ENGLISH VERSION...

Evaluación de un mortero preparado con agregados reciclados de un concreto mejorado por carbonatación: Una mirada a la construcción sustentable

Assessment of a mortar with recycled aggregate from a concrete improved by carbonation: A look to a sustainable construction

A. Muñoz *, N. Torres *, A. Guzmán [1]*

* Escuela Colombiana de Ingeniería Julio Garavito, Bogotá, COLOMBIA

Fecha de Recepción: 15/03/2018
Fecha de Aceptación: 01/08/2018
PAG 25-32

Abstract

In this research, some of the physical, mechanical, and durability properties of mortars were evaluated. These mortars were prepared with partial replacements of the natural fine aggregate (NFA) by recycled fine aggregate (RFA) and carbonated recycled fine aggregate (CRFA) in amounts of 0%, 25%, and 50%. For this purpose, 3 groups of mortar mixtures were elaborated with a w/c ratio of 0.65. The results showed that an increase in the percentage of replacement of the CRFA led to an improvement in the mortar compressive strength, as well as a lower superficial absorption rate.

Keywords: *Recycled concrete, carbonation, mortar, mechanical properties, durability*

Resumen

En este artículo, se evaluaron algunas de las propiedades físicas, mecánicas y de durabilidad de morteros preparados con reemplazos parciales de 0%, 25% y 50% del agregado fino natural (AFN) por agregado fino reciclado carbonatado (AFRC) y sin carbonatar (AFR). Para ello, se elaboraron 3 grupos de mezclas de mortero, con una relación a/c de 0,65. Los resultados obtenidos demostraron un aumento en la resistencia a la compresión del mortero y una menor tasa de absorción superficial, conforme se incrementó el porcentaje de reemplazo del AFRC.

Palabras clave: Concreto reciclado, carbonatación, mortero, propiedades mecánicas, durabilidad

1. Introduction

In the elaboration of mortar, the use of recycled fine aggregates that come from concrete waste is the next step that the construction industry must make, for the protection of the environment and the effective usage of resources. The effects of the production of concrete over the environment are of great concern. Mainly, because of the extensive use of this material around the world (Fernández-Jiménez & Palomo, 2009). This popularity has led to an annual world consumption of almost 20 billion cubic meters of concrete. This means that the carbon footprint of the process of production doubled in only 15 years (1990-2005) (Mehta & Meryman, 2009), in which most of the greenhouse gases come from the production of clinker (Mehta & Meryman, 2009). Therefore, it is evident that the construction industry uses a great amount of renewable and non-renewable resources. This is evident in the fact that it is responsible of 50% of the exploitation of raw material, as well as the consumption of 40% of the energy produced worldwide. As a product of this, the construction industry generates 50% of the waste found in landfills. These residues may come from the demolition of structures that have reached the end of their service life, or that did not fulfill the security and seismic-resistant requirements, as well as structures that have been damaged in an irreparable way during natural disasters (Oikonomou, 2005).

On that basis, various methodologies have been developed with the purpose of mending the environmental problem, and the disposal of construction and demolition waste. As a result of this, concrete waste has been used in new mortar and concrete mixtures, as a total or partial replacement of natural aggregates. In comparative terms, recycled aggregates present a greater absorption, lower bulk and nominal density, lower shape factor, and lower resistance to abrasion in the Los Angeles machine, as well as in the Micro-Deval (Bojaca, 2013). The partial or total replacement of natural aggregate with the concrete waste processed in recycling plants represents a relief for natural resources. Likewise, if the crushing of the aggregate takes place in the project site, the savings are greater.

[1] Corresponding author:
Escuela Colombiana de Ingeniería Julio Garavito, Bogotá, COLOMBIA.
E-mail: alvaro.guzman@escuelaing.edu.co

There are two types of recycled aggregate: Recycled Coarse Aggregate (RCA) and Recycled Fine Aggregate (RFA). Surrounding the particles, there is cement paste, which creates a porous and fragile layer that increases the porosity of the new mixture; thus, decreasing its quality and facilitating the formation of micro-cracks within the new mortar or concrete (Geng & Sun, 2013).

Various authors have tested concrete samples, using partial replacements of recycled aggregates, whether they are coarse (Sim & Park, 2011) (Bojaca, 2013; Evangelista & de Brito, 2010), fine (Ledesma et al., 2014), or clay brick waste (Chaparro, 2012). In some instances, it was found that depending on the quality of the concrete, the mechanical properties of these mixtures are comparable to the ones with natural aggregate, although some durability properties are affected.

Due to the growth of attention for mortars and concretes elaborated with recycled aggregates, some methodologies have been developed and studied, in order to improve their properties. One of these is the process of submitting the recycled aggregates to accelerated carbonation with carbon dioxide (CO_2). This method has proven to be efficient and environmentally friendly, enhancing some properties of the cement paste adhered to the coarse (Shi et al., 2015) and fine (Molano et al., 2015) recycled aggregates.

Tests carried out on recycled aggregates, show that the carbonation treatment increases the compressive strength and the electrical resistivity of the specimens that contain them (Ramezanianpour, Ghahari, & Esmaeili, 2014). The above, is mainly attributed to the production of calcium carbonate ($CaCO_3$) during the reaction between the calcium hydroxide ($Ca(OH)_2$) contained in the cement paste, and the injected carbon dioxide (CO_2). These results encourage the adoption of the carbon capture and storage (CCS) technologies, which can reduce substantially the environmental degradation by safely storing the CO_2 (Sanna, Dri, Hall, & Maroto-Valer, 2012).

Over recent decades, the use of CRA in new concrete mixtures has become very common, especially when considering the improvement of its properties via accelerated carbonation. However, much of the information regarding this topic focuses on concrete, leaving the research on carbonated fine aggregate and its use in mortar mixtures, in the background.

In this set of materials, the behavior of mortar mixtures with carbonated and non-carbonated recycled fine aggregate was evaluated by means of mechanical and durability tests. This study represents a contribution to the field, as it also intends to spread the information and reduce the questions of this subject.

2. Materials and Methods

For this investigation, a special cement for the elaboration of concrete mixtures was used. This cement had a density of 3.07 g/cm³ and a Blaine fineness of 4213 cm²/g. Its chemical composition was determined with the X-ray fluorescence test (XRF) and it was found that it consisted of CaO (61%) and SiO_2 (21%). On the other hand, the physical properties of the NFA, RFA, and CRFA (granulometry, density and absorption) were determined under the guidelines of the ASTM C136-14 and ASTM C128-05 test. The NFA corresponded to river sand, while the RFA was obtained through the crushing of concrete cylinders from the laboratory. The RFA was submitted to accelerated carbonation for a period of 15 days. The carbonation chamber was set with a temperature of 23 °C, RH of 65%, and a CO_2 concentration of 10%. The time of permanence was defined as the necessary for an optimum carbonation. The above, was defined as the point in which there was no notice of a significant variation in the density and the percentage of absorption of the CRFA. The optimum time was 15 days with the mentioned variables of the carbonation chamber.

The variables involved in the elaboration of the mortar samples are shown in Table 1. In total, 5 mixtures with partial replacements of NFA/RFA/CRFA were made. The consideration of the moisture content and the absorption of the sand in a design by volume, allowed the correction of the amount of water. Table 1 also shows the amount of aggregate used in each mixture.

The mortar was designed for a compressive strength of 17.5 MPa, which would classify it as a type M mortar, according to the guidelines of the ASTM C270. A 0% of replacement represents the standard mixture, whereas the values of 25% and 50%, represent the replacement of NFA with RFA and CRFA.

Table 1. *Type and amount of aggregate with mix ratio*

Mixture	Fine Aggregate (kg/m³)		Mixture
	Natural	Recycled	
FA0	1480	FA0	0,65
RFA25	1083	RFA25	
CRFA25	1083	CRFA25	
RFA50	703	RFA50	
CRFA50	703	CRFA50	

With the purpose of identifying $Ca(OH)_2$ before the carbonation treatment, and the synthesis of $CaCO_3$ after the mentioned treatment, the RFA and CRFA were characterized through a Thermogravimetric Analysis (TGA) and the Differential Thermogravimetry Analysis (DTG). This was done at a heating rate of 10 °/min from room temperature, up to 1000 °C.

The mixing process was done following the guidance of the standard ASTM C305-14. The cylinders had a diameter of 45 mm and high of 90 mm. The compressive strength of the specimens was assessed at the curing ages of 3, 28, 90, and 180 days, as specified in the standard ASTM C39.

The physical properties of the mortar samples (density and absorption) were evaluated on specimens with a thickness of 50 mm and a diameter of 100 mm, according to the requirements of the standard ASTM-C642, at the curing ages of 28, 90, and 180 days. Moreover, the initial surface absorption test (ISAT) was determined on 100 x 200 mm cylinders, following the procedures specified in the British Standard BS 1881: Part 208: 1996, at the curing ages of 28, 90, and 180 days, on three specimens for each test date.

3. Results and discussion

3.1 Physical properties of the aggregates

The granulometry of the natural and recycled aggregates is shown in Figure 1.

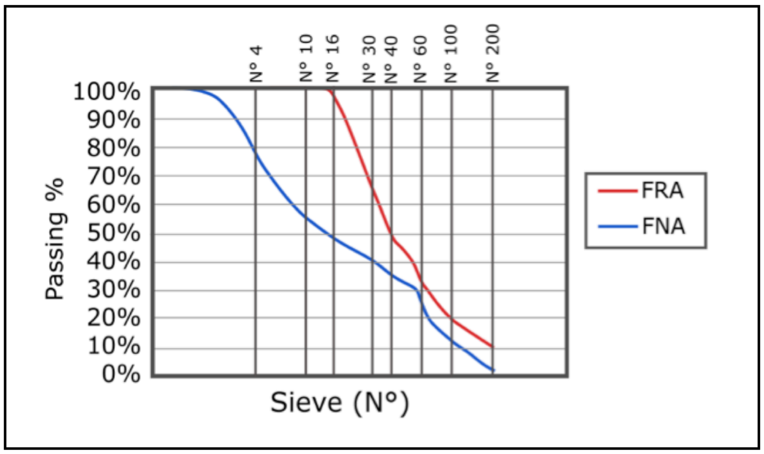

***Figure 1.** Particle size distribution of the NFA and RFA*

The particle size distribution of the RFA evidenced a predominance of fines, with a fineness modulus of 1.77. This is due mostly to the trituration of the concrete. Regarding the NFA, it showed a well-graded curve, as well as a fineness modulus of 3.36.

In respect to the absorption and the bulk and nominal density, the results for each aggregate are shown in Table 2.

***Table 2.** Physical properties of the natural, non-carbonated recycled, and carbonated recycled aggregates*

Property	Fine Aggregate		
	NFA	RFA	CRFA
Absorption (%)	2,10	8,82	7,25
Bulk Density (g/cm³)	2,64	2,20	2,40
Nominal Density (g/cm³)	2,65	2,46	2,67

A difference of 16.7% was found between the bulk densities of the NFA and the RFA, being the RFA the one with the lowest value. This result is attributed to the lower density of the cement paste adhered to the recycled aggregate. Accordingly, this mortar has a greater porosity than the one with natural aggregate, as mentioned by Bojaca (2013). Moreover, the bulk density of the CRFA was the closest one to the NFA value (9.1% lower), as reported by authors such as Molano et al. (2015). This increase in the bulk density is associated with the presence of $CaCO_3$ (calcium carbonate), which is the product of the reaction between $Ca(OH)_2$ and CO_2. The above, because $CaCO_3$ has a molar mass of 218.89 g/mol, which is almost three times the one of $Ca(OH)_2$ (74.09 g/mol). Likewise, the carbonation treatment decreased the absorption of the recycled aggregate from 8.82% to 7.25% which is similar to the result reported by authors such as Zhang et al. (2015). This behavior was attributed to the precipitation of calcium carbonate on the pore structure of the cement paste adhered to the aggregate; which saturates the structure and hampers the flow of water (Bertolini et al., 2014).

3.2 Thermal analysis

Figures 2 and 3 show the thermal analysis of the RFA and CRFA. In relation to the former, three peaks related to a mass loss were observed (Figure 2). These were associated with a moisture loss (50–120 °C), calcium hydroxide breakdown (400-450 °C) and a low consumption of the carbonates of the aggregate (≈ 600 °C). The above concurs with the assessment of BroomField (2006), (Izquierdo et al., 2013).

Similarly, in the CRFA curves, three mass-loss peaks are evident (Figure 3). These were attributed to moisture evaporation (45-107 °C), dehydration of calcium aluminate hydrates (CAH) and of calcium aluminosilicate hydrates (CASH) (200-220 °C). The last process was not evidenced in the RFA, possibly due to the low amount of these compounds in the cement paste of the studied aggregate. Lastly, a greater amount of decomposed calcium carbonate was seen (650-750 °C), which imply a significative conversion from calcium hydroxide ($Ca(OH)_2$) in $CaCO_3$ because of the carbonation process.

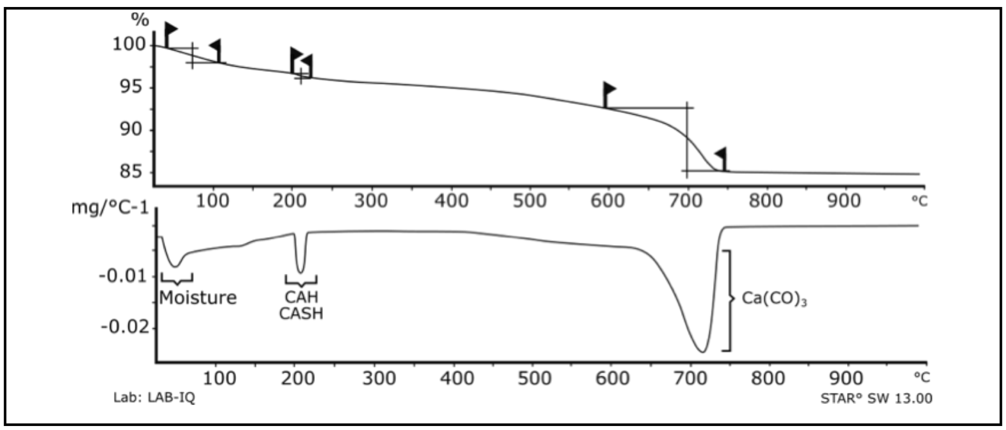

Figure 2. *TGA and DTG curves of the RFA*

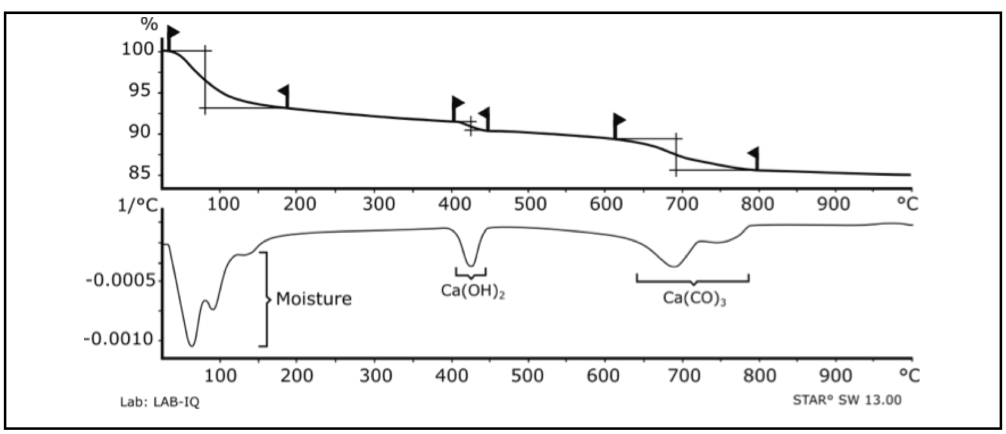

Figure 3. *TGA and DTG curves of the CRFA*

3.3 Absorption of the hardened mortar

The results of the mortars absorption test are shown in Figure 4.

It is evident that all the mixtures exceed the results of the FA0 at 30 and 90 days. This is associated with the greater absorption of the RFA, in comparison to the natural aggregate. This is also evident in the fact that the absorption increased along with the amount of replacement of RFA and CRFA. This behavior turned at day 180, when mixtures RFA25, CRFA25 and CRFA50 presented results equal or lower than the ones of the standard mixture. Concerning the replacement of NFA with RFA and CRFA, a significant difference (+2%) was only found between mixtures with 25% RFA and 25% CRFA. It may be inferred that the effects of the CRFA on the mortar absorption depend more of its granulometry and percentage of replacement, than of its carbonation state.

3.4 Density of the hardened mortar

The density results of the hardened mortars are shown in Figure 5. It is evident that density results for all ages are similar in mortars elaborated with NFA, RFA, and CRFA. This differs from what was expected, which was that the greater density of the CRFA in comparison with the RFA, would be reflected in the mortars density.

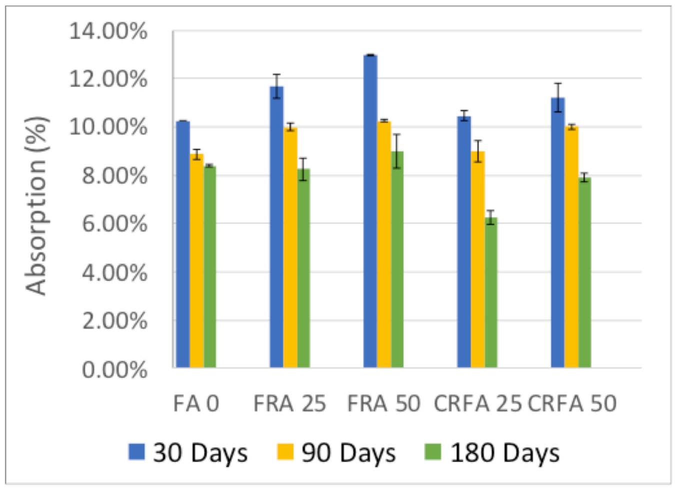

Figure 4. *Mortar absorption*

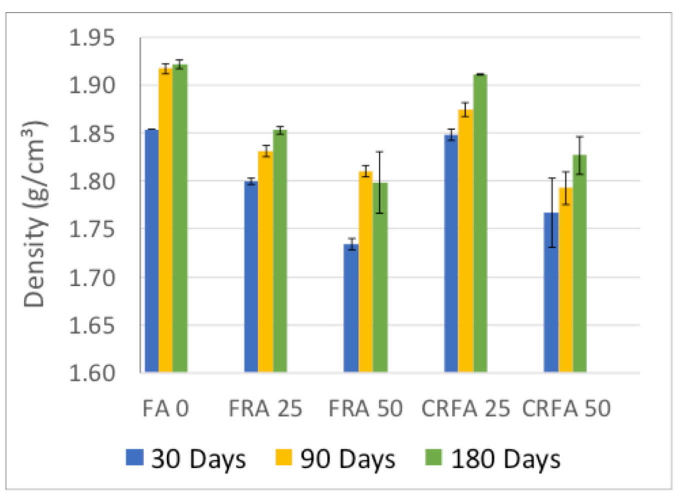

Figure 5. *Mortar density*

3.5 *Compressive strength of mortars*

Overall, the mixtures with RFA showed a pronounced detriment of the compressive strength of the mortar (Figure 6). On the other hand, the mixtures that had CRFA incorporated, showed a similar or slightly lower behavior than the one of the control mixture. The above is evident in the fact that at 180 days, the compressive strength results of the mortars RFA25, RFA50, CRFA25, and CRFA50, were respectively 27%, 24%, 1%, and 5% under the strength of the standard mixture. Therefore, the mixtures with a CRFA addition manage to show compressive strength values near to the ones of the control mixture. This behavior could be related to the greater strength of the calcium carbonate $CaCO_3$ in comparison to calcium hydroxide $Ca(OH)_2$. This has been identified and explained by authors such as Ramezanianpour et al. (2014), who obtained a 22% increase of the strength, when comparing CRFA with NFA.

From these results, it may be inferred that the porosity of the mortar with an RFA addition is not entirely compensated by its filler effect. Moreover, the lower density and greater absorption of the RFA, have a negative impact on its strength. The above refutes the results found by Ledesma et al. (2014), who attributed a strength gain to the filler effect of the fine fraction of the aggregate, which was replaced up to a 10% by recycled aggregate.

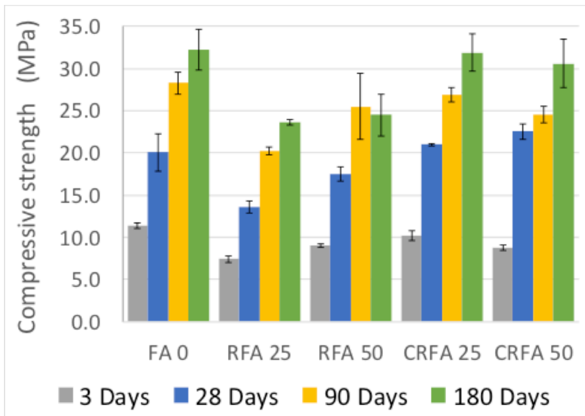

Figure 6. *Compressive strenght of mortars*

3.6 Initial surface absorption test (ISAT)

The results of the ISAT performed on the mortar mixtures after the initial 10 minutes of the test are shown in Figure 7. It is evident that for all the mixtures in every age, the absorption rate increases with the amount of replacement of RFA and CRFA, in respect to the standard mixture. This behavior is attributed to the greater porosity and absorption of these mixtures. Therefore, the replacement of NFA with RFA and CRFA resulted counterproductive regarding its initial absorption rate.

With the obtained results, it is not possible to claim that carbonation of the RFA results in a significative improvement of permeability. The above means that the pore structure of the mortar is not affected noticeably by the carbonation of RFA.

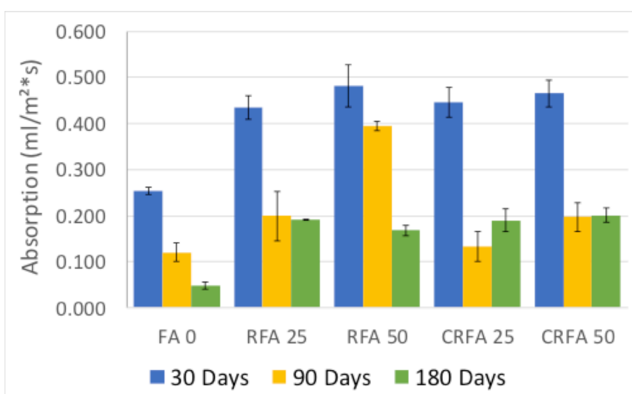

Figure 7. *ISAT of the mortars after the initial 10 minutes of the test*

3.7 Permeability (k) and resistance to penetration (m) (sorptivity)

Figures 8 and 9 show the sorptivity results of the mortars, in terms of their permeability and resistance to penetration, at different curing ages. In general, the addition of RFA and CRFA to the mortars led to greater values of permeability and lower values of resistance to penetration, in respect to the control mixture. This was associated with the higher values of absorption of the RFA and CRFA when compared to the NFA.

It is important to note that mortars with a CRFA addition showed a lower negative effect in permeability and resistance to penetration, than mortars with RFA. This was due to the fact that the precipitation of calcium carbonate on the pore structure of the cement paste during the process of carbonation, causes a saturation of the structure and hampers the flow of water (1et al., 2004).

Moreover, as it was expected, as the curing age increased, all the mixtures lost permeability and gained resistance to the penetration of external substances (water). This is related to the refinement of the pore structure by the hydration products (CSH gel), which leads to a loss of its inside connectivity. The above means that the flow through the big capillaries decreases, forcing the water to flow slowly through the smaller pores of the CSH gel (Garboczi & Bentz, 1999). Therefore, there is a reduction of the effects of the RFA and CRFA on the permeability and resistance to penetration of the mortar.

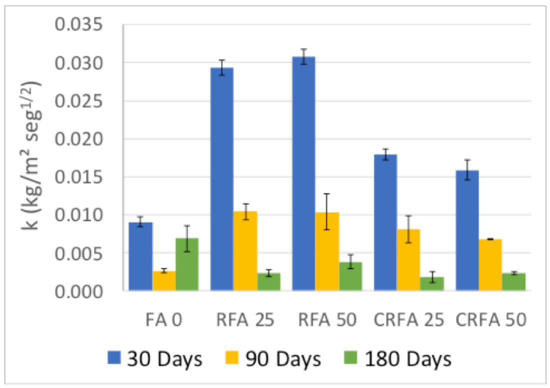

Figure 8. Water permeability values (k) of the mortars

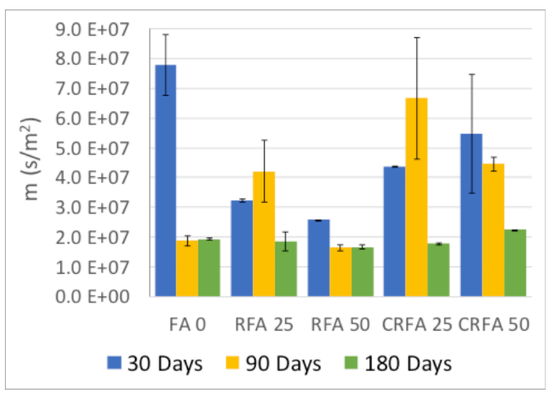

Figure 9. *Resistance to the penetration of water (m) of the mortars*

4. Conclusion

The accelerated carbonation treatment to which the RFA were submitted, proved to be an effective method for the enhancement of the physical properties of the RFA, under the mentioned conditions (10% CO_2, 25 °C, and 65% RH, for 15 days), as it decreases their absorption and increases their density (17.8% and 9.1%, respectively).

It was found the filler effect of the RFA on the pore structure of the mortar does not compensate the loss in compressive strength due to its lower density and greater absorption. However, carbonation treatment showed a noticeable increase in the compressive strength of the mixture. This means the compressive strength of the CRFA mortars was close to the one of the FA mortar.

The improvement of the physical properties of the RFA by means of the carbonation treatment, allows its addition as a partial replacement of NFA in mortar mixtures, in percentages of up to 25% and 50%. This causes a slight detriment on the mechanical and durability properties of the mortars. Thus, from an environmental viewpoint, the use of carbonated recycled fine aggregates as a replacement of natural fine aggregate can become a great alternative for the construction industry.

5. Acknowledgements

The authors would like to thank the Escuela Colombiana de Ingeniería Julio Garavito (Colombia) for the provided support in relation to the financing and the development of this research; in particular with the investigations "Assessment of concrete recycled aggregates through the accelerated carbonation technique" (internal trawl of 2015) and "Durability of concrete elaborated with commercial carbonated recycled fine aggregate from concrete" (internal trawl of 2016).

6. References

ASTM C128 – 05 (2005), Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate. American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2005.

ASTM C270-14a (2014), Standard Specification for Mortar for Unit Masonry. American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2014.

ASTM C305-14 (2014), Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2014.

ASTM C39 / C39M-17b (2017), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2017.

ASTM C642-13, (2013), Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2013.

ASTM C128-15 (2015), Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2015.

ASTM C136-14 (2014), Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM, West Conshohocken, PA, 2014.

Bertolini L., Elsener B., Pedeferri P., Polder R. P. (2014), Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair (Second). WILEY-VCH.

Bojaca N. R. (2013), Propiedades mecánicas y de durabilidad de concretos con agregado reciclado. Escuela Colombiana de Ingenieria Julio Garavito.

BroomField J. (2006), Corrosion of steel in concrete - Understanding, Investigation and Repair (Second). Taylor & Francis.

Chaparro I. A. J. F. (2012), Hacia un desarrollo sostenible en la produccion de concreto a partir de desechos de construccion de mamposteria de arcilla, 1(1), 114.

Evangelista L., De Brito J. (2010), Durability performance of concrete made with fine recycled concrete aggregates. Cement and Concrete Composites, 32(1), 9–14. https://doi.org/10.1016/j.cemconcomp.2009.09.005

Fernández-Jiménez A., Palomo, Á. (2009), Properties and uses of alkali cements. Revista Ingeniería de Construcción, 24(3), 213–232.https://doi.org/10.4067/S0718-50732009000300001

Garboczi E. J., Bentz, D. P. (1999), Computational Simulation and Percolation Theory Applied To Concrete. Annual Reviews of Computational Physics VII.

Geng J., Sun, J. (2013), Characteristics of the carbonation resistance of recycled fine aggregate concrete. Construction and Building Materials, 49, 814–820. https://doi.org/10.1016/j.conbuildmat.2013.08.090

Izquierdo S., Diaz J., Mejía R., Torres J. (2013), Cemento adicionado con un residuo del proceso de craqueo catalítico (FCC): Hidratación y microestructura. Revista Ingenieria de Construccion, 28(2), 141–154. http://dx.doi.org/10.4067/S0718-50732013000200003

Ledesma E. F., Jiménez J. R., Fernández J. M., Galvín A. P., Agrela F., Barbudo A. (2014), Properties of masonry mortars manufactured with fine recycled concrete aggregates. Construction and Building Materials, 71, 289–298. https://doi.org/10.1016/j.conbuildmat.2014.08.080

Mehta P. K., Meryman H. (2009), Tools for reducing carbon emissions due to cement consumption. STRUCTURE Magazine, (January), 11–15. Retrieved from https://www.structuremag.org/wp-content/uploads/2014/08/C-BB-SustainableConcrete_MehtaMeryman-Jan091.pdf

Molano M., Torres N., Molano C. (2015), Evaluacion de los beneficios de la captura de CO2 para el tratamiento de agregados finos reciclados de concreto, como una estrategia para combatir el cambio climatico. Revista de La Escuela Colombiana de Ingenieria, (N° 99), 45–58.

Oikonomou N. D. (2005), Recycled concrete aggregates. Cement and Concrete Composites, 27(2), 315–318. https://doi.org/10.1016/j.cemconcomp.2004.02.020

Ramezanianpour A. A., Ghahari S. A., Esmaeili M. (2014), Effect of combined carbonation and chloride ion ingress by an accelerated test method on microscopic and mechanical properties of concrete. Construction and Building Materials, 58, 138–146.https://doi.org/10.1016/j.conbuildmat.2014.01.102

Sanna A., Dri M., Hall M. R., Maroto-Valer M. (2012), Waste materials for carbon capture and storage by mineralisation (CCSM) - A UK perspective. Applied Energy, 99, 545–554. https://doi.org/10.1016/j.apenergy.2012.06.049

Shi C., Li Y., Zhang J., Li W., Chong L., Xie Z. (2015), Performance enhancement of recycled concrete aggregate - a review. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2015.08.057

Sim J., Park C. (2011), Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. Waste Management, 31(11), 2352–2360. https://doi.org/10.1016/j.wasman.2011.06.014

Zhang J., Shi C., Li Y., Pan X., Poon C. S., Xie Z. (2015), Influence of carbonated recycled concrete aggregate on properties of cement mortar. Construction and Building Materials, 98, 1–7. https://doi.org/10.1016/j.conbuildmat.2015.08.087 .