RESEARCH ARTICLE / ARTÍCULO DE INVESTIGACIÓN
https://dx.doi.org/10.14482/inde.43.02.777.362

Mechanical Behavior of Concretes with Total Replacement of Natural Coarse Aggregate from Construction and Demolition Waste

Comportamiento mecánico de concretos con sustitución total de agregado grueso natural a partir de residuos de construcción y demolición

Robinson Rua-Patiño*
Juan Ospina-Correa**
Francisco Campillo-Machado***

* Ingeniar Research Group, Faculty of Engineering, Corporación Universitaria Remington (Colombia). Center for Seismic Projects and Research, Faculty of Mines, Universidad Nacional de Colombia, Professor. Civil Engineer. M.Sc.
Orcid-ID: https://orcid.org/0000-0003-0431-8625. robinson.rua@uniremington.edu.co

**Ingeniar Research Group, Faculty of Engineering, Corporación Universitaria Remington (Colombia). Department of Materials and Nanotechnology, Faculty of Mines, Universidad Nacional de Colombia, Professor. Materials Engineer. Ph.D.
Orcid-ID: http://orcid.org/0000-0003-0945-2188. juan.ospina@uniremington.edu.co

***Ingeniar Research Group, Faculty of Engineering, Corporación Universitaria Remington (Colombia), Head of the Civil Engineering Program. Civil Engineer, MBA.
Orcid-ID: http://orcid.org/0009-0000-3232-9861.
francisco.campillo@uniremington.edu.co.

Correspondence: Robinson Rua Patiño. Carrera 51 n.° 49-59, Tower 2, Medellín (Colombia).
Cell phone : 3002974300.

Abstract

The reuse of construction and demolition waste (CDW) in concrete has been widely researched, but concerns remain regarding its impact on mechanical performance. This study investigates the compressive strength of concrete made with recycled coarse aggregates. The mixtures were designed according to ACI-211.1-91, completely replacing natural coarse aggregate with CDW, using a 3:1 ratio of brick to recycled concrete, in sizes of 3/8" and 1". Various water-cement ratios (0.5 - 0.6 - 0.7) were evaluated. The results indicate that the 3:1 ratio with a 3/8" size and a water-cement ratio of 0.5 improves compressive strength by 33% compared to previous studies. This increase in strength suggests that the use of CDW can produce concrete suitable for structural elements, contributing to the development of more sustainable concrete without compromising mechanical performance. The findings of this study open new possibilities for using concrete with 100% replacement of natural aggregates by CDW while maintaining functional compressive mechanical performance.

Keywords: compression stress, light concrete, recycled coarse aggregates, recycled concrete, total replacement of aggregates.

Resumen

La reutilización de residuos de construcción y demolición (RCD) en concretos ha sido ampliamente investigada, pero persisten preocupaciones sobre su impacto en la respuesta mecánica. Este estudio investiga la resistencia a la compresión de concretos fabricados con agregados gruesos reciclados. Las mezclas se diseñaron de acuerdo con ACI-211.1-91, reemplazando completamente el agregado grueso natural por RCD, utilizando una relación de 3:1 entre ladrillo y concreto reciclado, en tamaños de 3/8" y 1". Se evaluaron diferentes relaciones agua-cemento (0,5 - 0,6 - 0,7). Los resultados indican que la relación 3:1 con un tamaño de 3/8" y una relación agua-cemento de 0,5 mejora la resistencia a la compresión en un 33% en comparación con estudios previos. Este incremento en la resistencia sugiere que el uso de RCD puede producir concretos para el uso de elementos estructurales, contribuyendo al desarrollo de concretos más sostenibles sin comprometer el desempeño mecánico. Los hallazgos de este estudio abren nuevas posibilidades del uso de concretos reemplazados con el 100 % de agregados naturales por RCD, con respuesta mecánica a la compresión funcional.

Palabras clave: agregados gruesos reciclados, concretos livianos, concretos reciclados, esfuerzo de compresión, sustitución total de agregados.

Fecha de recepción: 9 de julio de 2024
Fecha de aceptación: 13 de diciembre de 2024

INTRODUCCIÓN

The construction industry, continuously expanding due to the growing demand for housing and infrastructure, has a significant environmental impact, primarily due to the carbon footprint associated with its manufacturing processes [1], [2]. Among these, concrete production stands out as particularly polluting, accounting for 8% of global anthropogenic emissions in 2020, with an estimated consumption of 26 billion metric tons annually [3], [4], [5].

Like other materials used in construction projects, concrete generates large volumes of construction and demolition waste, which accounts for up to 30% of solid waste generated worldwide [6], [7]. To reduce this impact, various strategies have emerged to increase sustainability in construction projects, including the use of recycled aggregates from CDW. This strategy has gained relevance in recent decades, highlighting the possibility of manufacturing concrete with partial or total replacement of natural coarse aggregates by CDW [8], [9], [10], [11]. This approach aims to reduce the exploitation of natural resources, such as aggregates extracted from alluvial deposits, which have a significant environmental impact [12], [13], [14].

Previous studies have extensively investigated the use of construction and demolition waste as a partial or total replacement for natural coarse aggregates in concrete mixtures, with results that raise serious doubts about its viability in terms of compressive strength. E. Santiago et al. [15] showed that using a mixture of recycled brick ceramic and ethylene vinyl acetate (EVA) aggregates as partial substitutes for natural aggregates can increase compressive strength under specific conditions, such as 50% replacement. However, as the proportion of recycled aggregates increases, strength tends to decrease significantly. In cases where 25% of the aggregates are replaced with brick and 25% with EVA, compressive strength is reduced by more than 40%. Furthermore, J.S. González et al. [16], [17], [18] analyzed the impact of partially replacing natural coarse aggregates with recycled brick aggregates, finding that as the replacement increased from 35% to 70%, compressive strength decreased considerably. It was also observed that when using a heterogeneous mixture of CDW, compressive strength is even more affected, especially when 100% of the natural aggregates are replaced by CDW [19], [20]. This total replacement can reduce strength by up to 30%, casting doubt on the applicability of these concretes in structures requiring high mechanical performance.

The studies mentioned highlight a consistent pattern: the compressive strength of concretes with CDW decreases as the level of replacement of natural aggregates increases, especially when it approaches or reaches 100% [21], [22]. This loss of strength has been mainly attributed to the porous nature of CDW, which absorbs more water than natural aggregates, significantly altering the water-cement ratio of the mixture and affecting the quality of the final product [23]. Due to the inherent porosity and variability of CDW, the interaction between the components of the mixture is compromised, limiting its ability to achieve the necessary density and cohesion to efficiently support compressive loads [24], [25]. Therefore, the use of CDW in concretes has been considered problematic from a mechanical performance perspective, leading many researchers to question its use in structural applications that require high levels of compressive strength.

This study aims to explore new alternatives to improve the mechanical performance of concretes made with recycled aggregates, addressing the limitations observed in previous research. To this end, a combination of CDW with a 3:1 ratio of recycled brick to recycled concrete has been proposed to evaluate whether this ratio can mitigate the negative effects and improve compressive strength. Additionally, this study focuses on identifying the effects of different water-cement ratios (0.5 - 0.6 and 0.7) on the strength of these mixtures to optimize their design to maximize compressive strength and reduce the deficiencies observed in previous studies. It is expected that the results of this work will contribute to the development of more sustainable concretes that can be used in structural applications, minimizing the carbon footprint without compromising mechanical performance. Furthermore, this research aims to provide a more robust methodological approach to evaluate and overcome the limitations associated with the use of CDW, offering a viable solution for the construction industry in terms of sustainability and structural performance.

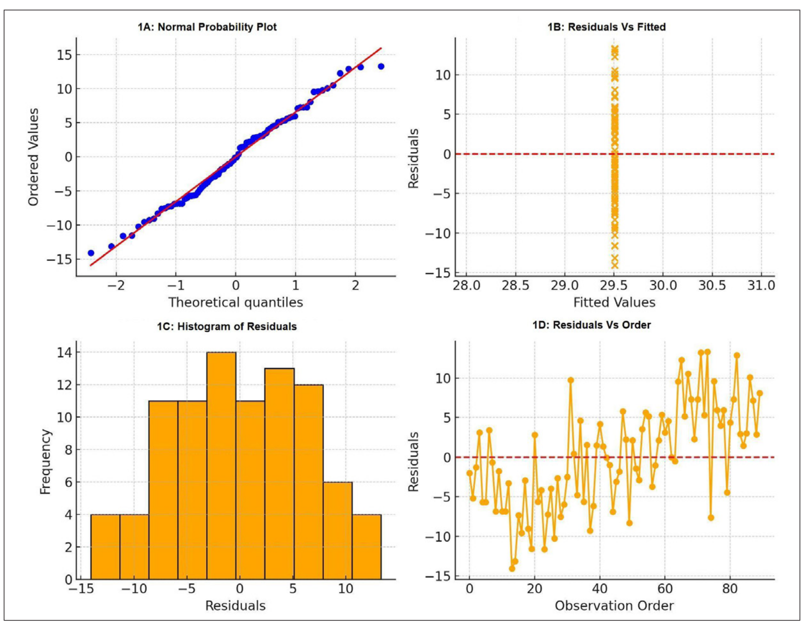
METHODS

Statistical Analysis

For this study, a combined factorial statistical model was designed to evaluate the compressive strength of concrete made with recycled aggregates from construction and demolition waste. The experimental design included two main factors: the coarse aggregate size, with levels of 1” and 3/8”, and the water-cement ratio, with levels of 0.5 - 0.6, and 0.7. Each factor combination was evaluated with three independent replicates, resulting in 18 experimental observations. This design allowed for the calculation of an experimental error with 10 degrees of freedom, ensuring the statistical robustness of the model. Statistical analysis was performed using a significance level of $\alpha = 0.05$, and the proposed factorial model explained 95.9% of the variability in compressive strength ($R^2 = 0.959$). Additionally, interactions between the main factors were evaluated, showing that specific combinations, such as aggregate size and water-cement ratio, significantly influence the results. To ensure homogeneous conditions, variables such as sample geometry, curing times, cement type, fine aggregate, and curing temperature were kept constant, ensuring the reliability and reproducibility of the data [26], [27].

The mathematical model for the factorial design is $Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}$, where Y_{ijk} is the compressive strength, μ is the overall mean, α_i and β_j represent the effects of aggregate size and water-cement ratio, and $(\alpha\beta)_{ij}$ is the interaction between these factors [28]. Replicated tests on multiple specimens confirmed the repeatability and reproducibility of the results. This analysis identified significant interactions between aggregate size and water-cement ratio, which notably influenced the compressive strength of the concrete.

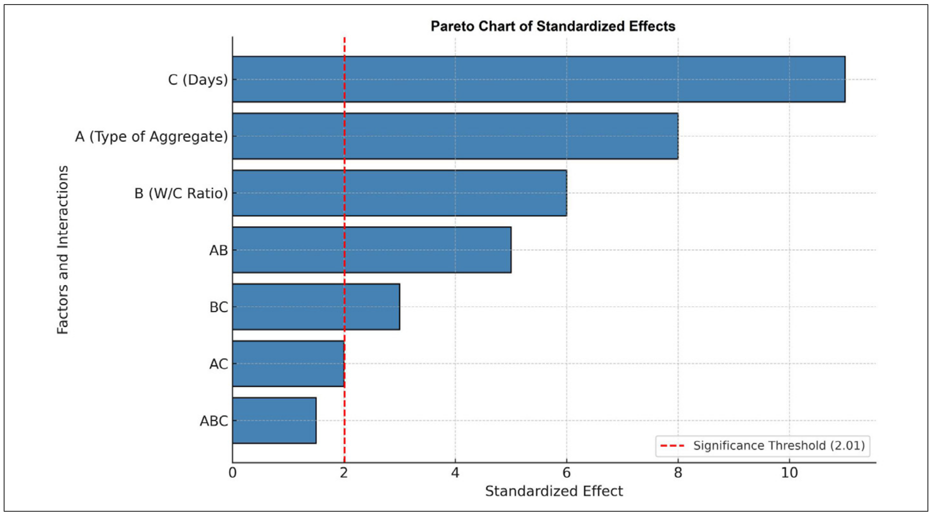
Figure 1 displays the residual plots that validate the robustness of the experimental design. Plot 1A confirms the normality of the residuals, as the points align closely with the theoretical line. In Plot 1B, the random dispersion of points around the reference line suggests homoscedasticity, indicating that the variance of errors is constant. Histogram 1C shows a symmetrical distribution, further reinforcing the normality of the residuals. Plot 1D verifies the independence of the residuals, as no systematic pattern is observed. These results ensure that key statistical assumptions are met, confirming the reliability of the experimental design and the validity of the results for rigorous analysis [29].



Source: own elaboration.

Figure 1. Normal Probability Plot (1A), Residuals vs Fitted (1B), Histogram of Residuals (1C), Residuals vs Order (1D)

The Pareto chart of standardized effects in Figure 2 was used to identify the most influential main factors and interactions affecting compressive strength. This analysis, conducted at a 95% confidence level ($\alpha = 0.05$), highlights that factor C (curing days) has the highest standardized effect, followed by factor A (aggregate type) and factor B (water-cement ratio). Significant interactions, such as AB (aggregate type and water-cement ratio), also contribute to explaining the variability observed in the results. The inclusion of this analysis reinforces the robustness of the statistical model employed and validates the importance of analyzing both individual factors and their combinations in the experimental design.



Source: own elaboration.

Figure 2. Pareto chart of standardized effects for compressive strength analysis

The analysis of variance ANOVA confirmed that the main factors, such as aggregate size, water-cement ratio, and curing days, have significant effects on the compressive strength of concrete ($p < 0.05$). The water-cement ratio had the greatest impact ($F = 48.22$), followed by aggregate size ($F = 22.54$) and curing days ($F = 12.34$). Additionally, a significant interaction between aggregate size and water-cement ratio was identified ($F = 5.00$), indicating that smaller aggregates are more sensitive to lower water-cement ratios. The model explained 95.9% of the variability ($R^2 = 0.959$) and met the statistical assumptions of normality, homoscedasticity, and independence, validating the experimental reliability and robustness of the factorial design.

Source	Sum of Squares	DF	Mean Square	F	p-value
Aggregate Size (A)	250.3	1	250.3	22.54	<0.05
Water/Cement Ratio (B)	524.7	2	262.35	48.22	<0.05
Curing Days (C)	133.2	1	133.2	12.34	<0.05
Interaction (AB)	54.3	2	27.15	5.0	<0.05
Error	54.3	10	5.43		
Total	962.5	15			

Source: own elaboration.

Figure 3. Analysis of variance ANOVA

Characterization of the Aggregate

For this study, two mixes were prepared with a design strength of 28 MPa. One mix was made with natural coarse aggregate, while the other used recycled coarse aggregate from CDW in a 3:1 ratio of recycled brick to recycled concrete, following the parameters of ACI-211.1-91 [30]. The concrete samples made with natural aggregate were labeled ML, while those made with CDW aggregate were labeled RCDW.

Density and absorption tests were conducted for both aggregates by ASTM C33/33M:2023 and ASTM C127:2015 standards to characterize their behavior [31], [32]. Additionally, a sieve analysis was performed to determine the particle size distribution [33]. The gradation was evaluated based on the parameters of ASTM C136/C136M:2019, and only the fractions retained on the 1” and 3/8” sieves were used for the RCDW concrete samples.

Furthermore, the densities of the natural and recycled coarse aggregates were determined through laboratory testing, assessing key parameters such as specific gravity (SG), loose unit weight (LUW), and compacted unit weight (CUW). These parameters provided a comprehensive analysis of the quality and behavior of both natural and recycled aggregates within the concrete mixtures.

The samples were processed using an agate mortar with acetone immersion to minimize phase alterations during grinding. X-ray diffraction (XRD) was performed at room temperature, employing a Panalytical X’Pert PRO MPD diffractometer. The analysis utilized Cu Kα1/Kα2 radiation (λ = 1.5406 Å) generated by a source operating at 45 kV and 40 mA, combined with a graphite monochromator. Measurements were conducted across a range of 5° to 80° (2θ) with 0.013° increments and a counting duration of 40 seconds per step [34].

The identification of crystalline phases relied on the X’Pert HighScore Plus v3.0c software and the Crystallography Open Database (COD). A quantitative assessment of mineral compositions was achieved through Rietveld refinement, which adjusted structural parameters to align with COD standards. The refinement workflow included two stages: the first focused on fundamental adjustments, such as scale factors, background corrections, sample displacement, and zero-point calibration; the second addressed advanced parameters like peak shape, asymmetry, lattice dimensions, and orientation preferences. Four iterations of refinement were necessary to finalize the model, with a weighted R-factor below 10% and closely matching the expected statistical profile (R-expected) [34].

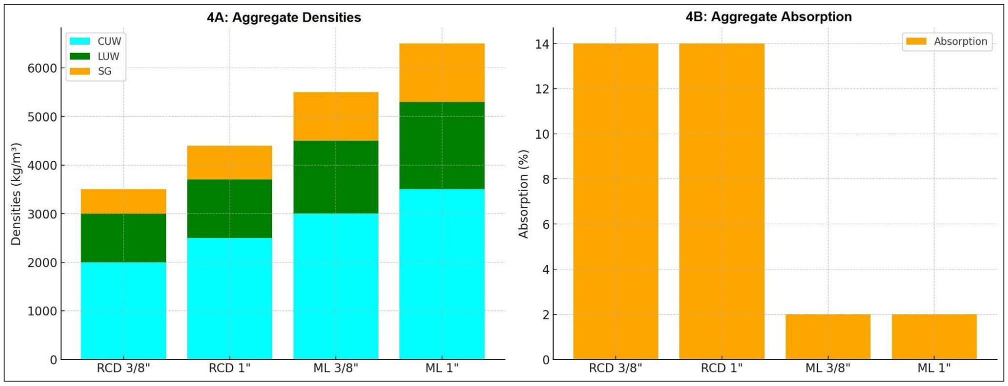
For microstructural and chemical characterization, a JEOL JSM 5910 LV scanning electron microscope, equipped with an OXFORD EDS solid-state detector, was utilized. The analyses were carried out under backscattered electron (BSE) mode with an acceleration voltage of 20 kV and a data acquisition time of 210 seconds. Sample preparation included mounting polished sections and applying a thin coating of colloidal gold [34].

RESULTS AND DISCUSSION

Mechanical Behavior

Plot 4A illustrates the densities of aggregates, comparing RCDW residues with ML aggregates. It is observed that ML aggregates, derived from natural sources, exhibit higher densities compared to RCDW aggregates, due to their more compact structure and lower porosity. The ML 1” aggregates achieve the highest total density while the RCD 3/8” and RCD 1” aggregates show a greater contribution of low-density components, such as brick and recycled concrete residues, which increase their water absorption capacity.

Plot 4B highlights the significant water absorption capacity of the recycled RCDW aggregates, with 14% absorption, in stark contrast to the natural ML aggregates, which show considerably lower absorption. This difference in water absorption capacity is attributed to the inherent porosity of recycled aggregates, which contain remnants of clay and other components that facilitate moisture retention. To mitigate this effect and adequately compare with natural aggregates, the RCDW aggregates were partially saturated for two minutes, reducing their water absorption from 14 % to a range of 2 - 3%. The inset in the top-right corner of Plot 4B shows the granulometric curve of the RCDW coarse aggregates, which follows the parameters established by ASTM C136/C136M:2014, demonstrating that the particles retained in the 1” and 3/8” sieves were selected for the preparation of RCDW concrete samples used in the compression tests performed at 7 and 28 days. This granulometric characterization ensures the comparability and experimental validity of the results obtained in the compression strength tests [35], [36].



Source: own elaboration.

Figure 4: Aggregate densities (3A) and Aggregate absorption (3B)

After 7 days of curing, the ML concrete samples exhibit superior mechanical performance across all aggregate sizes, reinforcing the well-established Hall-Petch relationship, which posits an inverse relationship between aggregate size and compressive strength. The data indicate that for water-cement (W/C) ratios exceeding 0.51, the compressive strength of ML concrete samples diminishes with increasing aggregate size. This reduction in mechanical strength can be attributed to the larger aggregate's tendency to create more significant discontinuities in the cementitious matrix, which act as stress concentrators under loading, thus reducing overall strength.

Conversely, the RCDW concrete samples demonstrate their best performance at a W/C ratio of 0.50. The compressive strength values of the 1" and 3/8" aggregate samples were found to reach 35% and 66.7% of their respective design strengths. However, these values remain significantly lower than the ML control samples, with reductions of 38% and 8%, respectively. This discrepancy is likely due to the irregular shape and rough texture of the RCDW aggregates, which hinder effective bonding at the aggregate-matrix interface. The poor bonding leads to the formation of micro-pores, which act as precursors for damage propagation under compressive stress. Additionally, at this early stage of curing, only 50% to 70% of the calcium silicate hydrate (C-S-H) gel, responsible for the majority of the concrete's strength, has formed, particularly due to the partial hydration of tricalcium silicate (C3S) phases [37], [38]. The Hall-Petch behavior observed in RCDW samples, though less pronounced, supports the understanding that smaller aggregate sizes enhance matrix continuity and reduce the number of potential failure planes [39].

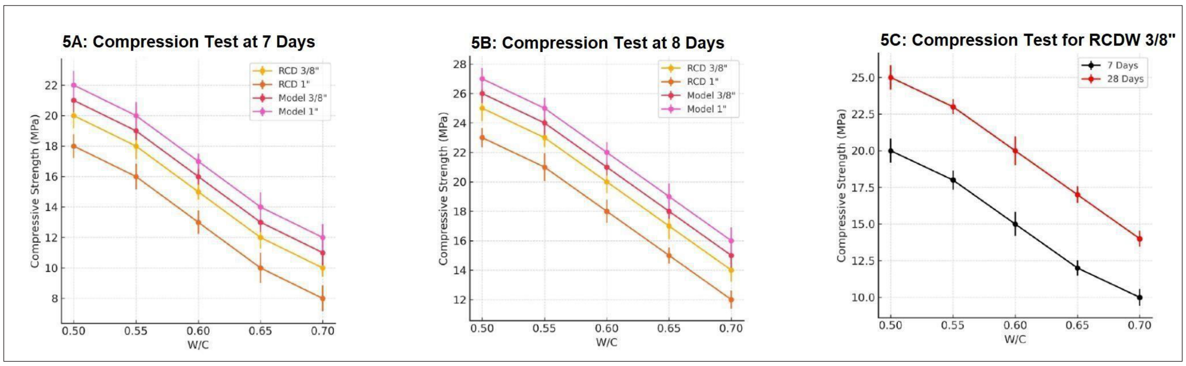
Plot 5B presents the compressive strength results of ML and RCDW concrete samples at 28 days. The ML 3/8" control sample with a W/C ratio of 0.50 achieved the design strength, highlighting its superior mechanical properties. In contrast, the ML 1" concrete sample, also with a W/C ratio of 0.50, achieved only 89.3% of the design strength. This shortfall may be attributed to increased porosity and the presence of larger interfacial transition zones (ITZ), which are more prevalent with larger aggregates, leading to weakened structural integrity. The other ML samples did not meet the design strength, averaging approximately 11.3% below the target strength. This highlights the importance of aggregate size in influencing the distribution and quality of ITZ regions, which are critical for strength development over time.

For the RCDW samples, the 1" and 3/8" aggregates with a W/C ratio of 0.50 achieved compressive strengths of 12 MPa and 21.5 MPa, representing 42.9% and 78.5% of the design strength, respectively. The lower performance of RCDW concrete can be linked to the higher water absorption capacity of recycled aggregates and their inferior mechanical properties compared to natural aggregates. The irregular surface texture of the RCDW aggregates exacerbates the formation of weak ITZ regions, reducing the overall compressive strength. Moreover, the presence of adhered mortar on recycled aggregates contributes to increased porosity, which limits the development of strength during hydration.

Plot 5C compares the compressive strength of RCDW concrete samples with 3/8" aggregates at both 7 and 28 days. At 7 days, the sample reached 66.7% of its ultimate strength, reflecting early hydration progress. By 28 days, the sample had achieved 78.5% of the design strength, illustrating the slower strength gain characteristic of recycled aggregates. This delayed strength development can be attributed to the incomplete hydration of cement particles and the presence of microcracks within the recycled aggregate, which limit the material's capacity to bear load during the early stages of curing. The increase in strength from 7 to 28 days highlights the role of continued hydration and densification of the microstructure, although the final compressive strength remains below that of conventional ML concrete.

The other water-cement proportions and aggregate size failed to exceed 50% of the design resistance in the same time order. These results allow us to infer that in the range of 0.5 – 0.6, a greater rate of change occurs than in the field of 0.6 – 0.7. This behavior is due to the Hall-Petch ratio of the RCDW aggregate, which is more susceptible to changes in its strength at low water-cement ratios. It is also possible to infer that the compressive strength of the concrete samples made with Ml and RCDW in the final curing stage varies depending on the water-cement ratio and the aggregate size. However, this phenomenon did not occur in the early curing stages for concrete samples made only with Ml.

Plot 5C shows the compression test for the RCD 3/8" concrete samples. This aggregate is smaller, significantly increasing the contact of the aggregate with the cementitious matrix. This increase in the aggregate-matrix bond helps reduce failure zones, improving overall performance and preserving the characteristics of lightweight concrete. Under these conditions, and for a water-cement ratio of 0.7 - 39.3% the design strength was reached after 28 days. For the other states and high absorption conditions, just 56.6% of the design resistance was achieved in the same period. These water-cement relations do not allow the adequate development of the $CaO\text{-}SiO_2\text{-}H_2O$ Hydrated Calcium Silicate gel, enabling the coalescence of pores and affecting its mechanical response [39].



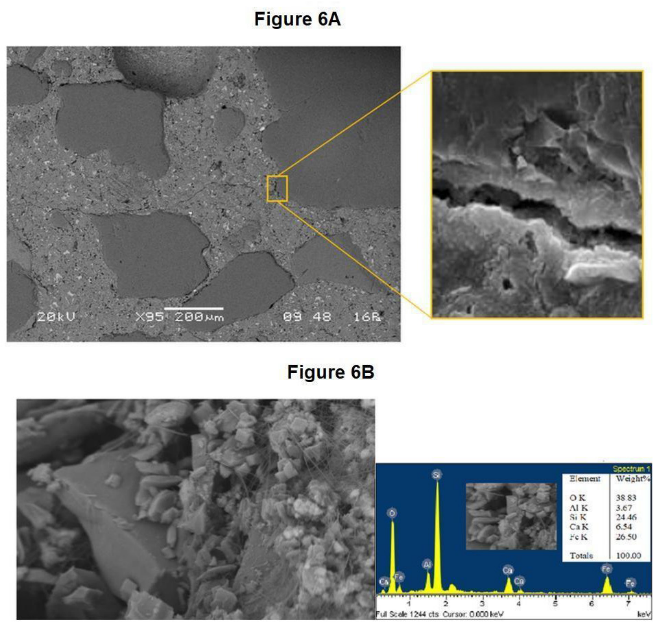
Source: own elaboration.

Figure 5. Illustrates the compressive strength results for ML and RCDW concrete samples

Phases Characterization

Figure 6B shows the SEM/EDS analysis to characterize the microstructure of the RCDW concrete sample with a water-cement ratio of 0.5 with 3/8" coarse aggregate. Porosities occur at the interface of the cementitious matrix and the aggregate. Also, it is observed that the microstructure is denser and more homogeneous when there is less presence of aggregates. The EDX spectra at the RCDW concrete sample allow for estimating the decrease in calcium content that possibly slows down the reaction rate. Due to the structure of the aggregate, and despite the saturation treatment, the diffusion process was not completed, in which the Ca^{2+} ions move to places of lower concentration to obtain a uniform distribution, allowing the refinement of the H-C-S pores hydrated [39]. Figure 6A, which corresponds to the SEM image of the RCD concrete sample with a water-cement ratio of 0.5 with 3/8" RCDW thick aggregate, allows us to observe how the interface between RCDW aggregate and the cementitious paste presents some low adhesion, as well as pores that behave as precursors of damage when the sample is mechanically failed in compression. The development of the pores is likely due to the physical characteristics of the aggregate that did not allow the C-S-H reaction to refine these voids.

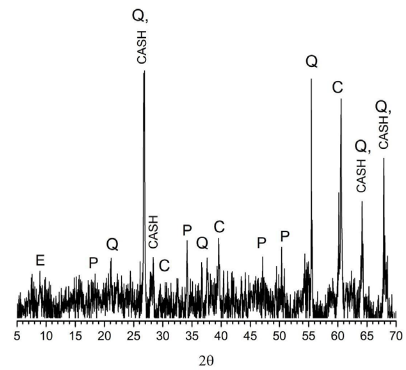
The RCDW concrete sample with a water-cement ratio of 0.5, a decrease was identified in the main peaks associated with Ca $(OH)_2$ in addition to very high $CaCO_3$ peaks, suggesting that the Ca $(OH)_2$ did not react adequately due to the lack of water in the mixture since the water supplied in the dosage was taken due to the porous condition of the coarse aggregates of the RCD concrete sample, which affected the production of the H-C-S gel and did not allow the achievement of the design resistance.



Source: own elaboration.

Figure 6. SEM images of the 3/8" RCDW sample with a water-cement ratio of 0.5 after 28 days curing

The main quartz peaks (SiO_2), as seen in Figure 6, indicate the presence of natural sand in the recycled aggregates, contributing to the concrete's strength and chemical stability. Calcite ($CaCO_3$), derived from recycled concrete, acts as a filler, improving densification and reducing porosity. Portlandite ($Ca(OH)_2$) reflects the ongoing cement hydration, suggesting potential long-term strength improvements. Finally, CASH compounds (calcium aluminum silicate hydrate) strengthen the cementitious matrix, enhancing the cohesion and durability of recycled concrete for structural applications.



Abreviatura	Componente	Fórmula química
Q= Cuarzo	Silicon Oxide	$Si\ O_2$
C= Calcita	Calcium Carbonate	$CaCO_3$
P= Portlandita	Calcium Hydroxide	$Ca(OH)_2$
CASH	Calcium Aluminum Silicate Hydrate	$Ca\ Al2\ Si_3\ O_{10}\ \cdot 6\ H2O$

Source: own elaboration.

Figure 7. XRD images of the 3/8” RCDW sample with a water-cement ratio of 0.5 after 28 days of curing

CONCLUSIONS

The development of new concretes with partial or total replacement of natural coarse aggregates with RCDW coarse aggregates allowed us to conclude that previous studies have reported that replacing 100% of the natural coarse aggregate with a heterogeneous mixture of RCDW coarse aggregate of concrete and recycled brick reduces compressive strength up to 30%, with a high density, up to 11.1% greater than concretes made with natural coarse aggregate. Furthermore, the replacement with RCDW coarse aggregate of recycled brick decreases the density of the concrete by up to 3 times. Still, it generates a notable deficiency in the final compressive strength of the material. In this sense, the literature recommends that the optimal replacement value of a natural coarse aggregate is 55% maximum since, above this value, there are considerable decreases in the final compressive strength, in some cases higher than 30%. The design of the 3/8” RCDW concrete proposed in this research obtained improvements in the results reported in the literature with a 100% replacement of the coarse aggregate. Compressive strengths were obtained with only 21.5% below the final resistance, obtaining an improvement of 33% in mixtures with 100% replacement of the natural coarse aggregate with RCDW coarse aggregate. In addition, it reduces the density of the concrete by 46.1%, which implies that it is in the lightweight concrete category.

These results were obtained for the RCDW concrete sample with a 3/8" thick RCDW aggregate with a ratio of 3:1 between brick and concrete, respectively, in addition to a water-cement ratio of 0.5. This 33% improvement in its mechanical behavior under compression is explained by the fact that the size of the aggregate presented a smaller interface with the cementitious paste, which allowed greater continuity of the cementitious paste, and the material behaved as a homogeneous system. In addition to the saturation treatment of the RCDW brick and concrete aggregates, these would not affect the water-cement ratio of 0.5 and the reactions derived from this condition. Improving this saturation process of aggregates could enhance the compressive mechanical response of RCD concrete. The results found in the development of this research allow the development of recycling processes and improvements of 33% in concrete with total replacement of natural coarse aggregate with RCDW coarse aggregate. Although the design strength of 28 MPa was not achieved, RCDW coarse aggregates are a viable option as a material replacement direction. These results also open a line of study of this type of material for constructing other kinds of construction systems. that are not structural but require relatively high mechanical resistance, such as regulated pavements.

ACKNOWLEDGEMENTS

This study was supported by the Engineering Research Group, Faculty of Basic Sciences and Engineering, Corporación Universitaria Remington, Medellin, Colombia, with institutional codes 4000000314-2022 and 4000000310-2022.

REFERENCES

[1] L. P. Güereca, "Evaluación comparativa de los impactos ambientales de la producción de clínker con combustible fósil frente a combustible derivado de los residuos municipales.," *Gaceta Instituto de Ingeniería, UNAM*, vol. 86, pp. 16–19, 2017.

[2] H. Yuan and L. Shen, "Trend of the research on construction and demolition waste management," *Waste Management*, vol. 31, no. 4, pp. 670–679, 2011, https://doi.org/10.1016/j.wasman.2010.10.030.

[3] R. Guo et al., "Global CO 2 uptake by cement from 1930 to 2019," no. 1, pp. 1791–1805, 2021.

[4] C. Zhang et al., "Life cycle assessment of material footprint in recycling: A case of concrete recycling," *Waste Management*, vol. 155, pp. 311–319, Jan. 2023, https://doi.org/10.1016/j.wasman.2022.10.035.

[5] K. Ram, M. Serdar, D. Londono-Zuluaga, and K. Scrivener, "Does carbon footprint reduction impair mechanical properties and service life of concrete," *Materials and Structures/Materiaux et Constructions*, vol. 56, no. 1, Feb. 2023, https://doi.org/10.1617/s11527-022-02090-9.

[6] H. Wu, J. Zuo, H. Yuan, G. Zillante, and J. Wang, "Resources, Conservation & Recycling A review of performance assessment methods for construction and demolition waste management," *Resour Conserv Recycl*, vol. 150, no. June, p. 104407, 2019, https://doi.org/10.1016/j.resconrec.2019.104407.

[7] D. Cheriyan and J. Choi, "A review of research on particulate matter pollution in the construction industry," *J Clean Prod*, vol. 254, p. 120077, 2020, https://doi.org/10.1016/j.jclepro.2020.120077.

[8] H. Le and Q. Bui, "Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance," *Constr Build Mater*, vol. 257, p. 119522, 2020, https://doi.org/10.1016/j.conbuildmat.2020.119522.

[9] W.-L. Huang, D.-H. Lin, N.-B. Chang, and K.-S. Lin, "Recycling of construction and demolition waste via a mechanical sorting process." [Online]. Available: www.elsevier.com/locate/resconrec.

[10] N. Cerqueira, A. Rangel, G. De Azevedo, and F. Redentor, "Evaluation of the Quality of Concrete with Waste of Construction and Demolition," no. January 2018, https://doi.org/10.1007/978-3-319-72484-3.

[11] A. Cardoza y H. A. Colorado, "Geopolymers Made of Construction and Demolition Waste: Current Trends and Perspectives," no. Apr. 2022, https://doi.org/10.1007/978-3-030-92563-5.

[12] M. Martín-Morales, M. Zamorano, A. Ruiz-Moyano, y I. Valverde-Espinosa, "Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish Structural Concrete Code EHE-08," Constr. Build. Mater., vol. 25, no. 2, pp. 742–748, Feb. 2011, https://doi.org/10.1016/j.conbuildmat.2010.07.012.

[13] G. M. Kondolf, "Geomorphic and environmental effects of instream gravel mining," 1994, https://doi.org/10.1016/0169-2046(94)90021-3.

[14] A. Kowalska y W. Sobczyk, "Negative and Positive Effects of the Exploitation of Gravel-Sand," Inżynieria Mineralna, vol. 15, no. 1, pp. 105-109, 2014. [Online]. Available: https://www.infona.pl/resource/bwmeta1.element.baztech-9175fff3-c319-45c8-a91b-f54cbe7f63cc/tab/summary. [Accessed: 18-Jul-2024].

[15] E. Q. R. Santiago, P. R. L. Lima, M. B. Leite, y R. D. Toledo Filho, "Mechanical behavior of recycled lightweight concrete using EVA waste and CDW under moderate temperature Comportamento mecânico sob temperatura moderada de concreto leve reciclado

produzido com resíduo de EVA e RCD," 2009. [Online]. Available: https://www.scirp.org/reference/ReferencesPapers.aspx?ReferenceID=2175321. [Accessed: 18-Jul-2024].

[16] J. S. González, F. L. Gayarre, C. L. C. Pérez, P. S. Ros, and M. A. S. López, "Influence of recycled brick aggregates on properties of structural concrete for manufacturing precast prestressed beams," *Constr Build Mater*, vol. 149, pp. 507–514, Sep. 2017, https://doi.org/10.1016/j.conbuildmat.2017.05.147.

[17] M. C. S. Nepomuceno, R. A. S. Isidoro, and J. P. G. Catarino, "Mechanical performance evaluation of concrete made with recycled ceramic coarse aggregates from industrial brick waste," *Constr Build Mater*, vol. 165, pp. 284–294, Mar. 2018, https://doi.org/10.1016/j.conbuildmat.2018.01.052.

[18] M. Bravo, J. De Brito, J. Pontes, and L. Evangelista, "Durability performance of concrete with recycled aggregates from construction and demolition waste plants," *Constr Build Mater*, vol. 77, pp. 357–369, Feb. 2015, https://doi.org/10.1016/j.conbuildmat.2014.12.103.

[19] M. Bravo, J. De Brito, J. Pontes, and L. Evangelista, "Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants," *J Clean Prod*, vol. 99, pp. 59–74, Jul. 2015, https://doi.org/10.1016/j.jclepro.2015.03.012.

[20] R. V. Silva, J. De Brito, and R. K. Dhir, "Performance of cementitious renderings and masonry mortars containing recycled aggregates from construction and demolition wastes," *Construction and Building Materials*, vol. 105. Elsevier Ltd, pp. 400–415, Feb. 15, 2016. https://doi.org/10.1016/j.conbuildmat.2015.12.171.

[21] S. M. Jian and B. Wu, "Compressive behavior of compound concrete containing demolished concrete lumps and recycled aggregate concrete," *Constr Build Mater*, vol. 272, Feb. 2021, https://doi.org/10.1016/j.conbuildmat.2020.121624.

[22] H. Sasanipour and F. Aslani, "Durability assessment of concrete containing surface pretreated coarse recycled concrete aggregates," *Constr Build Mater*, vol. 264, Dec. 2020, https://doi.org/10.1016/j.conbuildmat.2020.120203.

[23] H. Sasanipour and F. Aslani, "Durability properties evaluation of self-compacting concrete prepared with waste fine and coarse recycled concrete aggregates," *Constr Build Mater*, vol. 236, Mar. 2020, https://doi.org/10.1016/j.conbuildmat.2019.117540.

[24] C. S. Poon, Z. H. Shui, and L. Lam, "Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates," *Constr Build Mater*, vol. 18, no. 6, pp. 461–468, Jul. 2004, https://doi.org/10.1016/j.conbuildmat.2004.03.005.

[25] M. Aamer Rafique Bhutta, N. Hasanah, N. Farhayu, M. W. Hussin, M. B. M. Tahir, and J. Mirza, "Properties of porous concrete from waste crushed concrete (recycled aggregate)," *Constr Build Mater*, vol. 47, pp. 1243–1248, 2013, https://doi.org/10.1016/j.conbuildmat.2013.06.022.

[26] F. Yates, "The design and analysis of factorial experiments". Harpenden: Imperial Bureau of Soil Science, 1937, https://doi.org/10.1016/0169-2046(94)90021-3.

[27] R. Dunford, Q. Su, y E. Tamang, "The Pareto Principle," 2014. [Online]. Available: http://hdl.handle.net/10026.1/14054. https://doi.org/10.1007/978-3-030-92563-5.

[28] N. Langrené and X. Warin, "Fast multivariate empirical cumulative distribution function with connection to kernel density estimation," *Comput Stat Data Anal*, vol. 162, Oct. 2021, https://doi.org/10.1016/j.csda.2021.107267.

[29] W. Chantarangsi, W. Liu, F. Bretz, S. Kiatsupaibul, A. J. Hayter, and F. Wan, "Normal probability plots with confidence," *Biometrical Journal*, vol. 57, no. 1, pp. 52–63, Jan. 2015, https://doi.org/10.1002/bimj.201300244.

[30] D. E. Dixon et al., "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) Reapproved 1997 Reported by ACI Committee 211 Chairman, Subcommittee A," 1991. [Online]. Available: https://www.concrete.org/Portals/0/Files/PDF/Previews/211.1-22_preview.pdf. https://doi.org/10.14359/12264.

[31] "Designation: C33/C33M – 23 Standard Specification for Concrete Aggregates," ASTM International, 2023. https://doi.org/10.1520/C0033_C0033M-23.

[32] "Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate," ASTM International, 2015. https://doi.org/10.1520/C0127-15.

[33] "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," ASTM International, 2019. https://doi.org/10.1520/C0136_C0136M-19.

[34] J. D. Ospina-Correa, E. Mejía-Restrepo, C. M. Serna-Zuluaga, A. Posada-Montoya, J. G. Osorio-Cachaya, J. A. Tamayo-Sepúlveda, and J. A. Calderón-Gutiérrez, "Process mineralogy of refractory gold ore in thiosulfate solutions," *Hydrometallurgy*, vol. 180, pp. 151-160, 2018, doi: 10.1016/j.hydromet.2018.10.019.

[35] A. Katz, "Properties of concrete made with recycled aggregate from partially hydrated old concrete," *Cem Concr Res*, vol. 33, no. 5, pp. 703–711, May 2003, https://doi.org/10.1016/S0008-8846(02)01033-5.

[36] P. R. L. Lima, M. B. Leite, and E. Q. R. Santiago, "Recycled lightweight concrete made from footwear industry waste and CDW," *Waste Management*, vol. 30, no. 6, pp. 1107–1113, Jun. 2010, https://doi.org/10.1016/j.wasman.2010.02.007.

[37] D. Wang et al., "Mechanical performance of recycled aggregate concrete in green civil engineering: Review," Case Studies in Construction Materials, vol. 19, Dec. 2023, https://doi.org/10.1016/j.cscm.2023.e02384.

[38] J. W. Bullard, J. G. Hagedorn, M. T. Ley, Q. Hu, W. N. Griffin, y J. E. Terrill, "A critical comparison of 3D experiments and simulations of tricalcium silicate hydration,"

Journal of the American Ceramic Society, vol. 101, no. 4, pp. 1453–1462, Mar. 2018, https://doi.org/10.1111/jace.15323.

[39] F. Zhou, G. Pan, R. Mi, and M. Zhan, "Improving the properties of concrete using in situ-grown C-S-H," *Constr Build Mater*, vol. 276, Mar. 2021, https://doi.org/10.1016/j.conbuildmat.2020.122214.