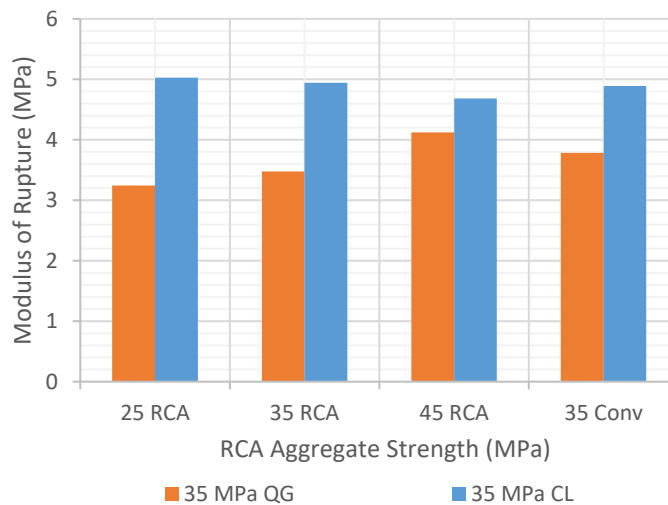


Figure 4.4. Modulus of rupture (MOR) as a function of the Aggregate strength (25, 35, 45MPa) and aggregate type (CL and QG) for 35 MPa RCA concrete mixtures.

4.7.5 Stiffness damage test (SDT)

Table 4.7 presents the results of modulus of elasticity (ME) and stiffness damage index (SDI) obtained for the CC mixtures designed in this work. ME results ranged from 27 to 39.5 GPa,

whereas SDI values varied from 0.09 to 0.14 for all mixtures. The greater the CC compressive strength and higher the ME and the lower the SDI, as expected.

Table 4.7 - Modulus of Elasticity (ME) and Stiffness Damage Index (SDI) for the CC mixtures

	Crushed Limestone			Quartzite Gravel		
	25	35	45	25	35	45
RCA strength (MPa)						
Modulus of Elasticity (GPa)	30.86	37.21	39.33	27.61	34.46	34.87
Stiffness Damage Index (SDI)	0.11	0.10	0.09	0.14	0.12	0.11

Figure 4.5 illustrates the results of ME and SDI of the different RCA concrete mixtures evaluated in this work. Analyzing the results below, one notices that the higher the RCA quality, the higher the ME obtained in the RCA mix. Moreover, RCA concrete mixtures cast with the CL presented higher ME than QG RCA mixtures for the three strength levels evaluated (i.e. 25, 35 and 45 MPa). ME values ranged from 32 to 39 GPa for CL RCA concrete and from 30 GPa to 35 GPa for QG RCA concrete. The SDI values obtained were inversely proportional to ME, as expected as per (Sanchez et al. 2017). The higher the material’s quality (i.e. less porosity and higher compressive strength), the lower the SDI results obtained. SDI results ranged from 0.09 to 0.11 for RCA made with CL and from 0.11 to 0.14 for RCA made with QG. In addition, the ME values found on the RCA mixes designed with the EV methods showed to be quite similar to the ones obtained in CC mixes. Otherwise, the SDI results obtained on the RCA mixtures were lower than the ones obtained in the CC mixes, which is somewhat unexpected.

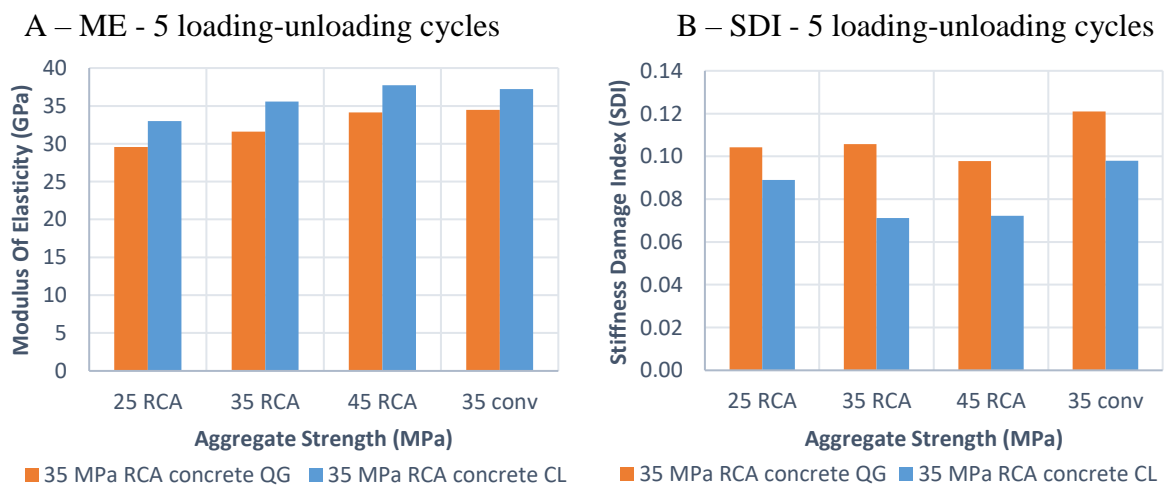


Figure 4.5. Responses of selected SDT output parameters as a function of the aggregate strength (25, 35, 45MPa) and aggregate type (CL and QG) for 35 MPa RCA concrete mixtures: A: Modulus of elasticity (ME). B: Stiffness Damage Index (SDI).

4.7.6 Ultrasonic pulse velocity (UPV)

Figure 4.6 indicates the UPV results performed on the 35 MPa RCA concretes containing all the distinct RCA sources used in this work. The results are the average values obtained at each age on 3 specimens for each concrete mix. Observing the results one may see that UPV values increase as a function of concrete maturity. However, this increase is not linear but rather presents a concave trend. Moreover, generally, for all the ages analyzed, the greater the RCA quality (i.e. compressive strength), the greater the UPV value. Otherwise, the results show that the type of the aggregate (i.e. CL vs QG) had little to no effect on the test outcomes.

In addition, UPV values measured for RCA concrete made with the use of EV mix design showed to be much less than the ones made by CC. The 28-day UPV values ranged roughly from 4470 m/s to 4660 m/s for RCA concrete and 4600 m/s to 5200 m/s for conventional concrete, which may be considered as “*very good to excellent concrete quality*” with low amount of porosity according to ASTM C597.

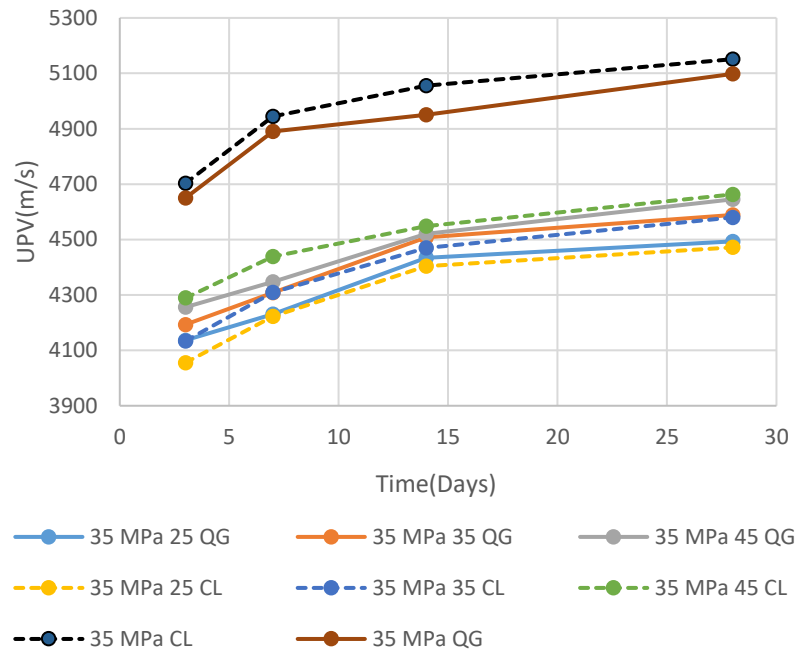


Figure 4.6. UPV test results performed on the 35 MPa RCA concretes incorporating CL and QG and presenting distinct RCA source qualities (25, 35 and 45 MPa).

4.7.7 Surface electrical resistivity (ER)

Figure 4.7 demonstrates the surface resistivity results performed on the 35 MPa RCA concretes incorporating the different RCA qualities (25, 35, 45MPa) and aggregate types (CL and QG). As with UPV, the results are the average values obtained from 4 measurements at each age on 3 specimens for each concrete mix. Analyzing the plot one clearly sees that surface ER values increase as a function of concrete maturity. This increase shows a more linear trend compared to UPV. Moreover, generally, for all the ages analyzed, the greater the RCA strength, the greater the surface ER value. In addition, concrete made with QG aggregate presented higher surface ER in comparison with the ones made with CL at the same strength. The latter shows that the type of the aggregate (i.e. CL vs QG) influences the test outcomes. According to the results, surface ER values measured on CC mixes showed to be higher than the RCA concrete made with the use of EV method. The 28-day surface ER values ranged roughly from 4.5 KΩ-cm to 10 KΩ-cm for RCA concrete and 6 KΩ-cm to 11 KΩ-cm for conventional concrete.

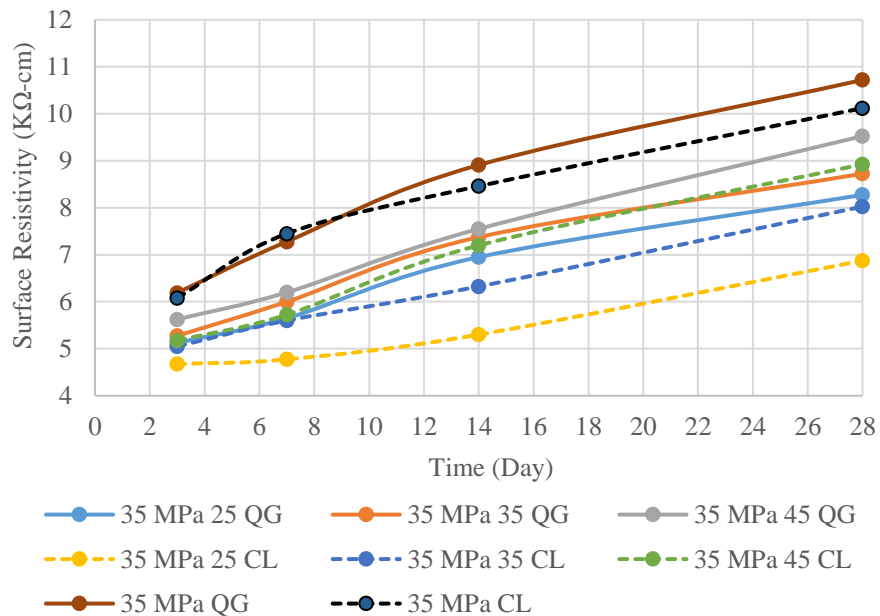


Figure 4.7. Surface resistivity results performed on the 35 MPa RCA concretes with corporation of different aggregate strength (25, 35, 45MPa) and aggregate type (CL and QG).

4.8 Discussion

In this study, concrete mixtures were cast through the use of the EV method containing RCA with different mechanical properties (i.e. 25, 35 and 45 MPa), and incorporating distinct original aggregate types (CL and QG). A number of chemical, mechanical and non-destructive methods were used to evaluate the influence of the RCA quality and source on RCA concrete mixtures.

4.8.1 Residual mortar (RM) content

The results in Section 4.7.1 showed that the amount of RM adhered to OVA in the RCA is quite high (over 34%). Thus it is anticipated that its properties may influence the behaviour of RCA concrete. The RCA concrete mixtures made with the use of CL presented higher RM content compared to the mixtures fabricated with QG. The latter is believed to occur due to the shape and texture of the aggregates used in this study; i.e. CL presents a more angular shape and rough texture compared to QG, which presents a more rounded shape and smooth texture. Higher angularity and surface roughness is expected to retain a greater RM amount during crushing by improving the friction between aggregate particles and mortar, especially at the ITZ. Furthermore, the greater the RCA quality (i.e. mechanical properties) the lower the difference between the mechanical properties of the aggregates and the mortar and thus very likely less RM is lost (i.e. RM is higher) during the crushing process. This phenomenon was seen especially in aggregates with high angularity and rough texture (i.e. CL), being less significant in aggregates with rounded and smooth texture (QG).

4.8.2 Mechanical properties of the RCA particles

LA abrasion test results indicated that higher mass percentage losses were found for RCA when compared to NA, as expected. The latter is due to the presence of RM adhered to the OVA in the RCA, which decreases its toughness and resistance to impact, both parameters measured through the LA test. Furthermore, according to CSA A23.2 16A, all the RCA mixtures tested met the threshold criterion (i.e. mass loss lower than 50%) and thus are considered suitable for use in

concrete. However, the difference between NA and RCA was slightly greater for RCA made with CL due to the higher RM attached to the crushed aggregates. If one compares the losses in a relative manner (i.e. considering the values obtained by the NAs as 100%), one may divide the deterioration degrees in three categories, namely: high (i.e. over 45% increase in mass loss, such as 48 % for 25 MPa CL), moderate (i.e. from 30% to 45% increase such as 43% and 40% for 35 and 45 MPa CL) and low (i.e. from 0% to 29% such as 12, 22 and 11% for 25, 35 and 45 MPa QG, respectively).

4.8.3 Mechanical properties of the RCA concrete

According to the results obtained in this study, the EV method seems to be a promising mix proportioning approach to mix- design RCA concrete with interesting properties in the fresh and hardened states. Moreover, it was possible to notice that the better the RCA quality, the higher the potential compressive strength of recycled mixtures. The latter is believed to be due to the lower initial porosity and final microcracks formation during the crushing process which may help in the control of inner cracking under compressive loads. Further microscopic analysis is needed to better and fully explain this phenomenon. Otherwise, the aggregate type did not appear to influence the compressive strength capacity of RCA concrete.

Flexure tests also showed that angularity and rough texture are very important parameters in RCA concrete since all RCA mixtures made by CL showed higher flexural strength results when compared to QG mixes. Moreover, for angular aggregates (i.e. CL), the quality of the RCA did not significantly influence the MOR of the RCA mixtures. Hence, the cracking and failure phenomenon of RCA concrete in tension seems to be more dependent on the texture features than the quality of the RCA for angular aggregates. Otherwise, when the surface phenomenon does not exist (i.e. QG case), the quality of RCA seems to start having an important role.

The results obtained from the SDT highlighted even more the results previously obtained in compression and flexure. Modulus of elasticity results seem to be linked to the quality of the RCA. Actually, it is well established that the ME in CC is extremely dependent on the type and amount of aggregates in the mixture. Yet, in RCA concrete, the ME seems to be also linked to the porosity

and microcracking present in the RM of the RCA. Furthermore, angularity of the particles seemed to increase ME due to a better bond with the cement paste. SDI values obtained were inversely proportional to ME, as expected. Moreover, all the SDI values found for the RCA mixtures lied within the range considered to be “negligible amount of damage” (i.e. SDI lower than 0.11-0.12) as per (Sanchez et al. 2017). With the use of the SDI data, it is possible to distinguish the different RCA qualities (i.e. less porosity and higher compressive strength) since better qualities presented lower dissipated energy during the loading/unloading cycles. RCA made by angular materials also presented lower SDI values when compared to RCA made by rounded aggregates, very likely due to the less porosity/flaws at the aggregates-cement paste vicinity due to its better bond. Conversely, RCA concrete specimens obtained lower SDI values than CC. These results were not expected and somewhat surprising since RCA is supposed to present “initial” lower inner quality than NA due to the presence of flaws and microcracking, which should increase their energy dissipation under cyclic load and thus their SDI. Therefore, the latter cannot be fully explained at this point and further analysis are needed in this regard. Nevertheless, it appears that every mechanical parameter assessed was at least partially affected by the RCA quality and source, emphasizing the importance of a quality control chart able to classify RCA qualities/sources prior to their use in concrete.

4.8.4 Non-destructive evaluation

NDT results were very interesting and completed quite well the chemical and mechanical procedures discussed before. UPV seemed to vary as a function of the RCA quality. This is due to the many reasons discussed in the previous section (i.e. higher porosity and cracking gives lower UPV results). Otherwise it does not seem to be influenced by the RCA source which is somehow surprising since according to the source more or less RM is found in the RCA. Likewise, surface ER was found to be dependent on the RCA quality. However, ER seemed to be also influenced by the aggregate type; i.e. rounded and smoother particles showed higher ER results. This is believed to be linked to the amount of RM. In the RCA, the higher the RM, the lower the ER since RM is likely more porous than the OVA itself.

4.8.5 Quality control procedure for evaluating RCA mixtures

Besides understanding the influence of the quality and source of RCA in the RCA concrete, this current project has a second and very important objective which is to propose a quality control procedure for determining the quality of the RCA concrete through the use of chemical, mechanical and non-destructive test procedures performed on the RCA particles and RCA concrete mixtures. In this work, some procedures seemed to be promising to benchmark RCA concrete inner quality such as the RM content, SDT (i.e. particularly the SDI parameter), UPV and ER. It is worth noting that the goal of this quality control is to report the potential influence of the RCA inner quality on the long-term behaviour of RCA concrete. Short-term mechanical properties such as 28-day compressive strength and modulus of elasticity are not accounted for in this evaluation because those properties are extremely dependent on the mix- proportioning itself. In other words, the water to cement ratio (and thus microstructure) might be changed to acquire a specific strength with different RCA qualities although their inner defects due to mineralogical formation, crushing and reuse would be quite different. In this context, the EV method showed indeed to be quite efficient to provide RCA concrete mixtures with interesting fresh state and hardened states.

Thereby, Table 4.8 indicates a summary of the results obtained in the above selected procedures, linking their results with the known RCA qualities used in this research. With the use of this table, one may identify some potential properties of RCA and RCA mixtures based on a single test result using a mix with 100% replacement of coarse aggregates with RCA. Furthermore, it should be stated that this is only the first trial in this regard based on a limited data set and further research is still needed, including mix- designing RCA concrete with different strengths and a much wider range of aggregates for comparison purposes. Yet, it seems to be a first step towards the development of a quality control procedure aiming to understand the influence of the quality of the RCA source and to decrease the variability of the final RCA mix.

Table 4.8. Quality control chart for assessing quality of the RCA in RCA mixtures.

Quality Control Chart	<u>Test procedure (measured at 28 days)</u>				
	RCA quality	RM %	Relative LA % In comparison with NA	SDI	UPV (m/s)
Low	34-40%	Over 45%	0.09-0.11	4570 and lower	8.0 and lower
Moderate	40-45%	30-45%	0.08-0.10	4570-4660	8.0-9.0
High	45-55%	0%-29%	0.06-0.09	Over 4660	Over 9.0

Analyzing the data above, one may notice that the higher the RCA quality, the higher the ER, UPV and RM and the lower the LA and SDI. It seems logical to have higher electrical resistivity and ultrasonic pulse velocity results in RCA concrete whenever a higher quality RCA (i.e. higher strength material) is used. Moreover, it also seems to be quite logical to have lower deterioration due to LA test (i.e. higher toughness) and lower dissipated energy over cyclic loads whenever a high quality RCA is used. However, the only parameter which may intrigue the reader at the first glance is the RM. According to the findings in this research, the higher the RCA quality, the more adhered RM a RCA sample will present. Therefore, the intuitive assumption that the higher the RM the lower the RCA quality does not apply here and should be further discussed.

First of all, it should be mentioned that whenever one thinks on the use of RCA material in concrete, one may think on two types of recycled materials: RCA from returned concrete and RCA from demolished concrete. In the current research, the samples were fabricated at the laboratory and moist cured for 28 days before being crushed to produce RCA. Therefore, the RCA used in this project should be treated as “returned concrete” and all the findings obtained in this work should only be valid/applied to RCA made by returned concrete. Second, in this study, only 35 MPa RCA concrete was fabricated and thus the comparison among the different samples presented actually two variables: 1) amount of RM in the RCA and; 2) quality of the RM. According to the results, it is better to have a RCA in the RCA concrete with high RM quality and amount than to have a low RM quality and amount attached RM. The results might have been different whether the strength of the RCA was kept the same; i.e. whether the RCA particles were only made by one RCA quality: e.g. 35 MPa. In that case, one might expect to have better performance of RCA

mixtures with lower RM adhered to the OVA. Finally, all the RCA material was crushed after 28 days and thus the vast majority of the hydration process should have taken place which indeed contributed to the higher amount of RM adhered to the OVA. It is expected then to have less RM percentages in returned concrete promptly crushed once the material returns to the concrete plant and with only a few hours of hydration developed. The latter would likely generate less RM for the same RCA quality. Anyway, further research is still needed so that this first step in developing a quality control procedure for RCA concrete could represent different scenarios applied in practice.

4.9 Conclusion

In this research, RCA concrete specimens were fabricated containing recycled aggregates with different mechanical properties (i.e. 25, 35 and 45 MPa), and incorporating distinct original aggregate types (CL and QG). A number of chemical, mechanical and non-destructive methods were used to evaluate the influence of the RCA quality and source on RCA concrete mixtures. The main findings obtained in this research are highlighted hereafter:

- Generally, the higher the RCA quality, the higher the quantity of attached RM to the OVA. This is believed to happen due to the lower difference between the mechanical properties of the RM and OVA for high qualities RCAs. Moreover, the higher the angularity and roughness of the surface, the higher the RM adhered;
- LA abrasion test does not appear to be suitable to distinguish different qualities of RCA, except when the results are compared to their specific original NAs. The relative increase in mass loss compared to a reference aggregate may be a potential indicator of RCA quality.
- EV method seemed to be able to mix- proportion RCA concrete mixtures that present interesting fresh (i.e. consistency) and hardened state properties (i.e. compressive strength and modulus of elasticity, since all the mixtures met their design criteria;

- The flexural capacity depends on the RCA source, especially on the angularity and surface roughness which very likely increase the cement paste-aggregate bond at the ITZ. However, this test does not appear to be able to distinguish different RCA qualities;
- The SDT and NDTs (UPV and especially the surface ER) seem capable of distinguishing the inner quality of different RCA sources;
- A quality control procedure based on chemical, mechanical and non-destructive tests is proposed in this work to assess the long-term quality of RCA concrete mixtures. Although promising, the current proposal should be treated as a first trial and further research is still needed, including mix- designing RCA concrete with different strengths and a much wider range of aggregates for comparison purposes.

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5 Summary and Conclusion

In this research, the EV method was used to fabricate RCA concrete mixtures with different mechanical properties (i.e. 25, 35 and 45 MPa) and aggregate types (CL and QG). The concrete was then crushed to produce coarse RCA. A number of chemical, mechanical and non-destructive methods were used to assess the effects of the RCA quality and source on the RCA concrete mixtures. The main findings are presented hereafter:

- Chemical assessment

The results in Section 4.7.1 indicated that high amounts of RM were adhered to OVA in the RCA (more than 34%). Therefore, it is expected that the properties of RM would influence the behaviour of RCA concrete. A higher RM content was observed in the RCA concrete mixtures made with the use of CL in contrast to the QG concretes. A greater RM is likely linked to the shape and texture of aggregates that were used in the test procedures; i.e. CL aggregate are more angular shaped and have a rough texture in comparison to QG aggregate, which have more rounded shapes and smooth texture. Higher RM in crushing is expected in more angular and rough surfaces due to the friction between aggregate particles and mortar, especially at the ITZ. In addition, better RCA quality (i.e. mechanical properties) leads to a smaller difference between the mechanical properties of aggregates and the mortar and consequently it becomes very likely that less RM will be lost during the crushing process. This occurrence was mainly observed in aggregates with high angularity and rough texture (i.e. CL), being less significant in aggregates with rounded and smooth texture (QG).

- Mechanical properties of the RCA particles

LA abrasion test results showed that due to the lower stiffness of RM compared to NA, a higher mass percentage loss was obtained. RCA concrete made with CL experienced a slightly greater difference between NA and RCA. According to CSA A23.2 16A, all of the aggregates evaluated over the abrasion test (i.e. RCA or NA) presented a suitable behaviour to be used in concrete since

the mass percentage loss for all the samples was lower than 50% (limit for deleterious substances and physical properties of aggregates). However, if one compares the losses in a relative manner (i.e. considering the values obtained by the NAs as 100%), one may divide the deterioration degrees into three categories, namely: high (i.e. over 45% increase in mass loss, such as 48 % for 25 MPa CL), moderate (i.e. from 30% to 45% increase such as 43% and 40% for 35 and 45 MPa CL) and low (i.e. from 0% to 29% such as 12, 22 and 11% for 25, 35 and 45 MPa QG, respectively). Therefore, one may conclude that the RCA source and quality influences its response in toughness (i.e. parameter measured through LA abrasion test) and thus the likely performance in RCA concrete.

- Fresh state properties

The EMV method was developed in the past to prove that similar behaviour might be obtained for RCA concrete whether a proper mix-design was used (i.e. RM is accounted for in the RCA mix). However, due to the low amount of cement paste in the design of the recycled mix, some challenges were encountered in the fresh state. The main fresh state problem of RCA mixes in the EMV method lies in the fact that the RM acts as an aggregate in the fresh state, although is a mortar (i.e. cement paste + sand + water) in the hardened state. If one takes that into account and is mandatory to match the amount of mortar and coarse aggregates in the recycled mix with a companion CC, the amount of new cement paste to be added in the mix may be too low and thus will result in stiff behaviour in the fresh state.

In order to avoid the abovementioned problem, the EV method is proposed in this project. The EV takes advantage of the interesting concepts of the EMV (such as RM), yet it incorporates in its design a higher amount of fine aggregates (and lower amount of coarse aggregate) which helps to reduce the viscosity and consistency of the recycled mix. The EV mix- designed mixtures in this work indicated interesting behaviour in the fresh state compare to the EMV method. Their consistency was still quite high (i.e. around 50 mm or slightly less) depending on the RM of the RCA, but all mixtures were easily vibrated, presenting very likely a shear thinning rheological behaviour (i.e. reduction of viscosity as a function of the torque applied). It is worth mentioning that in this study no chemical admixtures and SCMs were used to not introduce a new parameter to the system. Therefore, one might think that there is still room for improving the behaviour of

EV mix- designed RCA mixtures, without causing issues to their hardened and long-term performance.

- Hardened state and durability related properties

The EV mix-designed RCA mixtures investigated in this study demonstrated quite interesting mechanical performance. All the recycled mixtures met the strength criteria (i.e. compressive strength requirements). Moreover, similar values of modulus of elasticity compared to the reference CC mixtures were achieved throughout this study, which seems satisfactorily for use in structural applications. Most of the previous research found in literature showed a noteworthy reduction of modulus of elasticity in RCA mixes, very likely due to the multi-phase character of the material (i.e. OVA + RM; RM being much more porous than NA). However, in this study the modulus of elasticity of the recycled mixes seems to be kept due to a better packing of the granular skeleton (i.e. introduction of more fine particles in the system) of the recycled material. Additionally, durability-related tests such as UPV and surface ER confirmed their good behaviour and quality to be used in harsh climates, being acceptable according to guidelines and standards. Finally, the RCA mix made in corporation of the commercial RCA also performed quite promising, which gives to the new method a great potential. However, for the design of a much wider range of RCA with different qualities and incorporating distinct aggregate types. the EV still needs to prove its efficiency.

- Quality control procedure for evaluating RCA mixtures

Besides understanding the effects of the quality and source of RCA in the RCA concrete, the current research program recommended a quality control procedure for determining the quality of the RCA prior to its use in concrete through the use of chemical, mechanical and non-destructive test procedures. In this research, some procedures such as the residual mortar content, SDT, UPV and ER seemed to be promising to benchmark the RCA and RCA concrete quality. Table 4.8 demonstrates a summary of the results found in those procedures, linking them with the known RCA qualities used in this study. With the use of this table, based on a single test result, one may identify some potential properties of RCA and RCA mixtures. It is worth noting that further

research in this regard is still needed and this is only the first trial, containing mix-designing RCA concrete with different strengths for comparison purposes. Yet, it seems to be the first step towards a development of a quality control procedure aiming to have better understanding the quality of the RCA source and to reduce the variability of the RCA concrete.

- Eco-efficiency of EV mix- designed RCA mixtures

Damineli et al. (Damineli et al. 2010) proposed the use of an index, the so-called *Binder Intensity* (*bi*), which is defined as the amount of PC needed to achieve 1 desired unit of a given performance indicator; e.g., the amount of PC in kg/m^3 to obtain 1 MPa of compressive strength at a given time (i.e., 28 days, Equation 5.1) to evaluate the eco-efficiency of CC mixes.

$$bi = \frac{B}{CS} \quad 5.1$$

Where, B is the amount of binder (in kg/m^3), and CS is the compressive strength in MPa. Damineli et al (Damineli et al. 2010) benchmarked the *bi* indices in Brazil and around the globe and noticed that the greater the compressive strength, the lower the *bi* factor. In other words, high strength concrete mixtures implicitly have low *bi* indices and thus more sustainable with lower carbon footprint (Figure 3.8). Nevertheless, high *bi* factors are currently used in CC for civil infrastructure (i.e. from 20 to 40 MPa). Otherwise, to the authors' knowledge, very few studies were performed to quantify the *bi* factor of RCA concrete mixes in the past.

In this work, RCA mixtures were mix- designed through the EV method and RCA mixes with significantly reduced *bi* factors were found such as 10.4, 9.2 and 7.4 ($\text{kg m}^{-3}\text{MPa}^{-1}$) for 25, 35 and 45 MPa respectively. The latter indicates that besides being efficient for improving fresh and hardened states of RCA concrete mixtures, the EV method might also be an alternative towards a greener future in civil engineering.

6 Recommendations for future research:

After conducting a comprehensive laboratorial campaign and analyzing the results, trends and findings, some recommendations for future work can be drafted, as presented hereafter:

- Microscopic analysis need to be performed on different RCA concrete mixtures made with the use of the EV method. Several analyses might be performed, yet of the most urgent one is to search for the understanding of the mechanism of failure of RCA concrete presenting different mechanical properties and RCA source. The latter would bring valuable insight on the mechanical behaviour of RCA concrete and its difference from CC.
- Evaluate the maximum RM content to be used in the EV method so that RCA mixes designed with the method could still meet the required criteria.
- Determine the influence of using fine RCA in RCA concrete mixtures designed with the EV method on the fresh and hardened state properties of RCA concrete.
- Investigate the effect of particle size distribution and the use of particle packing models combined with the EV method on the fresh and hardened state properties of RCA concrete.
- Evaluation of the influence of different crushing methods (i.e. jaw vs. gyratory vs impact vs hammer crushing) on the properties of the RCA materials (fine and coarse RCA aggregate) as well as on the fresh and hardened state properties of RCA concrete designed with the EV method.
- Improve the quality control (QC) protocol developed over this MASc using a wider range of RCA qualities and sources along with a number of RCA mixes presenting distinct mechanical properties for further assessment and valuation.

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8 Appendix

8.1 Sample of calculation

In this section, an example of mix- proportion using the EV method is performed to systematically illustrate the 15 steps of the new procedure. For the sake of this example, a 35 MPa recycled concrete mixture made out of a 35 MPa RCA incorporating a crushed limestone (CL) is selected.

The first step of the EV method is to design a conventional concrete (CC) that will be used as the control mix. In North America, the most common procedure to mix- design conventional mixtures is the ACI method (i.e. absolute volume method). Therefore, with the use of ACI method, a 35 MPa CC is designed and its ingredients (i.e. cement, sand, coarse aggregate and water-to-cement ratio) are illustrated in Table 8.1

Table 8.1. 35 MPa conventional concrete proportions.

Conventional Concrete				
Mass*	Specific Gravity	Volume compounds*	Volume Paste***	Volume Aggregates
1	3.15	0.32	0.77	1.64
1.81	2.70	0.67		
2.64	2.72	0.97		
0.45	1.00	0.45		

* The mix- design in mass is presented in a ratio (i.e. ingredient / cement) basis;

** The volume compounds are the mass ingredients over the specific gravity of the materials;

*** Volume of paste is the summation of cement and water whereas the volume of aggregates is the summation of coarse and fine aggregates.

The second step in the EV method is to determine the RM content of the RCA. Therefore, a freeze-thaw procedure fully described in this Thesis is used to quantify the RM. Once the percentage of RM in the RCA is determined, the amount of aggregates in the RCA can be also calculated (i.e. RA%) as displayed in Table 8.2.

In the third and fourth steps of the EV method, one calculates the amount of cement in the RM (18.35% in this case, which can be either measured or assumed – in this example it was calculated based on the mass amounts of the ingredients; i.e. $1 / (1 + 1.81 + 2.64)$ and the amount of sand in the mortar, which is the balance (i.e. $100\% - 18.35\% = 81.7\%$, Table 2).

Table 8.2. Measured Residual Mortar Content (RMC), Residual Aggregate (RA).

RCA Aggregate			
RMC (%)	RA (%)	Sand in mortar (%)	Cement in mortar (%)
45.6	54.4	81.7	18.35

The following steps (fifth and sixth) are the calculations of the RCA and total RM in the RCA mix in mass. Considering 100% RCA, the amount of coarse aggregates in the RCA mix will be the amount of RA (%) * the amount of coarse aggregates in the CC mixture. Likewise the amount of total RM present in the mix will be the amount of RM content (%) * the amount of coarse aggregates in the CC. The volumes can also be calculated once the specific gravities of these materials are known (Table 8.3).

Table 8.3. Calculated values of Recycled Material RA and Residual Mortar RM.

	Mass RCA	Specific Gravity	Volume compounds
RCA	1.73	2.72	0.64
RM	0.91	1.93	0.47

Where:

$$RCA_{Mass} = \text{Coarse Aggregate}_{Mass} \times RA$$

$$RM_{Mass} = \text{Coarse Aggregate}_{Mass} \times RMC$$

According to the EV's concept, the RCA concrete needs to have the same amount of both cement paste and aggregates in volume than the reference CC. Therefore, since we are assuming to use 100% RCA in the RCA mixture, and knowing that RCA is comprised of OVA and RM, some aggregates should be added to the RCA mix to match the total volume of aggregates in the CC (i.e. $0.97 - 0.64 = 0.33$). To improve the fresh state of the RCA mixtures, the EV method suggests that supplementary amounts of aggregates should be partially divided into coarse and fine aggregates as a function of the sand-to-coarse volumetric ratio of the CC (i.e. $0.67 / 0.97 = 0.69$). Thus, the amount of supplementary sand (seventh step) should be $0.33 * 0.69$ and the supplementary coarse (eighth step) is calculated as $0.33 * (1-0.69)$. Finally, since new coarse RCA is being added to the mix, new RM will be also added to the mix and should be accounted for again in the calculations (ninth step). Table 8.4 displays the above values.

Table 8.4. Calculated supplementary amount of sand and coarse aggregate.

	RCA Concrete				
	Mass RCA	Specific Gravity	Volume compounds	Extra volume of aggregates	Sand/Coarse ratio
Supp. FA	0.62	2.7	0.23	0.33	0.69
Supp. CA	0.18	2.72	0.10		
RM Supp. CA	0.07	1.93			

The next steps in the EV procedure are the calculations of new and old cement and sand in the RCA mix (tenth to fourteenth steps). First, the old sand is calculated as the % of sand in mortar (81.7) * the RM mass (0.91) + the RM supplementary (0.07). Then the new sand will be the amount of sand in the CC minus the amount of old sand in the RCA. The same procedure is used to calculate the amounts of old and new cement, except that the % of cement in mortar is used instead of the % of sand in mortar. Table 8.5 illustrates the results obtained.

Table 8.5. Calculation of old and new values of sand and cement.

RCA Concrete					
	Mass RCA	Specific Gravity	Volume compounds	Volume Paste	Volume Aggregates
New cement	0.82	3.15	0.26	0.77	1.64
Old cement	0.18	3.15	0.06		
New sand	1.01	2.7	0.38		
Old sand	0.80	2.7	0.29		

Where:

$$\text{Old Cement}_{Mass} = \text{Cement in mortar}_{\%} \times \text{RM}$$

$$\text{Old Sand}_{Mass} = \text{Sand in mortar}_{\%} \times \text{RM}$$

$$\text{New Cement}_V = \text{CC Cement}_V - \text{Old Cement}_V$$

$$\text{New Sand}_V = \text{CC Sand}_V - \text{Old Sand}_V$$

Accordingly, the new RCA mixture presents the following ingredients in mass (Table 8.6):

Table 8.6. New mix proportions.

Mass RCA	
New Cement	0.82
Sand	1.64
RCA	2.89
Water	0.45

Where:

$$\text{Sand}_{Mass} = \text{New Sand}_{Mass} + \text{supplementary Sand}_{Mass}$$

$$\text{RCA}_{Mass} = \text{New RCA}_{Mass} + \text{supplementary RCA}_{Mass}$$

Finally, if one rounds Table 8.6 results to obtain the RCA mix- proportion in unit ratios (i.e. cement equals to 1, one obtains the final RCA proportions as illustrated below (table 8.7, fifteenth step).

Table 8.7. RCA final ingredients.

Mass RCA		
	ratio	Kg/m3
cement	1.0	321
sand	2.1	686
RCA	3.8	1223
Water	0.45	145