Use of construction and demolition waste as material as supplementary cementitious material and recycled coarse aggregate in self-compacting concretes

Uso de residuos de construcción y demolición como material cementicio suplementario y agregado grueso reciclado en concretos autocompactantes

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Resumen

En los últimos años, el uso del concreto autocompactante (CAC) ha ido aumentando desde su inicio, debido a la capacidad que tiene para llenar encofrados con alta densidad de aceros, por lo que el empleo de este tipo de concreto en la elaboración de muros delgados armados sería una solución al llenado incompleto de este tipo de elementos prefabricados. Por otra parte, el empleo de residuo de mampostería (RM) y agregado grueso reciclado de concreto (AGR) proveniente de residuos de construcción y demolición (RCD) como reemplazo del cemento (20 % en volumen) y del agregado grueso, respectivamente, daría un enfoque sostenible al concreto autocompactante. El objetivo de este estudio fue evaluar la influencia de los RCD en las propiedades en estado fresco (flujo de asentamiento, embudo en V y caja en L) y estado endurecido (resistencia a la compresión, tracción indirecta y compresión diagonal de muretes) de concretos autocompactantes. Las mezclas de CAC propuestas muestran que cuando se sustituye el cemento Portland y el agregado natural por RM y AGR, respectivamente, los concretos pueden satisfacer los requerimientos de las directrices europeas de European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC por sus siglas en inglés). En estado endurecido, los CAC con RCD lograron un desempeño aceptable en comparación con la mezcla de referencia (CAC-referencia). Todas las mezclas lograron una resistencia a la compresión superior a los 21 MPa (28 días), adecuada para muros divisorios de casas, de acuerdo con el Reglamento Colombiano de Construcción Sismo Resistente (NSR 10).

Palabras clave: concreto autocompactante; residuo de mampostería; agregado grueso reciclado, resistencia a la compresión; muretes.

Abstract

In recent years, the use of self-compacting concrete (SCC) has been increasing since its inception, due to the capacity it has to fill formworks with high steel density, so the use of this type of concrete in the production of reinforced thin walls would be a solution to the incomplete filling of this type of precast elements. On the other hand, the use of masonry waste (MR) and recycled coarse aggregate concrete (RCA) from construction and demolition waste (CDW) as a replacement for cement (20 % in volume) and coarse aggregate, respectively, would provide a sustainable approach to self-compacting concrete. The objective of this study was to evaluate the influence of CDW on the fresh state properties (settling flow, V-funnel, and L-box) and hardened state (compressive, indirect tensile, and diagonal compressive strength of walls) of self-compacting concretes. The proposed SCC mixtures show that when Portland cement and natural aggregate are replaced by MR and AGR, respectively, the concretes can satisfy the requirements of the European guidelines of the European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC). In the hardened state, the SCCs with CDW achieved an acceptable performance compared to the reference mix (SCC reference). All mixes achieved a compressive strength higher than 21 MPa (28 days), suitable for house partition walls, according to the Colombian Seismic Resistant Construction Regulation (NSR 10).

Keywords: self-compacting concrete; masonry residue; recycled coarse aggregate, compressive strength; low walls.

1. Introduction

Currently, in the construction of buildings and civil infrastructure, the use of precast concrete elements and the use of self-compacting concrete (SCC) have become very common, due to the different advantages that its use promotes, such as the reduction of time on-site and greater quality control (Wang; Kim; Cheng; Sohn, 2016; Han; Song; Liu; Huang 2019; Duan; Singh; Xiao; Hou, 2020). However, the use of construction and demolition waste (CDW) in precast elements or in the preparation of concrete structures has become essential (Nibhanupudi; Rahul, 2020), since the use of CDW allows to reduce the impact of these wastes on the environment and health, as well as improving the efficiency of available natural resources (González; Gayarre; Pérez; Ros; López, 2017). It is estimated that more than 25 billion tons of concrete are produced in the world, which is equivalent on average to 1 m^3 per person (Amer; Ezziane; Bougara; Adjoudj, 2016), and at the same time 10 billion tons of CDW worldwide, of which the United States contributes approximately 700 million tons, China contributes about 2.3 billion tons, and the European Union more than 800 million tons (Wu; Zuo; Zillante; Wang; Yuan, 2019).

An alternative solution to the problem generated by construction and demolition waste and the high demand for natural resources is the use of these wastes as aggregates in the production of concrete (Andal; Shehata; Zacarias, 2016; Ahmed; Tiznobaik; Huda; Islam; Alam, 2020; de Brito-Prado Vieira; de Figueiredo; John, 2020). The hardened concrete is crushed and processed to produce recycled aggregate concrete (RAC). Currently, RACs are used as a base and sub-base material, granular filler, and for the preparation of concrete and asphalt (Butler; West; Tighe, 2012; Tam; Soomro; Evangelista, 2018; Maduabuchukwu; Yap; Onn; Yuen; Ibrahim, 2020). The use of RAC helps to mitigate the deposition of CDW, which contributes to the preservation of the environment, in addition to reducing construction costs, since when these are used directly on the job site, it helps to minimize the costs of transportation, saving their final disposal in landfills, land reclamation, reduction of deforestation and extraction of natural aggregates from river beds, lakes and other sources that generate environmental problems (Boudali; Kerdal; Ayed; Abdulsalam; Soliman, 2016; Asutkar; Shinde; Patel, 2017; Ahmed et al., 2020). The use of recycled aggregates has been increasing, due to the importance of a sustainable development of the construction sector. Numerous investigations have been carried out on the potential use of recycled aggregates in the preparation of concrete, finding positive results (Poon; Chan, 2007; Kou; Poon; Wan, 2012; Xiao; Ma; Ding, 2016; Silva; Robayo; Mattey; Delvasto, 2016; Wang et al., 2017).

Construction and demolition waste has a varied composition, the vast majority of which are made up of concrete (around 40 %) and ceramics (around 30 %) (Oikonomou, 2005; Ozal; Yılmaz; Kara; Kaya; Şahin, 2016). Ceramic materials include fired clay brick residues that are generally mixed with Portland cement-based adhesive mortar (masonry residue- MR); this type of waste is generated in large quantities and its reuse is possible as a filler or as a supplementary cementitious material if it shows pozzolanic activity. The use of MR or hybrid powder from CDWs has been studied very little. However, satisfactory results have been obtained (Silva; Robayo; Mattey; Delvasto, 2015; Zhu; Mao; Qu; Li; John, 2016; Li; Lin; Chen; Kwan, 2020). The use of this material as a supplement to Portland cement is a great alternative and even more so when it is used in the preparation of self-compacting concretes (SCC), since this type of composite material allows the use of large amounts of filler or additions.

The SCC was developed in Japan in the late 1980s, due to the problems that occurred in highly reinforced structures, in addition to the problems in the emptying of the concrete when vibrated by inexperienced operators and generated inconveniences in the mixture. SCCs have plenty of advantages, such as shorter construction times, greater design freedom, easy filling in elements or densely reinforced structures without vibration, improvement in the work environment, and excellent surface finishing (Khayat; Hu; Monty, 1999; Sun; Chen; Xiao; Liu, 2020; Surya; Venkateswara, 2020).

This research project aims to facilitate the comprehensive use of masonry waste and recycled aggregate from CDWs. The workability of self-compacting concrete is of great importance, so fluidity, filling capacity and passing ability were evaluated by means of the Abrams cone slump flow tests, the V-funnel, and L-box tests, respectively. In their hardened state, mechanical properties, such as resistance to compression, indirect traction in cylinders, and diagonal compression in walls, were evaluated to determine their mechanical performance and possible applications in homes with the developed SCCs.

2. Experimental schedules

2.2. Materials

Portland Argos® general purpose cement, river sand, natural crushed gravel, masonry residue (MR) from wall demolition, and recycled coarse aggregate concrete (RCAC) from renovations at Universidad del Valle (Figure 1) were used for the preparation of SCCs. The natural coarse aggregate (NCA) and recycled (RCCA) were adapted with a maximum size of 12.7 mm for use. The masonry residue was subjected to a two-stage milling process. In the first instance, the MR was carried out with a size reduction using a jaw crusher and then in a ball mill, where a mean particle size of 26.6 μm was obtained. Also, the resistance activity index (RAI) was evaluated according to ASTM C618, where the MR presented a value of 82.6 %, being mechanically suitable as a pozzolanic material, since it surpassed the established limit (75 %). For the RCCA, a manual crushing was carried out using a baton and after that, it was passed through a jaw crusher with an adequate opening to obtain a maximum size of 12.7 mm, and thus meet one of the requirements set forth in the EFNARC for the production of SCC (EFNARC, 2002). A state-of-the-art SikaPlast MO superplasticizer (SP) was used to achieve adequate workability. The chemical composition of Portland cement and MR are shown in Table 1.

Figure 1. (a) Residue of masonry and (b) Residue of concrete
Source: own elaboration.

Table 1.
XRF analysis of Portland cement (OPC) and masonry residue (MR)

Oxide / element	OPC (% by mass)	MR (mass%)
SiO_2	19.13	54.09
TiO_2	0.26	0.88
Al_2O_3	4.42	15.51
Fe_2O_3	4.32	9.84
Mn_3O_4	0.03	-
MgO	1.6	3.50
CaO	57.7	8.73
Na_2O	NA	1.93
K_2O	0.28	1.30
P_2O_5	0.17	0.20
SO_3	2.32	-
LOI	9.78	3.47

N.D: not determined LOI: Loss to fire
Source: own elaboration.

The particle size distribution of the aggregates is evidenced in Figure 2. The sand has a fineness modulus of 2.55 while the coarse aggregates (NCA and RCCA), a maximum size of 12.7 mm. In Figure 2, it can also be seen that RCCA presents a greater fineness than NCA, which would mean a greater demand for water, due to a greater surface area. On the other hand, Table 2 shows that RCCA presents an absorption of 7.28 % due to the adhered mortar that gives it greater porosity, which is greater than that presented by NCA. The loss of workability due to the higher demand for water in SCCs with RCCA was corrected by using a higher dose of superplasticizer (SP), to keep the water/cementing ratio constant. The Los Angeles Coefficient presented by the coarse aggregates was 16.39 % and 33.65 % for the NCA and RCCA, respectively, which indicates that they are acceptable for the preparation of concretes, since the Los Angeles Coefficient did not exceed 50 % (ASTM C33).

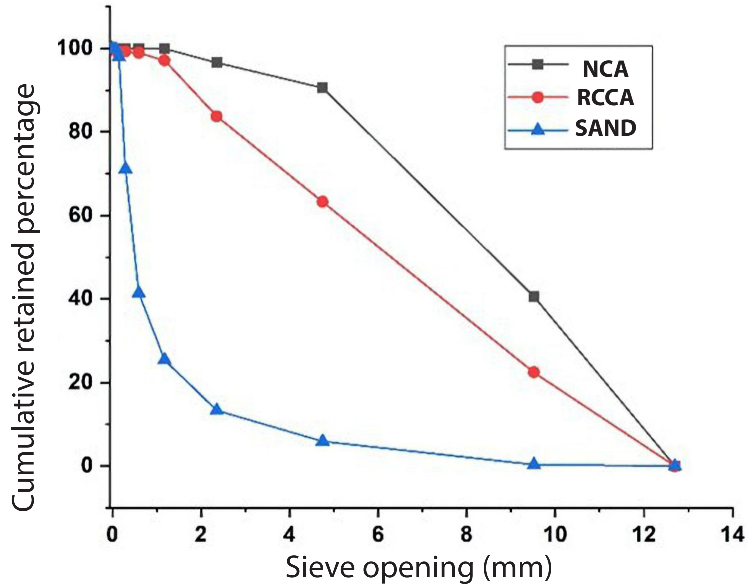

Figure 2. Aggregate particle size distribution for CCS mixtures
Source: own elaboration.

Table 2.
Characteristics of the aggregates used for CCS mixtures

Test	Regulation	Sand	NCA	RCCA
Apparent Density (Bulk)	NTC 237	2.57 g/cm3	2.54 g/cm3	2.26 g/cm3
Absorption	NTC 237/176	1.97%	2.01%	7:28
Loose Unit Mass	NTC 92	1.59 g/cm3	1.47 g/cm3	1.26 g/cm3
Compact Unit Mass	NTC 92	1.69 g/cm3	1.49 g/cm3	1.46 g/cm3
Fineness modulus	NTC 77	2.55	6.38	5.65
Organic Impurities	NTC 127	Color No. 3	-	-
Maximum Size	NTC 77	-	12.7 mm	12.7 mm
Los Angeles coefficient	ASTM C131	-	16:39	33.65 %

Source: own elaboration.

2.3. Mixing ratios

The mixed design of all SCCs in this study is presented in Table 3. The water content was kept constant at 225 kg/m^3 as well as the volume of cementitious (fines) at 16.1 %, and before the mixing process, the moisture correction of the aggregates was carried out. A control mix with 100 % OPC (SCC-reference) and natural aggregates, and three mixes of SCC with material from CWD as a partial replacement for OPC and/or NCA, were produced. The SCC with a 20 % replacement of OPC by MR was called SCC-20% MR, and the mixture they presented replaced in a volume of 10 % and 59 % of RCCA by NCA (the selection of this last percentage of RCCA was carried out according to a previous investigation by Silva; de Brito; Dhir (2015) and (Silva et al., 2016), they were called SCC-20% MR-10% RCCA and SCC-20% MR-59% RCCA, respectively. To satisfy the workability requirements of the European Project Group (EPG, 2005) to produce SCCs, the amount of SP was adjusted in a range of 4.99-5.79 kg/m^3.

Table 3.
Proportions of SCC mixtures

	SCC Reference	SCC-20 % MR	SCC-20% MM-10 % RCCA	SCC-20 % MR-59 % RCCA
MATERIAL	Proportions kg/m^3	Proportions kg/m^3	Proportions kg/m^3	Proportions kg/m^3
Cement (OPC)	500	400	400	400
MR	-	83.5	83.5	83.5
NCA	623.52	623.52	561.18	252.54
RCCA	-	-	55.48	323.46
Sand	946.34	946.34	946.34	946.34
Water	225	225	225	225
W/C ratio	0.45	0.45	0.45	0.45
SP additive	4.99	5.37	5.39	5.79

Source: own elaboration.

2.4. Workability

The fresh tests were carried out in accordance with the European specifications and guidelines for self-compacting concretes (EFNARC, 2002). The test results were compared with the EPG (2005). The tests that were carried out to measure the workability of the concretes were: the settlement flow test with the Abrams cone, the resistance to segregation by means of the V-funnel test, and the ability to pass through the L-box. All tests were carried out 8 minutes after starting the mix to avoid any loss of workability.

2.5. Tests in hardened state

The compressive strength was carried out on cylindrical specimens of 76.2 mm diameter and 152.4 mm high at different curing ages (28, 60, and 90 days) according to ASTM C39, and using an international ELE hydraulic press of 1000 KN capacity.

The indirect tensile strength was measured on 76.2 mm diameter and 152.4 mm high cylinders, after 28, 60, and 90 days of curing, according to the ASTM C496 specifications.

The diagonal compression test was performed on 400 mm x 400 mm x 90 mm walls in accordance with ASTM E519. The elements were cured underwater for a period of 28 days, during which time the strength was evaluated. Prior to the test, the walls were rotated 45 degrees to rest on the bottom corner and the vertical load could be applied to the top (opposite) corner.

3. Results and discussion

3.1. Workability

Table 4 shows the results obtained from the different mixtures in the fresh state. The settlement flow (SF) of all SCCs surpasses the lower limit (550 mm) established by the EPG (EPG, 2005). The greater the settlement flow, the greater the deformability of the material, indicating the mixture's capacity to reach a distant area from the point of the concrete's insertion (Manzi; Mazzotti; Bignozzi, 2017). The mixtures with RCCA showed SF values higher than the reference SCC, which is attributed to the slightly higher amount of superplasticizer (SP) used in these two mixtures. The reference SCC with 10 % and 59 % RCCA according to this test (settlement flow), is classified as SF1, suitable for unreinforced or slightly reinforced structures and castings by pumps and small sections where the horizontal flow is not prolonged. On the other hand, SCC with 20 % MR is classified as SF2, appropriate for various applications such as walls and columns (EPG, 2005).

The V-funnel test allows evaluating the viscosity and filling capacity, finding that the presence of MR and a higher dose of SP in the SCC generated a shorter flow time; however, when the SCC with MR presented in its dosage RCCA, the flow time in the V-funnel increased, which was attributed to the greater roughness and angularity (Santos; da Silva; de Brito, 2019). The mixtures are classified according to this test as VF1, indicating that all SCCs have a good filling capacity (EPG, 2005). The L-box test assesses the ability of concrete to pass through reinforcements. It was found that the throughput index (H2/H1), which is the ratio of heights of the horizontal (H2) and vertical (H1) section, decreases as the RCCA content increases. However, values within the acceptability range (≥ 0.80) were obtained, according to the EPG and are classified as PA2 (EPG, 2005). The mixtures showed good performance in their fresh state.

Table 4.

Results of workability tests of SCC mixtures

Test	SCC Reference	SCC-20% MR	SCC-20% MR-10% RCCA	SCC-20%-59% RCCA
Settling flow (mm)	600	660	640	630
L box (H2/H1)	0.80	0.85	0.83	0.82
V-funnel (s)	3.84	3.31	3.63	3.52

Source: own elaboration.

3.2. Compressive strength

The compressive strength results of the SCC mixtures are presented in Figure 3. In general, the mixtures at different curing ages that contained CDW in their composition showed a decrease in compressive strength. A decrease of the order of 12.3 % in the compressive strength at 28 days of curing was observed when 20 % of OPC was replaced by MR in that same period, being congruent with the IAR presented by the MR at 28 days, where the resistance to compression of the mortar with MR decreases compared to the reference mortar. At 90 days of curing, the decrease was 10.2 % for the mixture with MR compared to the reference SCC. This reduction is attributed to the moderate pozzolanic effect that the masonry residue presents, being similar to the behavior reported by other authors (Malhotra; Mehta, 1996; Schackow; Stringari; Senff; Correia; Segadães, 2015). It is likely that SCC 20 % MR developed a resistance similar to reference SCC at longer curing periods, this attributed to the fixation of portlandite (calcium hydroxide) and the active phase of the MR. Therefore, the fall in resistance at early ages can be compensated by the pozzolanic activity of the MR that will be improved at long curing ages (Naceri; Hamina, 2009).

On the other hand, the SCC-20% MR with replacements of 10 % and 59 % of RCCA by NCA presented a reduction in compressive strength of 14.3 % and 34.9 %, respectively, which is attributed to the bonded mortar to recycled aggregate that presents a weak porous structure that affects the failure mode of concrete, in addition to the poor adherence between the bonded mortar and the recycled aggregate (Behera; Bhattacharyya; Minocha; Deoliya; Maiti, 2014). On the other hand, the influence of RCCA with respect to mechanical action also depends on the level of replacement (Ajdukiewicz; Kliszczewicz, 2002; McNeil; Kang, 2013); as it can be seen, the lower performance was presented by the SCC with 59 % of RCCA, in relation to the SCC that had 10 % RCCA in its composition. Another factor that influences the compressive strength is the interfacial transition zone (ITZ), since the old ITZ governs the strength of concrete when the mix has a low water/cementitious ratio. Additionally, the ITZ is one of the weakest areas in concrete and when RCCA is used, the new concrete will feature an old and a new interface area (Figure 4).

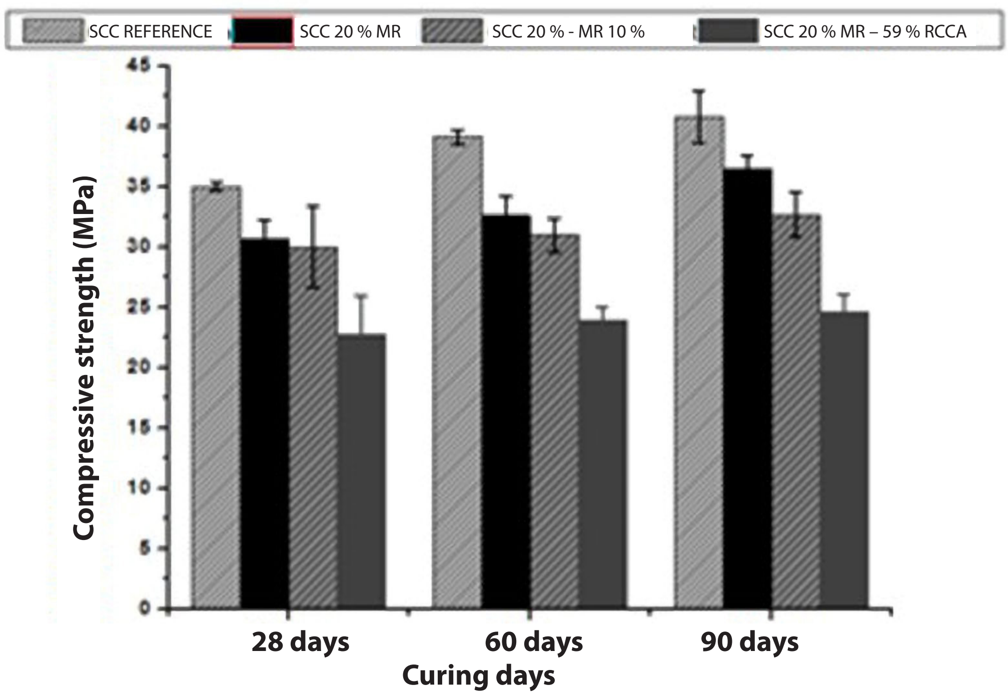

Figure 3. Compressive strength of SCC mixtures
Source: own elaboration.

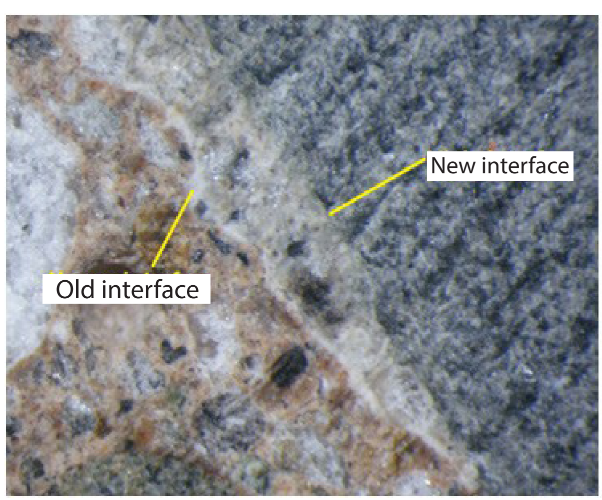

Figure 4. Section view of the old and new ITZ of the SCC 20% MR with RCCA
Source: own elaboration.

3.3. Indirect tensile strength

The compressive and tensile strength are properties of concrete that must be known for the design of structures. In some practical applications, such as unreinforced concrete structures, structures under seismic load, pavements, and slabs, the value of the tensile strength is even more important than the compressive strength (Zain; Mahmud; Ilham; Faizal, 2002). According to the available information, indirect tensile strength is another property that is affected by the presence of recycled aggregate (Khoshkenari; Shafigh; Moghimi; Mahmud, 2015; Silva et al., 2015). Figure 5 shows the indirect tensile strength of SCCs at 28, 60, and 90 days of curing. All the mixtures with CDW presented a lower resistance to indirect traction compared to the reference SCC, which is more notable in the mixture with a higher amount of RCCA (SCC 20% MR-59 % RCCA), where there is a reduction of 25.2 % of this property at 28 days of curing. This behavior is attributed to the presence of higher porosity and lower resistance of RCCA. Also, McNeil; Kang (2003) mention in their review research that the mortar adhered in the recycled aggregate is responsible for the decrease in the indirect tensile strength (McNeil; Kang, 2013).

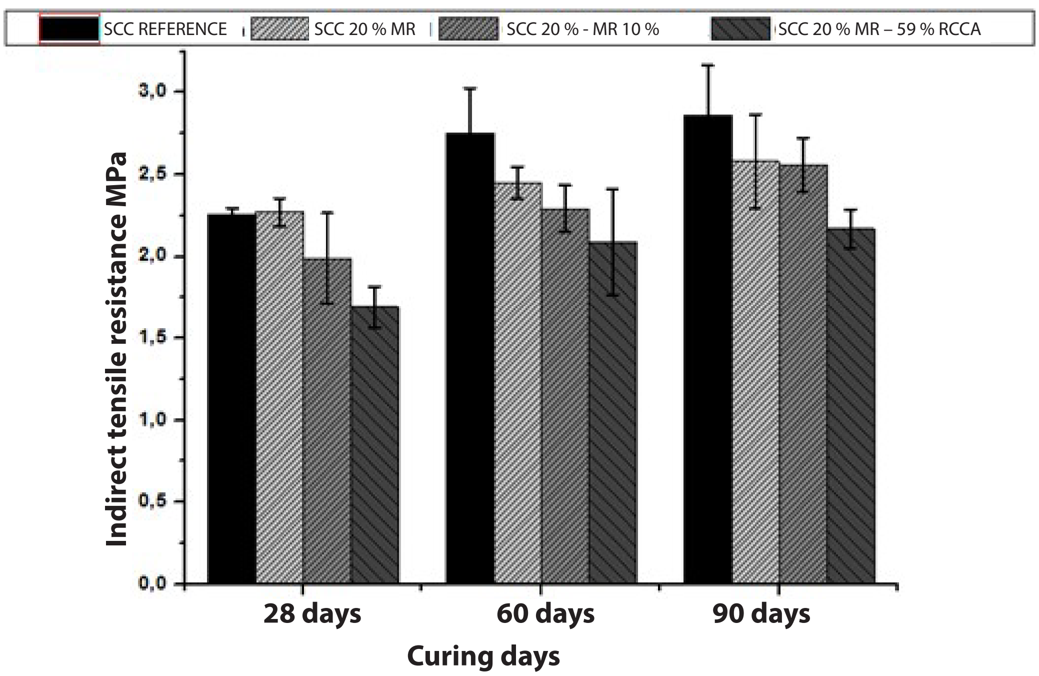

Figure 5. Indirect tensile strength of CCS mixtures
Source: own elaboration.

3.4. Diagonal compressive strength of walls

The determination of the diagonal compressive strength of the walls was carried out 28 days after curing, in which three samples were used for each type of mixture. Figure 6 shows the assembly carried out for the execution of the test. Figure 7 shows the maximum applied load values of each of the SCC mixtures. Regarding the performance of the walls, the typical associated failure is caused by the loss of geometric stability of the wall due to pressure exerted, generating excessive deformations in the last state (Golondrino; Bonilla; Gaviria; Giraldo, 2008). Like the resistance to compression and indirect traction, this resistance is affected by the presence of CWD, either as a replacement for OPC or natural aggregate, presenting a decrease in performance. The SCC 20 % MR presented a loss of resistance of 4.53 % and the SCCs with 10 % and 59 of RCCA showed a lower performance of 6.05 % and 15.41 %, respectively, compared to the reference wall.

Figure 6. Test carried out on SCC walls
Source: own elaboration.

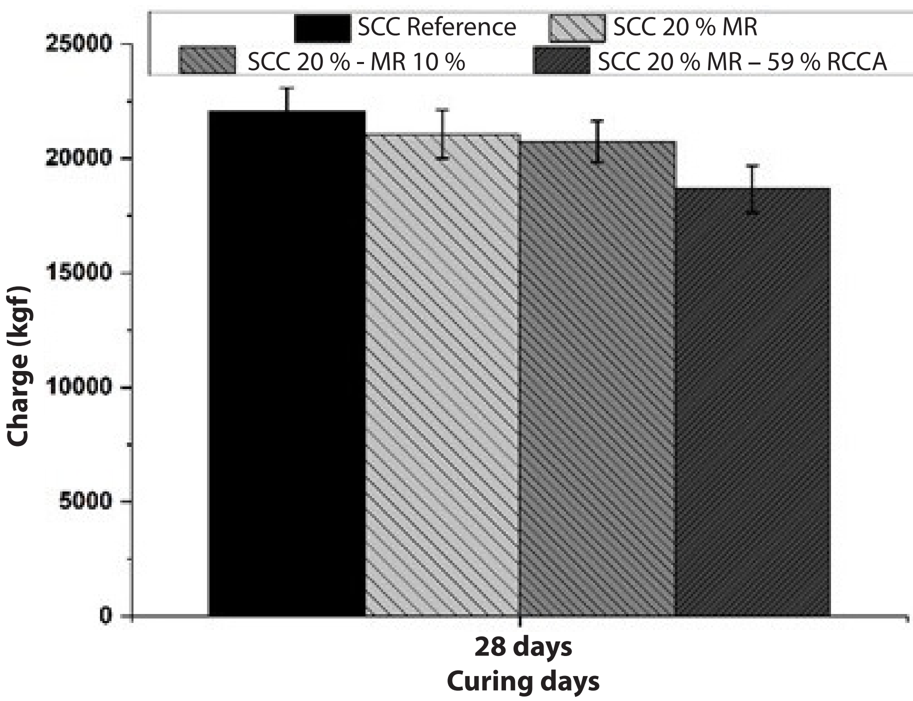

Figure 7. Maximum load applied to walls of SCC
Source: own elaboration.

4. Conclusions

Based on the results of the fresh and hardened properties of SCCs with MR as the material supplemental cementitious and RCC as AGN, the following conclusions are considered:

The use of masonry residue in the production of self-compacting concrete as a partial substitute for cement is technically feasible because the SCCs where there was the presence of MR met the workability requirements, such as adequate fluidity, good filling capacity, and passing capability. In addition, in the hardened state, the SCCs with MR showed acceptable mechanical properties such as compressive strength, which exceeded the minimum strength (21 MPa), according to NSR-10 Title C for concrete structures with DMO and DES capacity.

At long curing ages (90 days), the SCC with MR generated a greater resistance gain compared to the reference SCC.

The use of recycled coarse aggregate affects the workability of self-compacting concrete, due to its morphology and greater absorption capacity, for which greater use of superplasticizer additive must be made to counteract this effect on the properties in its fresh state.

The resistance to compression, indirect traction and diagonal compression of walls is affected by the use of construction and demolition waste when the recycled coarse aggregate (RCCA) is used an addition (MR) and/or as natural aggregate the recycled coarse aggregate (RCCA), presenting a greater loss of this property when the amount of RCCA is greater.

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