Concrete with recycled aggregates as urban sustainability project

El concreto con agregados reciclados como proyecto de sostenibilidad urbana

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Abstract

This article addresses the preparation of a concrete using recycled aggregates obtained from the rubble recovery of concrete and masonry works. The study shows some aspects such as: compressive strength at 3, 7, 14, 28, 56 and 91 days; porosity, ultrasonic pulse speed and carbonation; economic costs compared to a conventional concrete; and a review of the public policies on sustainable construction and the use of rubble, in the city of Medellin, Colombia. For some mixes, the compressive strength and the ultrasonic pulse speed measurements were approximately the 98% of that of the reference mix. Likewise, the mix prepared with 100% of recycled aggregates showed a difference in the carbonation deepness of only 0.7 mm compared with the mix of reference for a simulated age of 27 years. The results obtained with the replacement of natural coarse and fine aggregates in 25%, 50%, and 100%, and the advance in the political-administrative guidelines of the city in the last eleven years, allow deducing the possibility of preparing structural and non-structural concretes for massive use in the construction area.

Keywords: *Sustainable construction, inverse mining, recycled concrete, urban ecosystem, integrated project management*

Resumen

Este artículo aborda la confección de un concreto usando agregados reciclados obtenidos de la valorización de escombros de concreto y mampostería. Se muestran aspectos como resistencia al esfuerzo de la compresión a 3, 7, 14, 28, 56 y 91 días; porosidad, velocidad de pulso ultrasónico y carbonatación; costo económico en comparación con un concreto convencional; y una reseña de las políticas públicas de Construcción Sostenible y aprovechamiento de escombros formuladas en Medellín, Colombia. La resistencia al esfuerzo de la compresión y las medidas de velocidad de pulso ultrasónico en algunas mezclas fueron del orden del 98 % de la mezcla de referencia; así mismo la mezcla confeccionada con 100 % de agregados reciclados, mostró una diferencia en cuanto a la profundidad de carbonatación de tan solo 0.7 mm con respecto a la mezcla de referencia para una edad simulada de 27 años. Los resultados obtenidos con sustituciones de agregados naturales por agregados reciclados gruesos y finos en porcentajes del 25 %, 50 % y 100 %, y el avance en los lineamientos político-administrativos de la municipalidad en los once años recientes, permiten deducir la posibilidad de confeccionar concretos estructurales y no estructurales para uso masivo en la construcción.

Palabras Clave: Construcción sostenible; minería a la inversa; concreto reciclado; ecosistema urbano; gestión integral de proyectos

1. Introduction

To prepare a material as used as concrete requires non-renewable raw materials which in turn generate a negative environmental impact since they are mainly obtained by opencast mining. In this sense, the community of Medellin is being affected by quarry exploitation to obtain such aggregates, having as a consequence an environmental degradation of the urban crust, particulate material in the atmosphere and, derived from the demolition and building processes, disposal of building and demolition waste (C&DW) in sites that lost their potential as landscape or developable areas. With a generation of such type of waste of 8,000 t/day (AMVA; 2010) and an extractive activity which degrades the urban ecosystem, the citizens that overcome the 2 400 000 inhabitants (DANE; 2015) experience an increasing damage in their urban ecosystem, since to obtain one ton of aggregate for preparing concrete, it is necessary to remove many tons of the top soil, thus eliminating the biotic activity. Hence, the requirements for the building industry nowadays enforces the development of new management tools (Gracia and Dzul, 2007; Dzul and Gracia, 2009) which allow boosting the resources, mainly in countries with limited investment.

In Medellin, there are two elements that made difficult the implementation of construction projects that use recycled aggregates and concrete: the low cost of natural aggregates for concrete and the controlled disposal of C&DW. Moreover, it is necessary to add the unaware of certain characteristics related to the concrete physical-mechanical performance such as compressive strength at ages over 28 days and its durability before the atmospheric agents of the site. This scientific lacuna means a difficulty at the moment of undertaking construction projects with structures made of recycled concrete, since to guarantee the future performance of the building or civil work forms part of the constructor's contractual arrangements. It will be a great contribution to the Colombian scientific community to determine the compressive strengths of the recycled aggregates and concrete at the ages of 3, 7, 14, 28, 56 and 91 days as well as their performance before the atmospheric agents; to measure their absorption, carbonation and porosity in order to predict their durability. The community will have the necessary knowledge for introducing or not a new ecological material in the building activity, and also will have a base to justify the implementation of a public policy on sustainable construction at urban scale by using eco-materials.

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2. Materials and method

Description of the method used, characterization of the raw materials, tests and discussion of the results.

2.1. Selection of raw materials: *for the natural aggregates, those coming from quarries with optimal performance traceability in concrete mixes were chosen. For selected and crushed rubble, a proportion of 50 % of demolished concrete and 50 % of masonry of ceramic bricks with mortar were used, for the case of recycled fine aggregates. For coarse aggregate, only concrete waste was used. The aggregates were characterized through physical technics: fineness modulus, absorption percentage and dry bulk density.*

2.2. Resistance and durability tests: *cylindrical samples of 10 cm diameter and 20 cm height were prepared and introduced in a curing tank with lime-saturated water at a temperature of 23 ± 3ºC. Samples were taken to the hydraulic press to determine their compressive strength at ages of 3, 7, 14, 28, 56 and 91 days. Besides, some hardened concrete samples were analyzed to determine their performance regarding absorption, bulk density, porosity and carbonation. For these analysis, researchers used furnaces, ultrasonic pulse speed instruments and a camera saturated with* CO_2 *at 50 % and with a relative humidity between 50% and 60%, which is the most critical range for carbonation of the hardened concrete (Moreno E. et al., 2004).*

2.3. Standards and political-administrative framework: *current and ongoing agreements and decrees were identified and analyzed, that in Medellin and its metropolitan area address the management issues and leveraging of C&DW, and the implementation of sustainable construction from the public policies point of view.*

3. Results

3.1 Aggregates

Fine and coarse recycled aggregates were homologated to the distribution given by the natural aggregates of reference. Once the weights by sieves were distributed, the necessary amount of aggregates was selected in order to obtain the different types for substitution:

a) *natural coarse aggregate;* ***b)*** *natural fine aggregate;* ***c)*** *coarse aggregate 25-R: 75 % natural-25 % recycled;* ***d)*** *fine aggregate 25-R: 75 % natural-25 % recycled;* ***e)*** *coarse aggregate 50-R: 50 % natural-50 % recycled;* ***f)*** *fine aggregate 50-R: 50 % natural-50 % recycled;* ***g)*** *coarse aggregate 100-R: 100 % recycled;* ***h)*** *fine aggregate 100-R: 100 % recycled.*

*The fineness modulus shows that the coarse and fine aggregates, both those 100 % natural (**a** and **b**) and 100 % recycled (**g** and **h**), show the same value, since as it was previously explained, their weights were homologated for each sieve. Nevertheless, the coarse aggregates and fine 25-R (**c** and **d**) and 50-R (**e** and **f**) report a change since once the natural and recycled aggregates were mixed some grading tests were done.*

Table 2 shows the coarse aggregate characteristics. Table 3 shows the comparison for the fine aggregates.

Table 1. *Characteristics of the six types of aggregates used in mixes*

Variable	a	b	c	d	e	f	g	H
Maximum size (mm)	19.05	–	19.05	–	19.05	–	19.05	–
Dry bulk density (g/cm^3)	2.87	2.74	2.82	2,.69	2.63	2.66	2.53	2.52
Fineness modulus	7.20	3.30	7.40	3.45	7.57	3.50	7.20	3.30
Absorption percentage (%)	1.28	3.00	1.34	3.06	2.70	3.10	4.20	3.20

Table 2. *Comparison of coarse aggregates*

Variable	a	c	e	G
Dry bulk density (g/cm^3)	2.87	2.82	2.63	2.53
	(100 %)	***(98.26 %)***	***(91.64 %)***	***(88.15 %)***
Absorption percentage (%)	1.28	1.34	2.70	4.20
	(100 %)	***(104.69 %)***	***(210.94 %)***	***(328.13 %)***

Table 3. *Comparison of fine aggregates*

Variable	b	d	f	h
Dry bulk density (g/cm^3)	2.74	2.69	2.66	2.52
	(100 %)	***(98.18 %)***	***(96.03 %)***	***(91.97 %)***
Absorption percentage (%)	3.00	3.06	3.10	3.20
	(100 %)	***(102.00 %)***	***(103.33 %)***	***(106.67 %)***

3.2 Mix preparation, compressive strength and durability tests

3.2.1 Mixes preparation

Mixes were prepared in the laboratory of the Construction School of the Universidad Nacional de Colombia, Medellin, using a mechanical mixer. Portland grey cement, Type I, manufactured in Colombia, was used. Table 4 shows the cement specifications.

Four concrete mixes were designed a) ***0-R:*** *100 % natural aggregate; b)* ***25-R:*** *75 % natural coarse aggregate and 25 % of recycled coarse aggregate, and 75 % of natural fine aggregate and 25 % of recycled fine aggregate; c)* ***50-R:*** *50 % natural coarse aggregate and 50 % recycled coarse aggregate, and 50 % natural fine aggregate and 50 % recycled fine aggregate; d)* ***100-R:*** *100 % recycled aggregate. The concrete slump was fixed between 5 cm and 7.5 cm, using an A/C ratio of 0.50 for the three mixes.*

Regarding concrete mix proportioning, the most relevant issue was the difference showed in the cement and water consumption. The 0-R mix is the reference mix. Results are shown in Table 6.

3.2.2 Compressive strength tests

Thirty concrete samples were prepared for each one of the mixes, which is a total of 120 samples, using cylindrical specimens of 10 cm diameter and 20 cm height. Three specimens for each mix were selected for each failure age (NTC 1377; ASTM C192M). The results are shown in Table 7.

Table 4. *Properties of type I portland cement used for mixes*

Specific weight (g/cm^3)	Blaine (cm^2/g)	Compressive strength at 3 days (MPa)	Compressive strength at 7 days (MPa)	Compressive strength at 28 days (MPa)
3.10	2.800	9.00	16.00	26.00

Table 5. *Slumps of the concrete mixes*

Type of mix	Slump (cm)
0-R	6.84
25-R	6.50
50-R	6.35
100-R	6.05

Table 6. *Percentages of the difference in cement and water consumption*

Type of mix	Cement consumption in kg/m^3; difference (%)	Water consumption in kg/m^3; difference (%)
0-R	394.40; (0.00)	181.89; (0.00)
25-R	402.23; (2.10)	189.35; (4.10)
50-R	411.43; (4.32)	198.27; (9.01)
100-R	424.76; (7.71)	213.17; (17.29)

Tabla 7. Compressive strength, average of three specimens by age according to the NTC 1377 standard (ASTM C192M).

Mix	Resistance to compressive strength in MPa					
	3 days	7 days	14 days	28 days	56 days	91 days
0-R	11.35	15.60	19.26	23.51	26.84	27.39
25-R	11.15	15.33	18.90	22.91	26.35	26.83
50-R	10.82	14.93	18.55	22.28	25.71	25.93
100-R	10.10	13.89	17.33	20.33	21.92	23.02

Considering the 0-R mix as the reference mix (Figure 1), a comparison in percentage can be made regarding the compressive strength of the mix (Table 8, Figure 2), assuming that the 0-R mix is the 100 %.

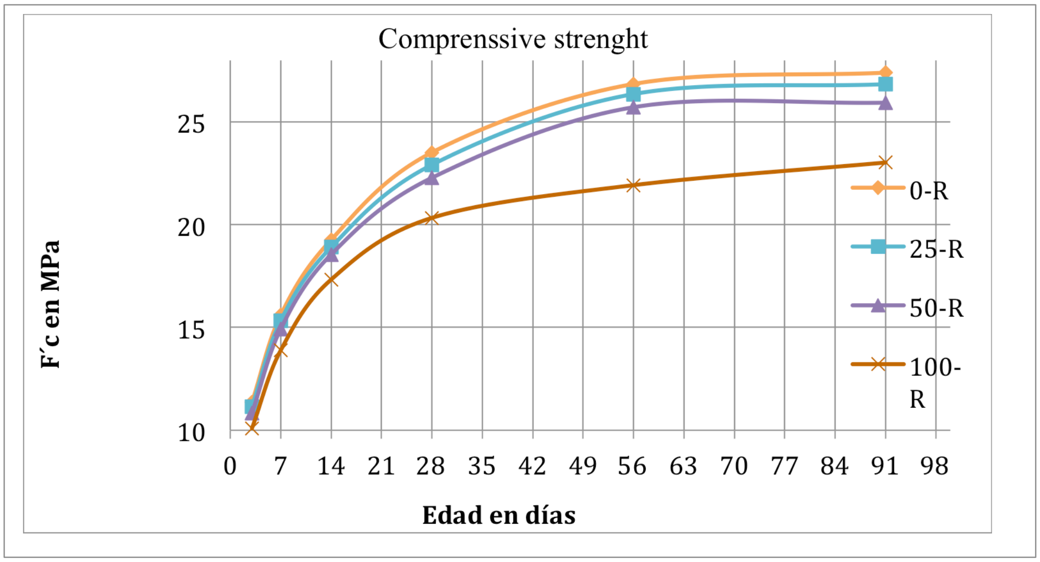

Figure 1. *Curve of compressive strength, evolution at 91 Days*

Table 8. *Compressive strength of the mixes*

Mix	Compressive strength performance in %					
	3 days	**7 days**	**14 days**	**28 days**	**56 days**	**91 days**
0-R	100.00	100.00	100.00	100.00	100.00	100.00
25-R	98.20	98.25	98.14	97.46	98.18	97.94
50-R	95.33	95.71	96.31	94.77	95.79	94.67
100-R	88.99	89.04	89.98	86.47	81.67	84.05

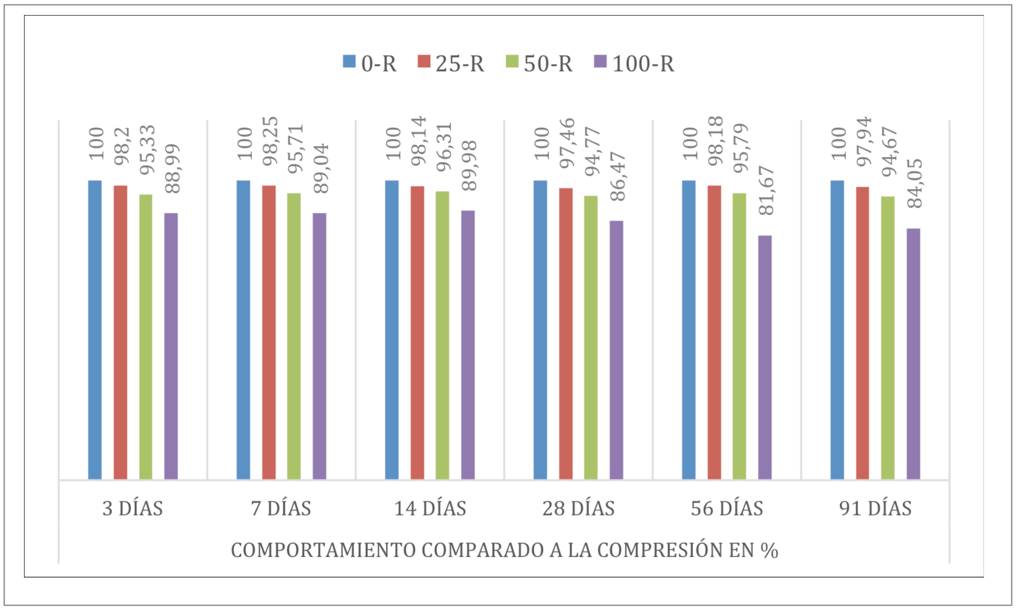

Figure 2. *Column diagram. Comparison of the compressive strength of the mixes*

The average for the six results of mix 25-R is 98.03 % in comparison with the 0-R reference mix, the average for the mix 50-R is 95.43 %, and that for the mix 100-R is 86.70 %. It should be noted that in the three mix of recycled concrete –with 25 %, 50 % and 100 % substitution– both the fine and coarse aggregate were replaced. Mehta and Monteiro recommends to replace up to 20 % of the coarse aggregate, since they found that when replacing a greater percentage, the resistance to the compressive strength decreases up to 20 %, although later researches have demonstrated that the performance for compressive strength is between 64 % and 100 % of that for a control mix (Mehta and Monteiro, 2006).

The American Concrete Institute (ACI), which in 1895 created the Committee 555 "Concrete with Recycled Materials", has published many researches about the performance and feasibility of recycled aggregates in concrete, with results that allow deducing the possibility of substituting natural aggregates for those obtained from the recycling of concrete demolished structures (ACI 555R-04, 2004). It has been reported that the resistances to compressive strength from mixes with 20% of substitutions of fine aggregates are the 98 % of that from the mixes prepared with natural aggregates (Evangelista L. and de Brito J., 2007).

Perhaps, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) is the entity that, along with the ACI, has worked the most in consolidating a knowledge base of articles and presentations in congresses with the objective of transforming the recycled concrete production and application in a practice with less uncertainties and more feasibility at industrial scale. Among its committees the "RILEM Technical Committee 121-DRG, Specifications for Concrete with Recycled Aggregates", is exclusively dedicated to the study and socialization of the advances in this sense. Attention should also be drawn to the reports prepared during decades by this entity (Hansen, T. C., 2004), reporting the performance of recycled mixes in regard to their compressive strength, durability through absorption, open porosity, carbonation and Ultrasonic Pulse Speed (UPS).

One of the recent works on recycled concrete for structural use, published by the ACI Journal Structural, reports the optimum performance of a six-store structure regarding earthquakes, finding that the performance before drifts and the seismic energy dissipation were comparable with those of a concrete structure made with natural aggregates. Even in the maximum level, the earthquake category, the recycled structure did not collapsed (Xiao T., Ding T. and Pham T., 2015). Likewise, the ACI Materials Journal reports a work where some beams were prepared in order to analyze their mechanical properties and shear resistance, replacing natural aggregates for recycled concrete aggregates in percentages of 50 % and 100 %, applying the international and American standards for beams shearing, finding that in the case of the elements with 100% replacement, their performance decreased 11 %, but beams with 50 % of recycled aggregates had a performance similar to the control samples (Arezoumandi M., 2015).

3.2.3 Durability Tests

The durability tests used were: Standard Test Method for Density, Absorption and Voids in Hardened Concrete according to ASTM C642-06 (Table 9); carbonation (Table 10) and ultrasonic pulse speed (Table 11). Results can be appreciated hereafter. Mix 25-R was not analyzed for carbonation and ultrasonic pulse speed tests.

Porosity

***Table 9.** Density, absorption and voids in hardened concrete*

Mix	Absorption after immersion and boiling (%)	Dry bulk density (g/cm^3)	Volume of permeable porous (Voids) (%)
0-R (1)	7.8	2.24	17.4
0-R (2)	7.8	2.24	17.5
Average 0-R	**7.8**	**2.24**	**17.5**
25-R (1)	7.9	2.20	18.4
25-R (2)	8.0	2.19	18.6
Average 25-R	**8.0**	**2.20**	**18.5**
50-R (1)	9.2	2.15	19.8
50-R (2)	10.1	2.12	21.3
Average 50-R	**9.7**	**2.14**	**20.6**
100-R (1)	12.5	2.01	25.1
100-R (2)	12.7	2.00	25.3
Average 100-R	**12.6**	**2.01**	**25.2**

As it can be observed, mix 25-R has a performance very similar to that of the reference mix. The other recycled samples also have a positive performance, as it is the case of mix 50-R whose dry bulk density was 95.54 %; mix 100-R obtained 89.73 % for the same measurement. Regarding the absorption and porosity values of hardened concrete, all mixes show a performance within the parameters established by different researchers such as D. K. Nekrasov, who says that concretes have porosities that varies between the 20 % and 30 %, or Aportela, who using limestone aggregates and a A/C ratio of 0.50 obtained an average porosity of 23.3 %. In relation to absorption, the values showed by the four mixes are within the range proposed by D.K. Nekrasov, that is, between 10 % and 20 % (Olivarez M., Laffarga J., Galán, C. and Nadal, P. 2003).

Carbonation

Cylindrical specimens were cut in sections of 5 cm height, and each section was subjected to eight and ten radial measurements in the carbonation area. As pH indicator, a phenolphthalein solution 1 % in ethylic alcohol was used.

Table 10. *Carbonation of ixes*

t1			t2			t3			t4		
0-R	**50-R**	**100-R**	**0-R**	**50-R**	**100-R**	**0-R**	**50-R**	**100-R**	**0-R**	**50-R**	**100-R**
3.45	4.85	3.30	4.50	9.20	8.25	4.4	10.90	9.00	7.00	9.80	7.40
2.15	1.60	1.60	3.30	9.00	11.65	2	14.10	9.10	10.10	9.60	4.60
0.00	0.00	3.20	5.25	6.50	1.30	3.6	16.00	6.60	9.30	6.00	5.50
3.30	0.00	0.00	8.85	12.00	6.75	2.8	8.60	5.60	5.20	14.70	9.10
0.00	4.10	4.70	5.95	7.45	7.45	20.8	6.10	5.20	6.00	12.90	9.20
2.30	1.75	2.70	4.20	9.35	4.90	1.50	10.00	14.00	14.40	15.40	9.10
3.20	0.00	3.90	2.10	11.60	7.75	2.7	12.40	8.00	5.40	17.80	8.80
2.10	1.45	1.90	5.35	9.80	5.70	10	8.90	12.80	6.40	14.80	11.10
1.50	4.90	1.20	–	–	–	0.4	11.60	9.00	5.30	15.10	8.30
–	–	–	–	–	–	–	–	–	14.80	7.80	17.50
Average (mm)											
2.00	2.07	2.50	4.94	9.36	6.72	5.4	11.0	8.8	8.40	12.40	9.10
Minimum (mm)											
0.00	0.00	0.00	2.10	6.50	1.30	0.4	6.1	5.2	5.20	6.00	4.60
Maximum (mm)											
3.45	4.90	4.70	8.85	12.00	11.65	20.8	16.0	14.0	14.80	17.80	17.50
Test time (days)											
14			35			55			76		
Test time (hours)											
336			840			1 320			1 824		

Table 10A. *Time equivalent in years for accelerated carbonation*

Exposure time	**t0**	**t1**	**t2**	**t3**	**t4**
Hours	0	336	840	1320	1 824
Days	0	14	35	55	76
√t		18.3	29.0	36.3	42.70
Real time (years)		**5.00**	**12.60**	**19.80**	**27.40**

Table 10B. *Resume of the accelerated carbonation*

Test time (days); years	**Carbonation deepness (mm)**		
	0-R	**50-R**	**100-R**
(0); 0	0.0	0.0	0.0
(14); 5.0	2.0	2.1	2.5
(35); 12.6	4.9	9.4	6.7
(55); 19.8	5.4	11.0	8.8
(76); 27.4	8.4	12.4	9.1

Although recycled samples show a better deepness of carbonation, they keep within the optimum performance range, since in the case of mix 50-R that shows the higher value (12.4 mm) in an exposure period equivalent to 27.4 years, it must be considered that, if it should form part of an structure located in Colombia, the national standard for earthquake resistance NSR-10 requires a covering of 50.0 mm minimum for the steel. In the case of the other two mixes, their performance is even better, being the reference mix 0-R the one with the lower value.

Ultrasonic pulse speed (UPS)

For this test, the cylindrical specimens were cured during 28 days immersed in lime-saturated water. After the curing period, they were dried during seven days at environmental temperature. The percentage of moisture content of the air-dried specimens and the ultrasonic pulse speed were measured. Table 11 shows the results obtained for mixes 0-R, 50-R and 100-R.

According to Malhotra, a concrete that presents an UPS between 3 660 m/s and 4 575 m/s is considered as good; under this range, it is considered as regular and over this range it is considered as excellent (Pardo F. and Pérez E., 2010). For mixes of normal use, that are between 21 MPa and 35 MPa, the optimum performance will be within the range of 3 660 m/s and 4 575 m/s.

3.3 Costs of the recycled and natural or conventional concrete

For the evaluation, it was considered a standardized industrial scale production of recycled aggregates manufactured by a recycling plant located in Medellin city, which allowed having a comparison element at the same production scale of the natural aggregates in the same area. The cost assessment was done considering one cubic meter for each aggregate substitution percentage, considering that the recycled aggregate costs 65 % less than the natural aggregate.

Table 11. *Ultrasonic pulse speed; *averaged values by specimen*

Sample	**Sample moisture (%)**	**Speed (m/s)***	**Average speed (m/s)**
0-R (1)	21.56	4 527.0	4 502.5
0-R (2)	21.00	4 478.0	
50-R (1)	23.30	4 447.0	4 437.5
50-R (2)	26.10	4 428.0	
100-R (1)	20.50	4 242.0	4 134.5
100-R (2)	20.60	4 027.0	

Table 12. *Cost Comparison between conventional and recycled concretes*

Ítem	**0-R** USD/m^3	**25-R** USD/m^3	**50-R** USD/m^3	**100-R** USD/m^3
Fine aggregate	9.53	8.55	7.89	6.01
Coarse aggregate	9.01	8.01	7.04	5.46
Cement	77.33	78.87	80.66	83.27
Water	0.081	0.087	0.091	0.098
Preparation	12.55	12.55	12.55	12.55
Total	**108.50**	**108.08**	**108.23**	**107.39**

3.4 Standards and Political-Administrative Framework in the period 2004-2015

Following is a table that describes the agreements and public politics in force during the period in the region in study.

Table 13. *Agreements and municipal resolutions on C&DW and sustainable construction*

Year	Agreement/Act	Description	Contribution to the study
2005	Study for the design of rubble waste assessment, through an integral management system of the same for the program *Producción Más Limpia* (Cleaner Production) in Medellin city.	It was based on researches done in the Universidad Nacional de Colombia Sede Medellín on rubble recycling for concrete manufacturing and its analysis from the point of view of semi-closed circle system of materials.	It showed the community the potentiality of supplying their own demands for public works through rubble valuation, proposing its use as aggregates for non- structural concretes.
2006	Regional Integrated Solid Waste Management Plans for the Aburrá Valley. 2005-2020. Agreement number 325, 2004.	This study took up and updated data of the Integrated Solid Waste Management Plan of Medellin, in the nine municipalities and made a projection to 2020 related to the Construction and Demolition Waste (C&DW) generation.	In relation to the C&DW, some strategies were identified for collecting the 100 %, and scientific and technological research to improve the model of collect-dispose towards a collect-valuate model.
2010	Make a proposal and implement Public Politics on Sustainable Construction in the Aburrá Valley. Agreement number 253, 2009.	Establish objectives that involve energy efficiency in buildings, water rational consumption, use of eco-materials through the C&DW valuation and tax incentives for the companies that build considering these parameters.	The *"Documento técnico de base para la elaboración de una Política Pública de Construcción Sostenible para el Valle de Aburrá"* was drawn up (AMVA; 2010). It exposes objectives and strategies to declare the sustainable construction as a binding fact in projects for the public and private sector.
2013	Decree 1609, 2013. Public politics for the rubble management in Medellin.	It regulates the Municipal Agreement 062, 2009 that establishes a Public Politics for the rubble management in Medellin.	It establishes the obligation of using percentages of the C&DW generated in the works; the use will be the minimum 5 % of the total square meters of the project, and that should increase every year in two points until reaching the 15 %.
2014	Metropolitan Agreement Number 5 (March 14th, 2014). It declares as a Metropolitan Fact the Sustainable Construction and the basic guidelines to implement a Public Politics for a Sustainable Construction in the Aburrá Valley.	It gives continuity to the guidelines established in the Agreement number 253, 2009; it considers as territory of application not only Medellin, but also the other eight municipalities over which the environmental control entity has jurisdiction.	It promotes the production and consumption of sustainable products, where the manufacturing of recycled concrete becomes an important strategy, since most of the works use concrete as the main building material.

4. Conclusions

This study concludes that although aggregates obtained from rubble recycling present differences in some of their characteristics, they may be used in construction as raw material for a new type of concrete, since not all concrete mixes are required for structural use. Nevertheless, it is possible to manufacture concretes for structural use as long as mixes with 25 % of substitution maintain the same performance, that is, same resistance, porosity and costs, regarding the reference mix, especially if it is considered that in all recycled mixes fine and coarse aggregates were substituted. In some countries, important structures have been built by substituting the 20 % of the coarse aggregate by recycled aggregate, as is the case of the bridge over the Turia river, in the city of Valencia, Spain (Alaejos P., Domingo A., 2005). Moreover, in Switzerland, since 2010, Andreas Leemann and Cathleen Hoffmann (2012) have been working on recycled structural concrete with encouraging results.

Mix 50-R showed a performance over 95 % regarding the compressive strength, compared with the reference mix; the porosity and absorption of mix 50-R also gave positive results and, regarding carbonation deepness and ultrasonic pulse speed, their performance is located among the optimum ranges in front of the possibility of using this type of mixes in conventional structures whose concretes require compressive strength resistances between 21 MPa and 35 MPa.

At international level, there are works that substitute only the natural coarse or fine aggregate by recycled ones, as well as there are others that substitute both. These studies concluded that, in general, aggregates density decreases between 5 % and 10 % and that the absorption increases drastically. The results are consequent with these obtained in the present study and with those described by others authors in different region of the world such as Egipt (Wagih A., El-Karmoty H., Ebid M. and Okba S., 2013), Spain (Olivarez M., Laffarga J., Galán C. and Nadal P. 2003), among others. Likewise, the compressive strengths reported in this paper are similar to those mentioned by other authors in other contexts. This allows deducing that it is possible to implement concrete manufacturing and production practices using concretes manufactured with recycled aggregates at local and regional level, scalable to global level; thus enabling a more reflexive flow regarding non-renewable raw material extractions and waste generation, always maintaining the rigor of the corresponding analyses on the intrinsic characteristics of the materials.

Taking into account that carbonation is one of the most critical factors for the durability of concrete structures, in general, the results are very good for all the mixes, including the reference mix. It can be observed that, at 27.4 years, the maximum deepness reached by the carbonation front was 12.4 mm for mix 50-R and 9.1 mm for mix 100-R, compared with the 8.4 mm of the reference mix. Besides, technical and scientific literature establishes that, for normal structural concretes, the standard deepness is about 20 mm at 20 years. In this sense, mixes show an average carbonation deepness of 9.97 mm at 19.8 years, being 11.0 mm the highest (50-R) one and 5.4 mm the lowest (0-R) one. Those measurements are largely under the standard deepness, and as it was previously mentioned, the Colombian earthquake standard requires a minimum covering of 50 mm for the steel reinforcement.

Mixes prepared with recycled aggregates cost almost the same as the reference mix, and although they need more cement, the cost of recycled aggregate is lower than that of the natural one. In such a case, many researchers and concrete manufacturers recommend to turn the savings generated by recycled aggregates into the increase in cement, in order to increase the mix compressive strength and durability.

This research has contributed to correlate the analysis of the performance of a recycled material with its economic feasibility and the possibility of producing it at urban scale supported by the legislation, in order to boost the production and consumption of an ecological concrete through binding actions such as decrees and public policies.

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