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Original

Influence of the Use of Recycled Material on the Properties of Concrete as a Partial Substitute for Natural Coarse Aggregate

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Abstract: The valorization of construction and demolition waste is a fundamental strategy for sustainability in the concrete industry. This study evaluated the effect of incorporating recycled concrete coarse aggregate (RCGA) and recycled porcelain coarse aggregate (RPGA), both individually and in combination, as partial substitutes for natural aggregate. Twelve formulations were analyzed using standardized physical and mechanical tests after 28 days of curing. The combined mixture M_2 (7.5% RCGA + 5% RPGA) exhibited optimal physical properties, reducing absorption by 68.81% and void volume by 68.49%. The individual formulations M_6 (7.5% RCGA) and M_{10} (5% RPGA) achieved superior increases in compressive strength (9.17% and 9.34%) and flexural strength (10.84% and 10.06%). Abrasion resistance was significantly improved in all optimized mixes. The study concludes that both individual and combined substitutions, in appropriate proportions, significantly enhance concrete properties, contributing to sustainable construction through waste valorization.

Keywords: **Aggregate, concrete, recycled material, porcelain, resistance.**

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1. Introduction

The volume of construction and demolition waste (CDW) has experienced a sustained increase recently because of the demolition and rehabilitation of obsolete buildings (Aditi, 2022). In response to this trend, many countries have made the use of recycled aggregates (RA) a standard practice. This has helped the concrete industry become more environmentally friendly (Seddik, 2017). A prime example is the Netherlands, where the construction industry recycles about 95% of the CDW waste it produces. This shows that industrial symbiosis is a successful way to move toward a circular economy model. This is especially evident in the processes of recycling and reusing construction materials (Yu et al., 2021).

In the Peruvian context, research on the use of recycled coarse concrete aggregate (RCGA) and recycled coarse porcelain aggregate (RPGA) is still in its early stages compared to developed countries. This gap represents a significant research opportunity, especially considering that in the national construction sector, CDW is becoming an increasingly critical environmental issue in cities like Cusco, Trujillo, and Callao.

Several studies reviewed suggest management models that prioritize steps to prevent, reuse, and ultimately recover construction and demolition waste. Research has revealed challenges with regulations and the lack of adequate infrastructure for managing CDW waste. Cusco alone generated an estimated 56,242 tons of CDW waste in 2019. The strategies identified involve evaluating various factors to select the optimal locations for treatment plants, studying and mapping key waste collection areas, and developing programs that engage the community in waste management. These initiatives aim to improve the management of CDW waste in a comprehensive manner, making a significant contribution to sustainable urban development in Peru (Flores, 2020; Molina, 2023; SEGAT, 2017).

From another perspective, the generation of construction waste is an unavoidable byproduct of modern economies. The decreasing availability of landfills, industrial growth, and stringent environmental regulations in both developed and developing countries have led to a global reassessment of methods for recycling and using CDW as recycled aggregates in large-scale construction projects (Tam et al., 2018). As a result, the production of concrete incorporating RA from demolished structures has gained considerable importance in construction initiatives, driven by the pressing need to preserve natural resources (Musa, 2022).

Environmental protection has long been a key priority in global decision-making frameworks. Environmental issues resulting from excessive natural resource consumption and their subsequent effects on terrestrial ecosystems are currently gaining increased awareness. The recycling of CDW goes beyond industrialized nations; developing countries are increasingly prioritizing this practice due to the rising global demand for construction materials (Elías et al., 2020). This phenomenon is evident in the significant increase in construction projects during periods of rapid urban expansion. This situation creates specific challenges in CDW management, such as the occupation of valuable land, contribution to air pollution, and the potential use of CDW as an alternative raw material source for new construction projects (Liu et al., 2020).

Numerous research initiatives have demonstrated the significant potential of recycled aggregates for structural concrete applications. Ulloa-Mayorga et al. (2018) confirmed that incorporating recycled porcelain and crushed concrete as aggregates in structural components is technically feasible and delivers satisfactory performance. In a separate, major study, Saravanakumar et al. (2021) documented significant improvements in concrete durability through the treatment of recycled aggregates with blast furnace slag.

Meanwhile, Yehia et al. (2015) highlighted the variability in recycled aggregate quality, pointing out the limitations of the current processing techniques. Further analyses by Attard et al. (2021), Nanya et al. (2021), and Vivek et al. (2022) conducted in-depth investigations on optimal replacement ratios of natural aggregates with recycled alternatives and their effects on concrete properties. Additionally, Makul et al. (2021) concluded that, while recycled aggregates can significantly contribute to addressing the socioeconomic challenges posed by concrete waste, there remains a substantial knowledge gap regarding their long-term performance and overall sustainability profile.

Despite the growing interest in aggregate recycling, there is a significant lack of research on the optimal ratios of recycled coarse concrete aggregate (RCGA) and recycled coarse porcelain aggregate (RPGA), particularly in Peru. Most previous studies have concentrated on these materials individually, neglecting the exploration of potential synergistic effects arising from their combined application. Moreover, the unique characteristics of construction and demolition materials in Peru present a challenge that must be addressed to assess their ability to partially replace natural aggregates, considering the local climate and construction standards.

To fill this gap, the present research was specifically designed to evaluate both RCGA and RPGA, both independently and in combination, to determine and compare their effects on the physical and mechanical properties of concrete. This comprehensive methodology will enhance construction adaptability across Peru while promoting sustainable development in line with established green building principles.

This study aims to assess the effects of incorporating recycled aggregates from construction and demolition waste materials when they partially replace natural coarse aggregates in concrete mixtures. Our primary focus is to propose the hypothesis that the partial substitution of natural coarse aggregates with recycled materials either maintains or potentially improves the physical and mechanical properties of concrete, offering a sustainable alternative without compromising its structural performance.

This research's significance lies in its potential to reduce the environmental impact of construction. Using recovered resources promotes the recycling of materials typically discarded, thus reducing reliance on natural aggregates, whose extraction is costly and harmful to the environment. Moreover, the increasing interest in sustainable construction practices shifts focus toward the development of alternative materials within the construction sector, without compromising concrete's quality or structural integrity. Consequently, understanding how recovered materials influence concrete performance is crucial for advancing responsible and sustainable construction practices.

2. Material and Methods

2.1 Materials

2.1.1 Naturals aggregates

Natural aggregates The minimal transportation costs related to the quarry's accessibility provide a significant advantage for regional construction projects. The sampling methodology employed specifically targeted areas with consistent extraction patterns to ensure material representativeness, focusing on regions with uniform composition. The Natural Coarse Aggregate (NGA) was chosen for its mineralogical purity, while the Natural Fine Aggregate (NFA) underwent a systematic sieving process to maintain granulometric uniformity. All materials were stored in airtight containers to prevent contamination or changes in their properties during transportation and storage.

2.1.2 Recycled aggregates

A systematic methodology was applied to produce RCGA and RPGA from CDW in Puno, Peru. The recycled concrete aggregate, sourced from construction and demolition debris, was processed according to the guidelines outlined in the Peruvian Technical Standard NTP 400.050 (2017), which governs the management of these and other recycled materials in the country. The protocol included thorough contaminant removal through material sorting and grading, followed by dimensional reduction using an impact crusher. The resulting material fractions were categorized based on specific quality parameters for the partial substitution of NGA. For RPGA processing, similar techniques were used for contaminant removal, size reduction, and granulometry refinement. After verifying compliance with the established technical specifications, all aggregates were transported and stored under laboratory-controlled conditions for subsequent physical and mechanical characterization testing.

2.1.3 Portland cement

Portland cement plays a critical role in Peru's construction sector. Portland pozzolanic cement type IP is of particular importance for this study due to its enhanced workability, excellent finishing qualities, and compatibility with the recycled materials used. This cement variant consists of a hydraulic binding agent made of Portland clinker combined with precise ratios of puzzolanic additions, meeting current technical regulations. Its specific gravity of 2.85 g/cm^3 was a key parameter for accurate cement dosage calculation in concrete mixtures, ensuring compliance with the strength and durability requirements set for the research program.

2.1.4 Water

In accordance with Peruvian legislation and international protocols, the production of concrete and mortar requires the use of water that meets specific quality standards to maintain the material's integrity. The NTP 339.088 (2021) states that mixing water must be free from contaminants such as oils, acids, alkaline substances, salts, or organic matter that could compromise concrete properties.

Additionally, ASTM C1602 (2022) specifies that, in addition to the water itself, the raw materials used in processing must be chemically and physically harmless to the concrete and its components. Strict adherence to these technical specifications ensures that concrete structures possess the intended mechanical properties and demonstrate long-term durability.

2.1.5 Properties of aggregates

Table 1 shows that the physical and mechanical properties of the aggregates, both natural and recycled, meet the parameters of the ASTM C33 (2024), ASTM C29 (2023), ASTM C127 (2025), ASTM C128 (2025), ASTM C131 (2020), ASTM C136 (2025), and NTP 400.016 (2020) standards.

The specific gravities of the NFA are 2.52 g/cm^3 and those of the NGA are 2.48 g/cm^3. These values are within the expected range of 2.4–2.9 g/cm^3, demonstrating that they have good density for structural uses. RCGA and RPGA have slightly lower values (2.27 g/cm^3 and 2.33 g/cm^3, respectively) due to their higher porosity.

Table 1. Properties of aggregates.

Properties	NFA	NGA	RCGA	RPGA
Mass-specific weight (g/cm^3)	2.52	2.48	2.27	2.33
Water absorption (%)	2.95	2.83	3.09	2.96
Moisture content (%)	5.76	2.78	2.76	3.68
Fineness module	3.01	—	—	—
Dry compacted weight (kg/m^3)	1,307	1,513	1,521	1,537
Loose dry weight (kg/m^3)	1,550	1,698	1,704	1,721
Nominal maximum size (mm)	—	19.05	19.05	19.05
Abrasion resistance (%)	—	30.71	31.65	29.77
Magnesium sulfate resistance (%)	—	10.55	11.75	11.1
Sodium sulfate resistance (%)	—	22.15	24.25	23.89

Regarding absorption, all evaluated aggregates comply with the regulatory limits, recording values below the maximum permitted threshold of 3.5%. However, the recycled aggregates exhibit moderately higher absorption rates than their natural counterparts, which reflects their more porous nature. NFA exhibits a high moisture content (5.76%), a circumstance that demands rigorous control during the batching process of concrete mixtures. Its fineness modulus of 3.01 indicates that it is a relatively coarse fine aggregate, a factor that could influence the workability of the resulting mixtures.

The unit weights of NGA, RCGA, and RPGA are still within the normal ranges. These are 1400–1800 kg/m^3 for compacted and 1200–1700 kg/m^3 for loose. This study confirms its adequate density and quality for structural concrete applications.

Regarding abrasion resistance, values of 30.71% for NGA, 31.65% for RCGA, and 29.77% for RPGA were obtained. Simultaneously, the durability tests through exposure to magnesium sulfate yielded values of 10.55%, 11.75%, and 11.1%, respectively, while the results obtained with sodium sulfate were 22.15%, 24.25%, and 23.89%. All these parameters fall within the limits specified by ASTM C-131 and NTP 400.016 standards, validating the suitability of these materials for use in structural concrete.

2.2 Methods

The study used an experimental design with a quantitative approach to systematically evaluate the partial replacement of natural coarse aggregate (NCA) with recycled concrete coarse aggregate (RCCA) and recycled porcelain coarse aggregate (RPCA) in controlled quantities. The research established four combined experimental groups and four differentiated independent groups, in addition to a control group composed of conventional concrete.

The determination of the specific combined percentages of NGA substitution was (M_1=5%+2.5%, M_2=7.5%+5%, M_3=10%+7.5%, and M_4=12.5%+10% of RCGA and RPGA). As well as for the independent groups of (M_5=5%, M_6=7.5%, M_7=10%, and M_8=12.5% for RCGA; M_9=2.5%, M_{10}=5%, M_{11}=7.5%, and M_{12}=10% for RPGA respectively), based on previous research and preliminary evaluations.

These ranges were selected considering the optimal balance between environmental sustainability and the preservation of adequate mechanical properties. According to previous studies, RCGA replacements below 5% would not provide sufficient environmental benefits, while replacements above 12.5% would greatly affect structural performance. In the case of RPGA, its greater hardness and susceptibility to brittleness justify the selected range. This range allows for the evaluation of its complementary behavior with RCGA in various proportions. These incremental intervals facilitate the precise identification of the optimal threshold for each combination and the independence of the materials.

Mechanical and physical tests were conducted on 100 specimens: 75 cylindrical samples and 25 rectangular ones. These were subjected to a standardized curing process for 28 days. Parameters such as density, absorption, void volume, abrasion resistance, and flexural strength were thoroughly evaluated and analyzed to determine the functional effectiveness of the recycled materials.

2.2.1 Mix design

The mix design was carried out carefully following the ACI 211.1 (2022) guidelines on concrete facing freeze-thaw cycles (Category F1). With the aim of achieving a design compressive strength of 28 MPa, 12 specific dosages and one control sample were formulated. The cement used had a specific gravity of 2.85 g/cm^3. The constant parameters were set as a slump of 3–4 inches (76.2 to 101.6 mm), a total air content of 5%, and a water-cement ratio of .41, as shown in Table 2.

A fundamental aspect of this study is the maintenance of constant critical parameters across all mixtures. The cement content (448.15 kg), the water volume (167 L), the water-cement ratio (.41), the air content (5%), and the doses of additives remain unchanged. This strategy allows any variation in the properties of the concrete to be attributed exclusively to the type and amount of recycled aggregates.

The experimental design is structured into three distinct groups to evaluate both the combined and individual effects of the recycled materials. The first group (M_0-M_4) includes increasing percentages of recycled concrete aggregates (RCGA) and recycled permeable concrete aggregates (RPGA) together. The analysis starts with a control mix, M_0, which does not contain any recycled materials. Then it progresses to M_4, which contains 12.5% RCGA and 10% RPGA, replacing a total of 215.48 kg of natural aggregate.

The second experimental series (M_0, M_5–M_8) exclusively examines RCGA as the sole recycled component. In these mixtures, substitution levels range from 0% in the control specimen to 12.5% in M_8, incorporating 119.58 kg of RCGA. The quantity of natural coarse aggregate decreases proportionally from 957.69 kg in the control mixture to 838.11 kg in M_8, preserving volumetric balance. The third experimental series (M_0, M_6–M_{12}) assesses the effects of RPGA in isolation. Substitution percentages range from 0% to 10% in M_{12}, incorporating 95.63 kg of recycled porcelain. Following the methodology of the previous series, the natural coarse aggregate content systematically decreases from 957.69 kg to 862.06 kg to accommodate the addition of the recycled material.

2.2.2 Granulometry of aggregates

The granulometric analysis, presented in Figure 1, provides a comprehensive characterization of the particle size distribution across all evaluated aggregates. NFA displays a particle distribution curve that fully falls within the limits defined by the ASTM C33 (2024) standard, confirming its suitability for structural concrete applications. This conformity indicates that NFA has a well-balanced particle arrangement, which is crucial for ensuring that concrete mixtures maintain proper cohesion and workability.

Table 2. Mix design in wet weight proportions.

RCGA+RPGA	Unit	M_0	M_1	M_2	M_3	M_4
Cement	kg	448.15	448.15	448.15	448.15	448.15
Water	L	167.05	167.03	167.95	166.86	166.78
Aimix 400 additive	kg	0.22	0.22	0.22	0.22	0.22
Euco 37 additive	kg	4.03	4.03	4.03	4.03	4.03
Accelguard 100 additive	kg	3.59	3.59	3.59	3.59	3.59
Air -F1	%	5.0	5.0	5.0	5.0	5.0
Fine aggregate	kg	615.49	615.49	615.49	615.49	615.49
Coarse aggregate	kg	957.69	886.86	837.98	790.09	742.21
RCGA + RPGA	kg	—	71.83	119.71	167.60	215.48
RCGA		M_0	M_5	M_6	M_7	M_8
Coarse aggregate	kg	957.69	909.95	886.0	862.06	838.11
RCGA	kg	—	47.74	71.69	95.63	119.58
RPGA		M_0	M_9	M_{10}	M_{11}	M_{12}
Coarse aggregate	kg	957.69	934.0	909.95	886.0	862.06
RPGA	kg	—	23.69	47.74	71.69	95.63

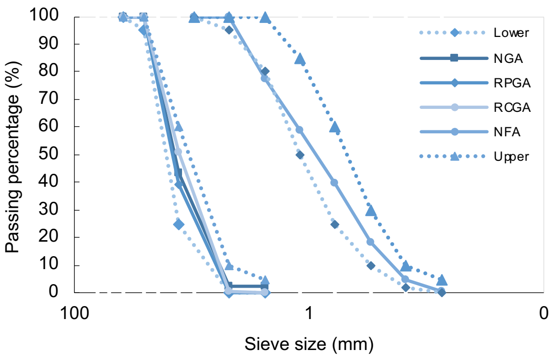

Figure 1. Granulometry analysis of aggregates.

Regarding coarse aggregates, both natural and recycled variants show particle size distribution curves that remain within the parameters set by the ASTM C33 standard. The NGA stands out due to its balanced gradation, which enhances the beneficial properties of concrete. Meanwhile, both RCGA and RPGA exhibit a more concentrated particle size distribution pattern. While this feature reveals their recycled origin, it allows for their integration into concrete mixtures without significantly compromising the mechanical performance of the final product.

2.2.3 Sclerometry

In accordance with the ASTM C805 (2025) protocol, sclerometry testing was conducted on concrete block specimens made from recycled materials. These blocks were designed to achieve a compressive strength of 28 MPa, with ten impact measurements taken on each specimen. This non-destructive testing method is significant due to its alignment with the NTP 400.050 (2017) criteria, which provides specific guidelines for the classification of CDW and the appropriate handling procedures. This standardized classification and control framework aims to optimize the recovery of valuable materials while minimizing the environmental impacts associated with it.

2.2.4 Workability of the mix

Slump measurements of fresh concrete were carried out using the Abrams cone, following the procedures outlined in ASTM C143 (2026), and NTP 339.035 (2022) standards. The testing process involved filling the truncated cone mold with fresh mixture in three equal-volume layers. Each layer was systematically compacted using a standardized steel rod, with 25 uniformly distributed strokes applied. The upper surface was leveled by removing excess material, and the mold was lifted vertically with steady, controlled movement, allowing the mixture to deform under the force of gravity. The measurement between the original cone height and the final height of the deformed concrete mass was recorded as the slump value. To enhance result reliability, this procedure was repeated in triplicate for each mixture design, and the representative average value was calculated for analysis purposes.

2.2.5 Absorption, density, and void volume

The porosity of the concrete, a determining parameter of its durability, was evaluated following the procedure established in the ASTM C642 (2022) standard. The weighing process of the samples was carried out in three sequential stages after 28 days of concrete curing, with a stabilization criterion of a mass variation of less than 0.5%. The minimum volume required for the samples exceeded 350 cm^3. The test specimens consisted of cylindrical concrete discs with a diameter of 50 mm. Each specimen was subjected to a drying process in an oven at a constant temperature of 110°C for 24 hours, followed by controlled cooling in a desiccator. The initial weight before drying was recorded, and subsequently, the weight after completing this process was documented, repeating it until a mass variation of less than 0.5% was achieved.

2.2.6 Compressive strength

In accordance with current U.S. regulations, the compression strength tests were conducted following the guidelines established in ASTM C39 (2024). The procedure was applied to cylindrical concrete specimens after a standardized curing period of 28 days. All specimens were prepared by grinding and polishing their load-bearing surfaces before being tested in the universal machine. It was carefully verified that the application of the load coincided with the geometric center of the specimen's longitudinal axis. Throughout the testing procedure, the load application rate was regulated to maintain values between 15 MPa and 55 MPa/min. Concurrently, critical parameters including total applied load, axial deformation, and time elapsed until specimen failure were systematically documented.

2.2.7 Flexural strength

Prismatic concrete specimens measuring 150 mm × 150 mm × 500 mm were produced according to ASTM C78 (2022) standards and then cured in a humidity chamber under controlled environmental conditions for 28 days. Before testing, the specimens underwent surface finishing, removing irregularities that could affect the accuracy of the results. The tests were performed using a universal testing machine. Each specimen was placed on simple supports, with load application carried out through a centrally positioned device at the midpoint. The load application rate was controlled between 0.90 and 1.20 MPa/min, with both the applied force and resulting deflection systematically recorded until specimen failure occurred. The results were evaluated based on standardized concrete flexural strength parameters to assess material quality.

2.2.8 Abrasion strength

Following the ASTM C944 (2019) protocol, this experimental procedure measures concrete surface abrasion resistance using cylindrical specimens with a diameter of 150 mm and a height of 75 mm. After a 28-day curing period, the specimens were prepared in three layers, each compacted with 25 strokes using a standardized rod, followed by 15 lateral taps with a rubber mallet. Each specimen was then cured individually for an additional 24 hours before testing. The initial mass of each specimen was recorded before testing began. Next, the specimen was placed in a rotary abrasion apparatus set to 200 RPM with a constant force of 9.8 N. The test involved three 2-minute abrasion cycles, with surface cleaning between each. Upon completion of the test, the final mass of the specimen was recorded, and the weight loss was calculated as the abrasion resistance indicator.

3. Results

3.1 Sclerometry

The non-destructive evaluation of concrete utilizing the sclerometer, or rebound hammer, provides a preliminary assessment regarding the quality of concrete manufactured with recycled materials. Table 3 presents the sclerometry test results obtained from concrete specimens containing recycled aggregates.

The concrete's estimated average strength reached 32.1 MPa, exceeding the specified design strength of 28 MPa by 14.64%. This notable increase confirms compliance with design requirements and demonstrates the favorable performance of recycled aggregates when properly processed and proportioned within mixtures. These preliminary findings hold significance as they enable quality verification of recycled materials through nondestructive methods. This result provides an initial reference point before conducting more comprehensive evaluations of physical and mechanical properties across various experimental mixtures.

Table 3. Recycled concrete sclerometry test.

No.	Compressive strength		Variation
Impacts	Required (MPa)	Obtained (MPa)	(%)
10	28	32	14.29
10	28	34	21.43
10	28	31	10.71
10	28	31.5	12.5
10	28	32	14.29
Average	28	32.1	14.64

3.2 Workability of the mix

Table 4 presents comprehensive data regarding workability characteristics across various concrete mixtures, evaluated through slump testing. For each of the twelve experimental mixtures plus the control mixture, three distinct slump measurements were documented, and their average values were calculated.

Table 4. Workability of the mix.

Groups	Slump 1 (mm)	Slump 2 (mm)	Slump 3 (mm)	Average (mm)
M_0	86.36	81.28	83.82	83.82
M_1	88.9	86.36	83.82	86.36
M_2	88.9	93.98	91.44	91.44
M_3	86.36	81.28	83.82	83.82
M_4	83.82	78.74	81.28	81.28
M_5	88.9	86.36	86.36	87.21
M_6	86.36	86.36	86.36	86.36
M_7	83.82	88.9	88.9	87.21
M_8	86.36	88.9	86.36	87.21
M_9	83.82	83.82	88.9	85.51
M_{10}	88.9	81.28	83.82	84.67
M_{11}	83.82	83.82	86.36	84.67
M_{12}	81.28	81.28	88.9	83.82

The results reveal significant patterns concerning recycled aggregate mixture behavior. Mixture M_2, containing 7.5% RCGA and 5% RPGA, demonstrates the highest average slump value (91.44 mm), indicating favorable workability for this recycled material combination. On the other hand, mixture M_4, which has the highest percentages of recycled materials (12.5% RCGA and 10% RPGA), has the lowest average slump value (81.28 mm). This suggests that using higher percentages of recycled aggregates may make the mixture less workable.

Mixtures containing exclusively RCGA (M_5-M_8) display remarkably consistent slump values ranging between 86.36 mm and 87.21 mm, indicating this material exerts less influence on workability compared to combinations or RPGA independently. It is noteworthy that all mixtures remained within the target slump range (3-4 inches, approximately 76-102 mm), indicating that the mixture design effectively compensated for the increased absorption capacity of recycled aggregates by maintaining consistent water-cement ratios and proper admixture dosages.

This data confirms that recycled aggregates can be incorporated into structural concrete without significantly compromising workability, representing a significant finding for applications in the construction industry.

3.3 Absorption, density, and void volume

Table 5 presents significant physical properties of the concrete mixtures examined, highlighting key parameters from a materials engineering perspective: water absorption, apparent density, and void volume. These indicators are critical for assessing the mechanical performance and durability of concrete, especially when recycled materials are used as partial substitutes for natural aggregates.

Water absorption shows considerable variability among the mixtures, with values ranging from .63% to 2.58%. Mixture M_2 (7.5% RCGA + 5% RPGA) has the lowest absorption (.63%), representing a 68.8% reduction compared to the control mixture M_0 (2.02%). This behavior may be attributed to optimized particle packing effects between the two recycled aggregate types. In contrast, M_8 (12.5% RCGA) shows 1.13% absorption, followed by M_{12} (10% RPGA) at 2.58%, representing increases of 40.1% and 27.7%, respectively, relative to M_0.

The bulk density values range from 5.73 g/cm^3 (M_{10}) to 6.73 g/cm^3 (M_8). The M_{10} mix (5% RPGA) shows the lowest density (5.73 g/cm^3), while M_8 (12.5% RCGA) presents the highest (6.73 g/cm^3). No clear linear correlation is observed between the substitution percentage and the density, suggesting the influence of other factors, such as the degree of compaction and particle size distribution.

The void volume shows a clear correlation with water absorption, with values ranging from 3.64 g/cm^3 in M_2 to 14.33 g/cm^3 in M_{12}. The mixtures with the lowest void volume (M_2, M_6, M_{10}) also exhibit the lowest absorption values, confirming the expected relationship between porosity and absorption capacity.

It is particularly noteworthy that the M_2 mix (7.5% RCGA + 5% RPGA) demonstrates superior physical properties even when compared to the reference concrete. This behavior may be attributed to a synergistic effect between the two types of recycled aggregates, likely due to an optimization of the particle size distribution that enhances packing and, consequently, leads to a more refined porous structure. This phenomenon is referred to as the “filling effect,” where finer particles fill the spaces between the coarser ones, increasing packing density.

In contrast, mixtures with high individual percentages of RCGA (M_8) or RPGA (M_{12}) show a deterioration in physical properties, suggesting that the controlled combination of both materials in specific proportions could constitute an effective strategy to mitigate the adverse effects typically associated with the incorporation of recycled aggregates in concrete.

These results indicate that there is an optimal percentage of combined substitution that could improve the physical properties of concrete, offering opportunities for the development of more sustainable mixes without compromising, and even improving, their performance.

Table 5. Absorption, density, and void volume.

Code	Water absorption (%)	Bulk density (g/cm^3)	Void volume (g/cm^3)
M_0	2.02	6.47	11.55
M_1	1.46	6.22	8.32
M_2	.63	5.97	3.64
M_3	1.68	6.33	9.61
M_4	2.41	6.65	13.82
M_5	1.52	6.1	8.49
M_6	1.13	5.87	6.19
M_7	2.33	6.16	12.55
M_8	2.83	6.73	16.0
M_9	1.76	6.37	10.07
M_{10}	1.2	5.73	6.42
M_{11}	2.29	6.37	12.73
M_{12}	2.58	6.52	14.33

3.4 Compressive strength

The compressive strength results shown in Figures 2a, 2b, and 2c exhibit different behaviors depending on the type and amount of recycled aggregates added to the cement mix. Figure 2A illustrates the mechanical behavior of the matrices that simultaneously incorporate RCGA and RPGA. The M_2 formulation exhibits the maximum strength with 32.51 MPa, representing a 6.04% increase compared to the reference matrix M_0 (30.66 MPa). An initial increasing trend is observed from M_0 to M_2, followed by a progressive decrease for M_3 and M_4. The M_4 formulation, which uses more recycled materials (12.5% RCGA and 10% RPGA), shows a decrease of 9.9% (27.62 MPa) compared to the control. This behavior shows that there is an ideal percentage of combined substitution (which corresponds to M_2). If this percentage is exceeded, the compressive strength suffers considerable damage.

Figure 2B focuses exclusively on the influence of RCA. It reveals that the compressive strength increases with the addition of RCA until it reaches its maximum value in formulation M_6 (7.5% RCA) with 33.47 MPa, which represents a 9.17% increase compared to M_0. The matrices with more RCGA (M_7 and M_8) have higher strengths than the control mix (improvements of 2.42% and 1.71%, respectively), although they are lower than those of M_6. These results demonstrate that RCA, used as the only recycled material, significantly enhances the compressive strength of concrete when incorporated in optimal percentages.

Figure 2C analyzes the behavior of the matrices with the incorporation of RPGA. A gradual increase in compressive strength is observed with the addition of RPGA, reaching its peak in the M_{10} mix (5% RPGA) with 33.52 MPa, which means a 9.34% increase compared to M_0. The matrices with higher percentages (M_{11} and M_{12}) show greater strengths than the reference (increases of 2.17% and 1.23%, respectively), but they are lower than M_{10}, confirming that there is an optimal substitution percentage.

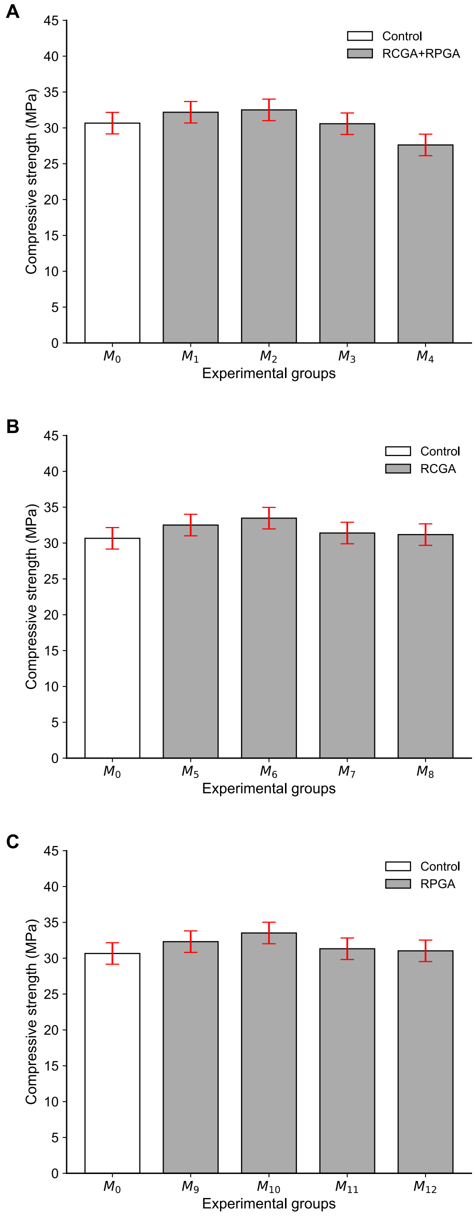

Figure 2. Compressive strength of concrete.

These experimental findings demonstrate a notable correlation between previously analyzed compression and flexural behavior. Both RCA and RPA, when utilized individually at optimized proportions (7.5% for RCA and 5% for RPA), significantly enhance concrete mechanical properties. However, when both materials are incorporated simultaneously, the optimal combined percentage differs from that observed for physical properties. This evidence suggests differentiated influence mechanisms operate depending on the specific property being evaluated.

3.5 Flexural strength

The analysis of the flexural strength (Figures 3a, 3b, and 3c) of the various formulations evaluated reveals differentiated mechanical behaviors depending on the type and proportion of recycled aggregates incorporated into the cementitious matrix. Figure 3A illustrates the mechanical behavior of matrices that simultaneously incorporate RCGA and RPGA. The M_1 formulation exhibits the maximum strength with 3.16 MPa, representing a 4.29% increase compared to the reference matrix M_0 (3.03 MPa). However, it can be seen that the strength values decrease as the replacement percentages increase in mixtures M_2, M_3, and M_4. Particularly, formulation M_4, which incorporates the highest proportions of recycled materials (12.5% RCGA and 10% RPGA), shows a reduction of 6.92% (2.82 MPa). This behavior evidences the existence of an optimal threshold for combined substitution, beyond which the flexural strength experiences a progressive deterioration.

Figure 3B, focused exclusively on the influence of RCA, reveals a differentiated behavior pattern. The resistance increases steadily with the addition of RCGA, reaching its peak in formula M_6 (7.5% RCGA) with 3.36 MPa, which represents a 10.84% increase compared to M_0. The matrices with higher proportions of RCGA (M_7 and M_8) maintain strengths superior to the control mix, although lower than M_6. These results demonstrate that RCA, used as the only recycled material, significantly enhances the flexural mechanical properties of concrete when incorporated in optimal percentages.

Figure 3C analyzes the behavior of the matrices with the incorporation of RPGA. In line with the behavior observed for RCGA, an initial increase in flexural strength proportional to the addition of RPGA is evident, reaching its maximum value in formulation M_{10} (5% RPGA) with 3.33 MPa, which represents a 10.06% increase compared to M_0. The matrices with higher percentages (M_{11} and M_{12}) show strengths that are higher than the reference but lower than M_{10}, confirming that there is an optimal substitution percentage.

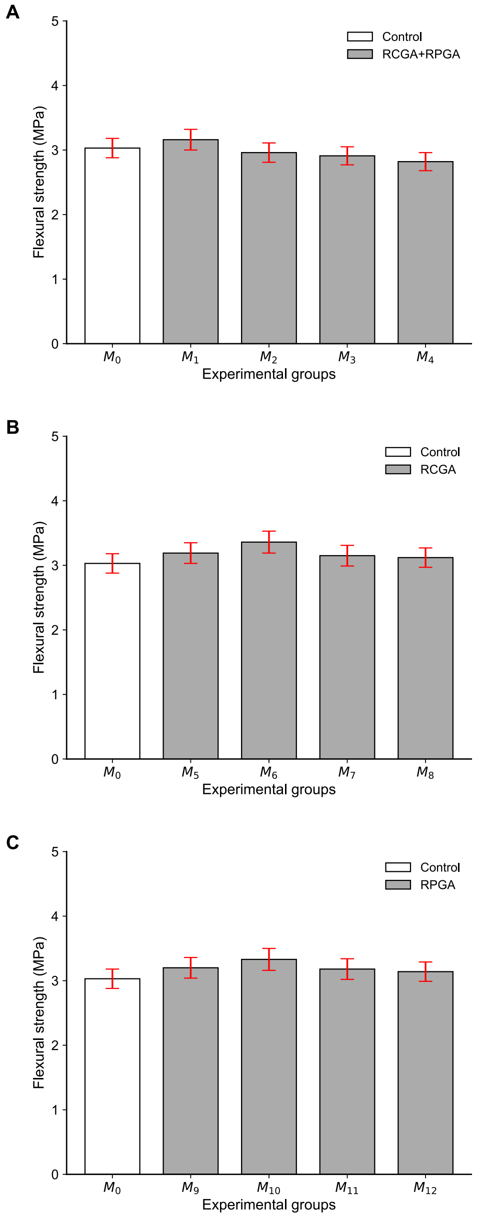

Figure 3. Flexural strength of concrete.

These experimental results indicate that both RCGA and RPGA, when used individually in optimized proportions (7.5% for RCGA and 5% for RPGA), enhance the flexural mechanical properties of concrete. However, when both materials are incorporated simultaneously, the synergistic benefit is reduced and limited to more conservative replacement percentages. This information is significant for creating sustainable cement matrices that aim to maximize the use of recycled aggregates without affecting their structural performance in resisting bending forces.

3.6 Abrasion strength

The abrasion resistance results shown in Table 6 show how different cement matrices behave differently in underwater conditions. The measurement of mass loss in percentage during the three standard test cycles provides key information about the surface quality of the evaluated samples.

The comparative analysis of the results reveals that the reference matrix (M_0) exhibits an average mass loss of .69%. Notably, certain formulations with the incorporation of recycled aggregates exhibit significantly superior tribological resistance. The M_6, M_2, and M_{10} mixtures show reductions in mass loss of 65.2%, 60.9%, and 62.3%, respectively, compared to the control formulation. This observation goes against the common idea that mechanical properties are always damaged in matrices that include recycled materials.

There is a statistically significant relationship between tribological resistance and the physical characteristics that have been analyzed previously. The M_2 formulation (7.5% RCGA + 5% RPGA), which previously showed good physical properties such as the absorption coefficient and void volume, continues to perform well under abrasion conditions. This letter suggests that there is a relationship between the porous microstructure and the abrasion resistance on the surface.

Table 6. Abrasion strength.

Code	Cycle 1 (%)	Cycle 2 (%)	Cycle 3 (%)	Average loss (%)
M_0	.98	.53	.57	.69
M_1	.21	.19	.76	.39
M_2	.20	.31	.31	.27
M_3	.63	.36	.43	.47
M_4	.53	.90	.58	.67
M_5	.06	.27	.74	.36
M_6	.09	.35	.29	.24
M_7	.61	.31	.42	.45
M_8	.35	1.01	.56	.64
M_9	.06	.32	.74	.37
M_{10}	.13	.36	.29	.26
M_{11}	.31	.66	.42	.46
M_{12}	.31	1.09	.57	.66

The sequential analysis of the abrasion cycles provides relevant information about the structural homogeneity of the matrices. The formulations M_1, M_2, M_6, and M_{10} show a fairly consistent behavior over the three cycles, indicating a uniform distribution of phases on the material's surface. On the contrary, the M_4, M_8, and M_{12} mixtures show significant changes between cycles. This variance is due to the differences in how the recycled aggregates are distributed in the cement matrix.

The systematic evaluation of the impact of the substitution percentage shows that matrices with moderate proportions of combined substitution (M_2 and M_6) have better tribological properties than those with high percentages of individual substitution (M_4, M_8, M_{12}). This discovery supports the idea that there is a synergistic effect between RCGA and RPGA when combined in optimal proportions.

4. Discussions

The sclerometry tests reveal superior mechanical behavior in both specimens with combined and individual recycled aggregates, with an average strength of 32.1 MPa, exceeding the design strength (28 MPa) by 14.64%. This favorable correlation aligns with Kazemi et al. (2019), who demonstrated similar reliability in concrete with a high content of recycled aggregates. Our findings confirm the efficacy of the non-destructive methodology and the capability of individual recycled materials (RCGA, RPGA) and their combinations to surpass traditional structural standards.

The evaluation of the settlement in all the studied formulations (combined M_1-M_4 and individual M_5-M_{12}) demonstrates compliance with the specified design range (78.74-93.98 mm). This preservation of rheological properties contrasts with trends reported by Hui et al. (2022) and Khaoula et al. (2021), who identified a reduction in workability with individual recycled aggregates. Mineral additives can mitigate this behavior, achieving approximate improvements of 11% in settlement, as noted by Fawzy et al. (2023). Our results confirm that both mixtures with combined and individual aggregates can maintain adequate workability through precise adjustments in the water/cement ratio.

The physical properties observed in our mixtures exhibit behaviors that partially contrast with trends documented in the scientific literature. While Bai et al. (2024) indicate higher porosity in concretes with recycled aggregates, our formulations M_1-M_2 (combined), M_6 (7.5% RCGA), and M_{10} (5% RPGA) exhibited significantly lower absorption values than the control, with M_2 (0.63%) standing out over the individual formulations M_6 (1.13%) and M_{10} (1.2%). These favorable results align with Khaoula et al. (2021) and Helsing et al. (2024), who determined that moderate substitutions, both individual and combined, can improve these physical indicators. However, the mixtures with high substitution percentages (M_4, M_8, M_{12}) exhibited less favorable properties, confirming the warnings of Fawzy et al. (2023) about the existence of critical substitution thresholds.

The analysis at 28 days reveals remarkable behaviors in both experimental groups. Among the combined mixtures, M_1 and M_2 exhibited higher strengths than the control (4.96% and 6.04% increases), while M_3 maintained equivalent strength and M_4 showed significant reduction (9.90%). In individual formulations, M_6 (7.5% RCGA) reached 33.47 MPa (9.17% increase) and M_{10} (5% RPGA) 33.52 MPa (9.34% increase), outperforming the best combined formulations.

These results partially contrast with trends described by Bai et al. (2024) and agree with Ozbakkaloglu et al. (2018) and Santillána (2018), who documented that single moderate substitutions could outperform conventional concrete. Fawzy et al. (2023) reported similar trends in concretes optimized with individual and combined recycled aggregates.

The results reveal differentiated behaviors between formulations. In combined mixtures, M_1 outperformed the control by 4.29% (3.16 MPa vs. 3.03 MPa), while M_2-M_4 showed progressive decreases. In individual formulations, M_6 and M_{10} reached the maximum values (3.36 MPa and 3.33 MPa), representing increases of 10.84% and 10.06%, respectively. These improvements partially contradict trends documented by Santillána (2018) regarding reductions in flexural strength with recycled aggregates. The progressive decrease in mixtures with higher percentages coincides with findings by Ozbakkaloglu et al. (2018) and Khaoula et al. (2021), confirming the existence of differentiated optimum ratios for individual and combined substitutions.

Both combined and individual mixtures demonstrated outstanding abrasion resistance. Mixture M_2 reduced material loss by 60.9%, while M_6 and M_{10} achieved significant reductions of 65.2% and 62.3%, respectively. These findings contradict the observations made by Santillána (2018) and Helsing et al. (2024), who reported reduced abrasion resistance in concretes containing recycled aggregates. Research by Fawzy et al. (2023) and Bai et al. (2024) indicates that optimizing recycled aggregate proportions can significantly improve this property. The complementary relationship between porcelain and recycled concrete aggregates, in both individual and combined formulations, results in surfaces with enhanced wear resistance characteristics.

The results indicate that both individual and combined formulations can outperform conventional concrete performance when optimized proportions are used. Mixtures M_6 (7.5% RCGA) and M_{10} (5% RPGA) show superior mechanical strength compared to combined formulations, while M_2 (7.5% RCGA + 5% RPGA) offers the optimal balance in physical properties, particularly with regard to absorption characteristics (.63% versus 1.13% and 1.2%).

These findings align with recent studies by Rosado et al. (2022) and Helsing et al. (2024), who evaluated ceramic and recycled concrete aggregates both independently and in combination. Khaoula et al. (2021) and Fawzy et al. (2023) confirm that balanced proportions can produce positive synergistic effects. Specialized literature, as highlighted by Ozbakkaloglu et al. (2018), advocates for the systematic evaluation of both approaches. Our research demonstrates that by optimizing the proportions of various recycled materials, both individually and in combination, sustainable concrete with improved properties can be developed, making substantial contributions to waste valorization without compromising technical performance.

5. Conclusions

This study evaluated the impact of recycled materials, specifically RCGA and RPGA, on concrete properties when these aggregates partially replace NGA. Based on the results analyzed, the following conclusions can be drawn:

Sclerometry tests confirmed that specimens with recycled aggregates exceeded the design strength by 14.64%, validating both the non-destructive methodology and the potential of these materials for structural applications.

The composition of recycled aggregates significantly influences the physics-mechanical properties of concrete. Mix M_2 (7.5% RCGA and 5% RPGA) demonstrated notable improvements over the reference mix, with reductions of 68.81% in water absorption and 68.49% in void volume, evidencing the direct impact of aggregate composition on concrete performance.

The proposed mix design, based on ACI 211.1, adequately maintains the water-cement ratio at .41 across all experimental groups, emphasizing the importance of rigorous quality control to optimize the use of recycled aggregates.

The slump results indicate that recycled aggregates can be successfully incorporated without compromising workability. Mix M_2 achieved the most favorable average value (91.44 mm), while the other formulations with recycled aggregates maintained values within design parameters.

In terms of compressive strength, mix M_2 demonstrated the maximum value with an increase of 6.04% over the control mix, reaching 32.51 MPa. In contrast, the individual formulations M_6 (7.5% RCGA) and M_{10} (5% RPGA) exhibited superior increases of 9.17% and 9.34%, respectively, evidencing the superior potential of individual substitutions optimized for this specific property.

Regarding flexural strength, mix M_1 (5% RCGA and 2.5% RPGA) presented the best performance among the combined formulations, outperforming the control mix by 4.23% (3.16 MPa). However, the individual substitutions M_6 and M_{10} achieved increases of 10.84% and 10.06%, demonstrating greater efficiency in this property.

Abrasion resistance improved significantly with recycled aggregates, with reductions in wear loss of 60.9%, 65.2%, and 62.3% for M_2, M_6, and M_{10}, respectively, compared to the control mix, confirming the existence of optimal proportions to maximize this property.

The integrated analysis of physical and mechanical properties reveals that, while the individual formulations M_6 and M_{10} exhibit superior mechanical strengths, the combined mixture M_2 offers the optimal balance between all evaluated properties, particularly in absorption (.63%) and void volume (3.64 g/cm^3).

These findings have important implications for the construction industry in Peru, demonstrating that both individual and combined substitutions of recycled aggregates, in optimized proportions, can significantly improve the properties of concrete. This contributes to the valorization of waste without compromising technical performance. The selection between individual or combined formulations will depend fundamentally on the critical property for each specific application.

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Conflict of Interest

The authors declare that they have no conflicts of interest to disclose.

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