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Million tons of construction and demolition waste (CDW) are generated every year around the world, and most of them are not adequately disposed, generating significant pollution on water, soil and air. Additionally, the use of freshwater in industrial processes, such as the production of cement, concrete manufacturing and curing for newly-built structures; has damaged the health of our freshwater ecosystems, reducing their volume and hindering their natural cycle of renovation. Therefore, the incorporation of recycled aggregate (RA) and treated wastewater (TW) as substitutes for the usual aggregates (UA) and freshwater, could generate significant environmental benefits. In this research, a comparative analysis of the experimental results of the properties of fresh and hardened concrete with different replacement percentage of UA for RA, is presented; and as an innovation the use TW. The results show that, regardless of the replacement percentage and use of treated wastewater, a concrete with RA and TW (recycled concrete in extremis, CRiE) had a satisfactory and acceptable or equivalent performance, not differing significantly from the performance of conventional concrete (CC), confirming that the use of RA for concrete building is feasible.

KEYWORDS: recycled aggregates, recycled concrete, sustainable materials, treated wastewater.

Introduction

Concrete is the second most consumed material by man after water, it is estimated that the global annual average production of concrete is about one ton for every human being (World Business Council for Sustainable Develop 2009); therefore, the use of UA (main component of concrete) is increased along with cement production and use of concrete (Marie and Quiasrawi 2012).

On the other hand, millions of tons of CDW are generated (construction processes, demolition and restoration works in structures and buildings) (Suarez et al. 2006); as an example, only in Europe, United States and Japan, more than 900 million tons are generated each year (World Business Council for Sustainable Develop 2009). Because of that, it is important to search for new more-suitable alternatives for the environment, being the use of the RA of CDW, one of the most feasible, reducing the consumption of UA in the production of cement and concrete.

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The most ancient use of RA is on ancient Rome Empire roads, and afterwards, generally in Europe, at the end of World War II (Shing Chai Ngo 2004), from which, diverse documented researches have been reported promising results obtained with its use. In Japan, with more than a quarter century in the investigation of possible applications, there are achievements of its use, mainly as sub-base material in road construction (up to 96% of RA, in 2000) (Rao et al. 2007). However, although it has been demonstrated that the use of RA contributes to reducing the CDW and the use of the UA, these are considered as a low-quality materials, as their virgin properties (mechanical, physical and chemical) can be affected (Marinkovic et al. 2010). Additionally, the use of fresh water on the industry has caused an excessive extraction of groundwater sources, inducing to an excessive demand of surface water, and on the other hand, at the international level, an emerging critical environmental problem due to the lack of availability of new sources of supply (Van Den Heede and De Belie 2012).

There are previous investigations that address the search for new alternative sources of water supply for the production of concrete such as: water polluted with minerals, salts and other contaminants as those from streams, lakes and the sea (McCarthy 2008). These studies are focused on analyzing the effects presented in fresh and hardened concrete behavior, concluding that the results are not always satisfactory, since in some circumstances the concrete compressive strength decreases. Another alternative that has been explored (common practice in Germany) is the use of wash water from concrete, which is composed mostly of mixing water, cement and fine aggregate remnants, obtaining in general adequate results, and a similar behavior with regard to setting time, compressive strength, alkalinity and the chloride content, have been established (Silva and Naik 2010).

Finally, there are not many studies about the use of TW in the concrete production, so there are still unknown aspects to consider in terms of reaction that they might have on the concrete, due to the possible presence of contaminants. Therefore, the use of RA and TW in the production of concrete has significant potential to solve the problem that represents the final disposal of the CDW, the preservation of natural resources and the potential damages to the environment.

The use of RA from the CDW leads to a sustainable practice in the construction industry, as well as the consumption of alternative sources of water supply such as TW; so the main goal of this research is to establish the feasibility of using RA and TW for the manufacture of a new recycled concrete, calling it CRiE, which potentially have the ability to face obstacles precluding the use of RA, strengthen and improve the legislation to develop recycled materials, and provide users reliability to use them.

Materials

The construction materials employed in the experimental process were Portland Composite Cement (CPC) Type II 30R RS classified in accordance with NMX C414 ONNCCE 2004 (Anon n.d.) and ASTM C-595 (ASTM Standard C595/C595M 2016) standards. The UA were acquired to a local quarry, whereas the RA were obtained from “Concretos Reciclados”, factory in México City (19°19’12.3”N 99°03’16.2”W) which processes aggregates from CDW (Ramos Guevara 2007). The recycled coarse aggregate (RCA) used was produced from concrete waste graded in accordance with ASTM C 33 standard ASTM (Standard C33/C33M 2016), while the recycled fine aggregate (RFA) came from the fine remnants of the RCA crushing process.

It has been established that the quality of aggregates partially determines the characteristics of the concrete that contains them (in particular its strength and durability) (Paul 2011), standing out as most important some physical characteristics; its density, bulk density, water absorption, porosity, particle size distribution (including its texture and shape). The physical characterization obtained for the UA and RA used in this research are presented in Table 1, along with the standards under which the tests methods were carried out.

Table 1
Physical properties of aggregates

Property/Classification	ASTM	RCA	UCA	RFA	UFA
Density (D) [g/m^3]	C127	2.23	2.29	---	---
Water Absorption (WA) [%]		10.48	4.45		
Density (D) [g/m^3]	C128	---	---	2.11	2.31
Water Absorption (WA) [%]				17.58	3.20
Bulk density (BD) [kg/m^3]	C29	1254.99	1376.21	---	---
Fineness modulus (FM)	C33	---	---	4.00	2.50
Nominal maximum size (NMS) [mm]	C33	25.00	25.00	---	---

The D of UA used are within the normal range (2.4 to 2.9 g/cm^3) (Kosmatka et al. 2004); while the RA values referenced in the literature indicate that they decrease up to 10% compared to the UA (Marie and Quiasrawi 2012) (Marinkovic et al. 2010). Therefore, both aggregates used in this research have been considered suitable and appropriate. It is worth mentioning that the usual coarse aggregates (UCA) are 0.06 g/cm^3 heavier than the RCA, being the fine fractions those with the most significant differences (0.2 g/cm^3).

A high WA does not necessarily make the aggregates unsuitable; however, this could become in certain circumstances, an indicator of inadequate performance for concrete properties. As it is observed, the WA for both RA is greater than UA (6.03 and 14.38% in RCA and RFA, respectively). If RA fractions are compared, the RFA fraction exceeds 7.1% of RCA; these particular variations in the WA of RA is known and widely accepted to be attributed to old mortar adhered to the aggregate particles (Malešev et al. 2010; Thomas et al. 2016; Descarrega 2011; de Brito and Robles 2010; Silva et al. 2014; Marie and Quiasrawi 2012; Rao et al. 2007; Marinkovic et al. 2010; Paul 2011) (more porous), which concentrates on the RFA fraction by the effect of crushing process in the aggregates (mortar weaker than UA).

The BD represents the weight and space occupied by the aggregates, pores and gaps found between the particles, this property affects the demand for cement and influences the required proportion of coarse aggregate (CA) in the mix design (Kosmatka et al. 2004). The difference of BD between the RCA and UCA studied can be attributed to particles angularity of the RCA (concrete fracturing process and subsequent trituration), which causes an increase in the amount of gaps (poor particle arrangement), while UCA has a less aggressive production and because of its origin it has more rounded particles allowing a better particle arrangement. However, in despite of the previous differences and their implications, both aggregates are classified as suitable for a structural normal weight concrete (Kosmatka et al. 2004).

The FM describes fine aggregate (FA) particle size and thickness (bigger particles tend to have a higher FM), it sets the minimum amount of FA needed to fill the gaps between the CA, thus improving the workability of concrete (“lubricant” function for CA). The RFA of this investigation reached a FM above US standards (2.3 - 3.1) (ASTM Standard C33/C33M 2016), when compared to a usual fine aggregate (UFA), RFA has a higher FM; which must be considered to understand and explain the properties of concrete.

Granulometric profiles for RCA, UCA, RFA and UFA were tested using the standard specification ASTM C33 (ASTM Standard C33/C33M 2016) establishing the distribution of their particles sizes, the granulometric curves of the four aggregates used are shown in **Fig. 1** and **Fig. 2**, along with the standard limits. The CA (recycled and usual) meet the recommended particle distribution limits; while FA denoted that both recycled and usual are outside the standard limits (the UFA slightly above the upper limit and RFA far below the lower limit); so to obtain a suitable particle size, the RFA should be corrected or compensated by blending particles of different sizes. Notwithstanding the above, no changes have been established in any of the granulometric profiles of aggregates, assuming that the most common granulometric profiles are never perfect (naturally), and that this is a more common option for manufacturing an in-situ concrete and more practical for industry.

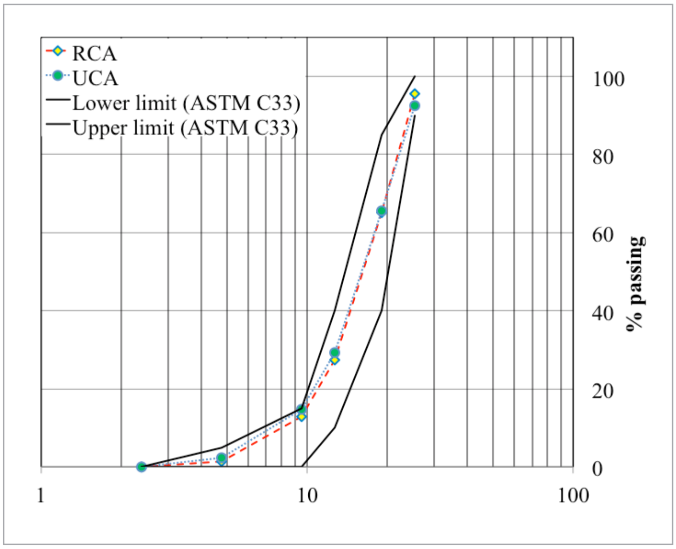

Fig. 1

Coarse aggregates granulometric curve

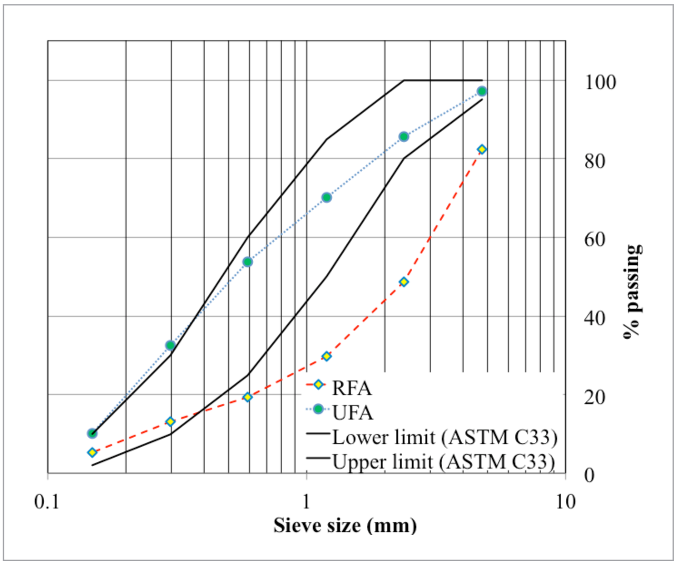

Fig. 2

Fine aggregates granulometric curve

Fresh water used in concrete mixtures was obtained from water supply facilities of the National Autonomous University of México (19°19'54.156" N, 99°11'5.647" W), satisfying the Mexican standards in accordance with the NOM-127-SSA (NOM-127-SSA1-1994 2010) that establishes permissible limits for fresh water quality, whereas the treated wastewater was obtained from the wastewater treatment plant "Cerro de la Estrella" (WTP-CE) located in México City (19°20'12.2"N 99°04'34.0"W), which meets the Mexican quality parameters corresponding to the maximum permissible contaminants for treated wastewater to be used in public services with direct human contact NOM-003-SEMARNAT (NOM-003-SEMARNAT-1997 2003).

To assess the possibility of using water from the WTP-CE as an alternative source for mixing water in concrete, some tests were conducted (see Table 2). The results are compared with the maximum limits set by ASTM C 94 (ASTM Standard C94/C94M 2016) and NMX-C-122-2004 (NMX-C-122-ONNCCE-2004 2004) (North American and Mexican standards, respectively); in both cases, all the required parameters are met except the content of fats and oils. The content of fats and oils can affect the development of concrete strength; it has been recommended that the content of mineral oil will not exceed 2.5% in cement weight (Kosmatka et al. 2004). Therefore, it has been considered that water of the WTP-CE will not cause significant effect on the strength of concrete (at least for its particular effect).

Table 2

Quality parameters of treated wastewater

Parameters/Standards	ASTM C 94 ppm	NMX-C-122 ppm	Water from WTP-CE
Chlorides as Cl: _ Prestressed concrete on in bridge decks (maximum) _ Other reinforced concrete in moist environment or contact with metals (maximum)	500 1000	600 1000	1.17
Sulfate as SO_4	3000	3500	70
Alkalies as Na^+	600	450	97
Total Alkalies as Na^+	600	450	97
Carbonates as CO_3	---	600	140
pH (H^+)	---	≥ 6.5	7.52
Organic material	---	150	22
Suspended solids in natural water	---	2000	6
Suspended solids in recycled wastewater *	---	35000	6
Fats and oils	---	0	0.056

* Wash water used for washing and cleaning mixer trucks, concrete pumps and other equipment is considered as recycled water.

Methodology

Several investigations (Kou 2006; Moriconi n.d.; Marie and Quiasrawi 2012; Shing Chai Ngo 2004; Maleševet al. 2010) have shown that concrete from mixes containing up to 30% of RCA have lower mechanical properties than concrete with UA, on the another hand, it is also known that compressive strength for CC is directly correlated to water-cement ratio (w/c); therefore in this investigation both criteria were considered as design parameters in the mixtures studied.

To ensure workability (without use of additives) the slump range of fresh concrete selected was 80-100 mm and in order to achieve a concrete strength of 25 MP (structural concrete) a w/c ratio of 0.62 was used for all mixtures. Three types of mixtures were defined to verify the feasibility of replacing UCA with RCA; a control concrete mixture (100% UA) and two with RCA (25% and 30% replacement of UCA with RCA. Additionally, to evaluate the feasibility of using a CRiE, the control concrete mixture was done using TW and two mixtures were done using 100% of RCA and RFA (one with fresh water and the other one with TW).

The concrete mix design was done using absolute volume method considering the properties obtained in the characterization of the UA and RA (Kosmatka et al. 2004); in which the masses proportions are determined assuming the aggregates are in saturated surface dry condition (SSD), then these are corrected by absorption and the moisture content of the aggregates. Concrete mix design in SSD is shown in Table 3.

The incorporation sequence of materials into the mixer could have a significant effect on the uniformity of concrete (ASTM Standard C94/C94M 2016), so the method used for the mixture process was following ASTM C 192 (ASTM Standard C192/C 192M 2016). Fresh concrete properties were determined in accordance with established standards: slump (S), air content (Ar) and unit weight (UW), according to the ASTM C 143(ASTM Standard C143/C 143M 2015), ASTM C 231 (ASTM Standard C 231 2014) and ASTM C 138(ASTM Standard C138/C138M 2016), respectively.

Cylindrical specimens of 150 mm x 300 mm were made for mechanical test, the conditions for making and curing the specimens were carried out in accordance with ASTM C192 (ASTM Standard C192/C 192M 2016). Compressive strength testing was performed according to ASTM C39

Table 3

Mix design in SSD

Aggregates	Mix with content of RCA			Mix with content of TW		
	C	R25	R30	C*	Cw	CRiE
	RF=0	RF=25	RF=30	RF=100	RF=0	RF=100
UCA	963	703	665	---	963	---
RCA	---	237	281	816	---	816
UFA	687	667	661	---	687	---
RFA	---	---	---	723	---	723

C = control, RF= replacement factor, R25 and R30 = mix containing 25% and 30% of RA, C*= total replacement with RCA and RFA, Cw= control mix with TW, and CRiE= C* mix with TW.

(ASTM Standard C39/C 39M 2016) using SATEC SF-1U UNIVERSAL tensile and compressive tester, using neoprene pads in both ends of the specimens (ASTM C1231 (ASTM Standard C1231/C 1231M 2015)); repetitiveness per variable was two specimens, at 14 and 28 days.

In addition, an analysis of scanning electron microscopy (SEM) was performed in two specimens of concrete (C and CRiE), in order to clarify the behavior of hardened concrete, the technique was performed with the microscope JOEL (JSM-651), taking and then conditioning a representative fraction of each specimen.

Results and discussion

Table 4

Testing results of fresh concrete

Properties	Mix with content of RCA			Mix with content of TW		
	C	R25	R30	C*	Cw	CRiE
	RF=0	RF=25	RF=30	RF=100	RF=0	RF=100
Ar [%]	2.4	2.4	2.6	2.7	2.5	2.8
S [mm]	95	90	90	80	90	85
UW [kg/m^3]	2132	2109	2115	2046	2144	2075

The results for fresh concrete testing are showed in **Table 4**. The Ar for a CC is in a range from 2% to 3% (Kosmatka et al. 2004) (concretes without air entraining admixtures); in this research, the Ar for the mixes is between 2.4% and 2.8%, so all mixtures are in the usual Ar range without significant differences between them. Therefore, the effect of using RCA, RFA or TW-together or separately, regarding this property, does not affect the mixtures studied.

It has been established that the Ar is directly correlated to the S (Kosmatka et al. 2004); likewise, the values obtained are within the range considered in the mix design (80 to 100 mm). However as operating experience of its use, C* and CRiE mixtures had poor workability and rough texture due to a high content of thick particles and greater WA of RFA; resulting in mixtures with low natural compaction and difficult to place in practice.

The highest UW corresponds to the mixture Cw, followed by C (with minimum difference), and the lowest belongs to C*; summarizing, the variation between all the samples studied only reached 4.5%, consistent with previous studies (Malešev et al. 2010).

The average results of the compressive strength of the specimens appear in **Fig. 3**, where two aspects of common behavior can be perceived: in the first, the results obtained at 14 days always manage to reach 86% of the design strength (Kosmatka et al. 2004); and second, the design strength is met; 25MPa (except CRiE).

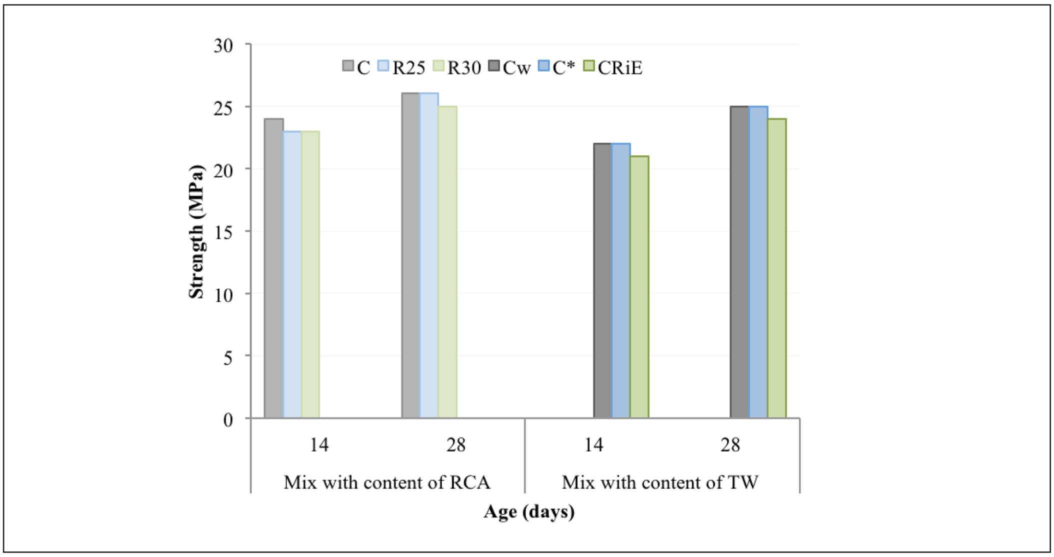

Fig. 3

Concrete strength

Analyzing the results of the specimens with different RF, a correlation was found between the RF and strength loss; 2% and 3% (R25 and R30 respectively with respect to C) at age of 28 days. In the other hand, comparing specimens Cw with respect to C, strength loss is 5.2% (both ages of study); and the difference between C* with CRiE (where also the only variable factor is TW), the compressive strength decreases by 3.5% and 1.2% for the 14 and 28 days, respectively. Finally, concerning the proposal for RF = 100%, were the first variable factor are RCA and RFA (C*) the strength loss with respect to C is 10.4% and 6.8% at 14 and 28 days, respectively.

As a hypothesis for the above behavior, in addition to adverse effects due to the physical properties of the RA (low D, high porosity), on the concrete mechanical behavior; it is suggested that the high porosity, the old adhered mortar on the original aggregates (higher concentration in the fine fraction of the aggregate), and the creation of new weaker areas around the aggregates called Interfacial Transition Zone (ITZ) - which is formed between a recycled aggregate (with adhered mortar) and the new concrete mortar; are the causes of strength loss. In order to validate this, images (SEM) were performed; seeing that in concrete with RA replacement these areas are wider with a noticeable increase present in the matrix (see Fig. 4).

Finally, because of the TW chemical studies and the minimum variations of strength between CRiE and a CC, it is concluded that the possibility of using this type of water in the creation sustainable concrete is feasible, practical and appropriate; thereby mitigating the demand of fresh water in the industrial manufacturing of concrete, besides contributing to the rational use of nonrenewable resources.

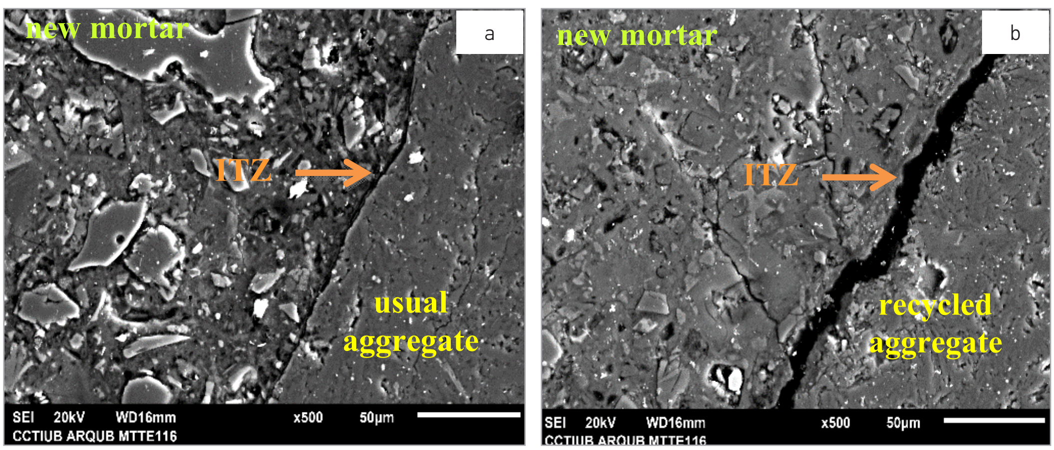

Fig. 4

SEM image with x500 zoom: a) usual concrete, b) concrete CRiE

Conclusions

Based on the research conducted, there is evidence of the feasibility to use (limited in some aspects of resistance and durability) the RCA and the TW as components of recycled concrete; considering this as a truth, the possible applications of recycled concrete may not be 100% comparable to the CC, but the rational use of materials in the constructive elements of low requirements makes possible its application. The above, allows to give solution to CDW and the TW, promoting the sustainability and the use of recycled materials in construction.

From the results of this research (tests on concrete fresh and compressive strength), it was observed that all mixtures of concrete containing the TW presented generally favorable values according to the regulations for concrete (even that the TW does not satisfy the limits of contents of oils and fats), therefore its use could be a viable alternative to reduce the consumption of fresh water through the use of TW. The TW of this study, can be considered as a source of water acceptable for the manufacturing of concrete; however, it is mandatory to carry out all previous analysis necessary that allow to guarantee the fulfillment of the regulation tolerances to ensure it as a constituent element of a concrete. In cases where these requirements are not achieved, it will be necessary to conduct a study of the possible affectation of the contaminant in the concrete, entailing that to use them, most pollutant substances that can cause deterioration in the strength and durability, must be removed. So the TW will have to be submitted to a constant control in wastewater treatment plants.

The RCA used are of high quality and no significant differences were present compared with UA, so it is possible to obtain a concrete with a satisfactory mechanical behavior, comparable with a CC. Moreover, the RFA has characteristics of poor quality so that it is unfeasible for structural use, however can be used in non-structural concrete elements.

The D and BD of RCA are not significantly lower, so that it meets the pre-established recommendations. In addition, workability, Ar and S do not show substantial effects in any of the treatments where RCA was used. In the mixture CRiE one centimeter less of slump was obtained with respect to the control mixture, so its value is insignificant and requires no correction for practical implementation. Finally, the WA of the RCA is greater with respect to a UCA, however, this does not affect the characteristics of the concrete. This increase of the WA in the RCA, can be decisive for the behavior of durability of the concrete recycled to its resistance to the freeze-thaw (cold climates); for which, will be necessary the accomplishment of future research that demonstrate this possible affectation to the durability (process of micro-cracking, number of freeze-thaw cycles tolerable, additions of improvement of the concrete, palliative concreting processes, etc.).

Finally, there is a clear need to expand this research; since more tests and series of different types and origins of the RCA and TW might generate a wide statistics that give strength and solidity to constructive, practical, and safe applications. The previous comment is based on the origin of the RCA and TW materials, with contents of very variable, complex and slightly usual pollutants in the composition of the concretes. Future studies, which established the tolerances of each pollutant in the different aspects of the strength and durability of concrete (separately or combined), as well as the search of criteria for the establishment of applications with low solicitations, will mark the future, acceptance and inclusion in the regulations of these new sustainable concrete. For the case of the TW, contents of substances organic, acidifying and reactive with the chemistry of the cement; as well as for the RCA, its origin (type of concrete which comes), process of crushing and shape of particles, are considered to be important variables to study in future research, to obtain a broader understanding of the concrete that include them.

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