

Article

Influence of High-Performance Recycled Aggregates on Mechanical Properties of High-Strength Concrete

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Abstract

One of the major challenges in developing a sustainable construction industry is the reincorporation of construction and demolition waste (C&DW) into the materials cycle. An interesting end-of-life cycle strategy is the recycling of C&DW as aggregates for new concrete. Although promising results have mostly been reported for applications with low mechanical and durability requirements, this research evaluates the use of a high-performance recycled concrete aggregate (HP-RCA), a low-porosity, high-abrasion-resistance aggregate obtained from the demolition of high-strength concrete, with almost no additional treatment, unlike what is traditionally required. First, the production and characterization of the HP-RCA was carried out, to continue with the manufacture of four high-strength concrete mixtures that included one reference (0%) and three with different natural coarse aggregate replacements (10%, 20% and 40%). Then, fresh and hardened properties were evaluated, with the main focus being mechanical properties (i.e., compressive strength, diametric compressive tensile strength and elasticity modulus). Results indicate that when the recycled aggregate content increased, the mechanical properties substantially improved, and the mixture with 40% replacement improved the compressive strength by 37.8% at 56 days. Although durability performance still needs to be further assessed, the mechanical results presented here are very promising for advancing a truly sustainable construction industry, especially considering that the extraction of natural coarse aggregates has significant environmental impacts and that the final disposal of C&DW remains a major environmental and economic challenge.

Keywords: recycled concrete aggregates; concrete waste; high-strength concrete; construction and demolition waste; circular economy



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1. Introduction

Concrete is the most widely used construction material worldwide and constitutes a fundamental pillar of modern infrastructure. However, its extensive production and consumption are associated with major environmental impacts, including high energy demand, substantial greenhouse gas emissions (e.g., carbon dioxide), and intensive extraction of natural resources. In particular, the cement and concrete industries are under increasing pressure to reduce their environmental footprint and adopt more sustainable and circular

production models [1–3]. These challenges have positioned concrete at the center of global sustainability and decarbonization strategies within the construction sector.

Beyond cement-related emissions, the extraction and processing of aggregates represent a major environmental burden, as aggregates constitute the largest volumetric fraction of concrete. At the same time, the construction industry generates massive amounts of construction and demolition waste (C&DW), much of which is still landfilled despite its potential for reuse and recycling. The implementation of circular economy principles in construction, particularly through the recycling of C&DW into recycled concrete aggregates (RCAs), has therefore gained increasing attention as a strategy to reduce natural aggregate consumption and mitigate waste-related environmental impacts [4–6].

Although recycled concrete aggregates offer a promising pathway for closing material loops, their widespread use remains largely limited to non-structural applications in most countries. For example, according to Ram et al. (2019) [7], while Spanish (EHE-08, 2010) and Hong Kong (HKBD 2009) standards allow 100% replacement of natural coarse aggregates with RCA in non-structural concrete, Indian standards permit 100% replacement of both natural coarse and fine aggregates with recycled concrete aggregate for non-structural concrete with compressive strength below 15 MPa (IS 383:2016). Other standards from countries such as Portugal (LNEC E-471, 2006) and Germany (DAfStB, 1998) do not specify a maximum allowable replacement level for non-structural applications; instead, they establish minimum density requirements for recycled concrete aggregate, which are 2000 kg/m³ and 1500 kg/m³, respectively. This is because conventional recycled concrete aggregate typically exhibits higher porosity, higher water absorption, adhered mortar, and greater variability compared to natural aggregates. These characteristics often lead to reduced workability, increased admixture demand, and potential deterioration of mechanical and durability-related properties, especially at high replacement ratios or in high-strength concrete [8–10].

According to Ram et al. (2019) [7], in the context of high-strength concrete (HSC), mixes with compressive strengths between 50 and 100 MPa, standards from countries such as Japan (JIS 5021, 2005), China (JGJ/T 240, 2011), Switzerland (OT-70085, 2006), the Netherlands (NEN-5905, 2005), Denmark (DCA, 1995), and Portugal (LNEC E-471, 2006) clearly specify conditions related to maximum allowable replacement levels, density-water absorption requirements, and durability parameters (i.e., sulfate and chloride contents) when using recycled concrete aggregates in high-strength concrete. In this case, as compressive strength increases, the contribution of the aggregate phase and the characteristics of the interfacial transition zone (ITZ) become increasingly important in governing mechanical behavior and stiffness [11]. Several studies have demonstrated that the performance of recycled concrete aggregate strongly depends on the quality of the parent concrete from which the RCA is produced [12]. In this regard, RCA derived from high-strength parent concretes has been shown to exhibit improved physical and mechanical properties, enabling higher replacement ratios without compromising strength [13,14]. For example, Jagadesh et al. (2024) [15] reported mechanical improvements of 15–20% in the compressive strength of high-strength concrete incorporating recycled concrete aggregates. Similarly, Rezar et al. (2024) [16] observed a 5–8% increase in the tensile strength of concrete mixes produced with recycled aggregates sourced from deconstructed high-strength concrete bridges. Although it is a different recycled material, the use of biochar highlights its potential to refine pore structure, enhance ITZ quality, and improve the mechanical and durability performance of geopolymer concretes [17].

Experimental investigations on high-strength recycled aggregate concrete have reported that RCA obtained from parent concretes with compressive strengths exceeding approximately 60 MPa can perform comparably to natural aggregates in terms of com-

pressive strength and stiffness, especially when appropriate mix design strategies are adopted [18]. Nevertheless, concerns related to durability, pore connectivity, and transport properties often persist, particularly at intermediate replacement levels, where the balance between adhered mortar content and additional hydration effects is not fully understood [19,20].

Recent research has explored various approaches to enhance RCA performance, which can be classified into methods that modify the RCA surface (e.g., carbonation, bio-deposition, use of pozzolanic materials) and those aimed at separating the old mortar from the natural aggregate (e.g., mechanical scrubbing, acid soaking, and microwave heating) [21–23]. While these strategies have shown promising results, they may introduce additional processing steps, costs, or environmental trade-offs. According to the recent comparative analysis by Prajapati et al. (2019) [24], untreated recycled concrete aggregate replacements above 20% lead to a significant reduction in both compressive strength and elastic modulus, an effect that becomes even more pronounced when the fine natural fraction is substituted. Consequently, there remains a need for systematic studies evaluating the intrinsic potential of high-performance recycled concrete aggregates (HP-RCAs), defined in this study as recycled concrete aggregates produced from high-strength concrete waste without significant additional treatment procedures.

In addition to aggregate-related challenges, high-strength concretes are commonly produced with very low water-to-cement ratios, which significantly increase the risk of early-age autogenous shrinkage and associated cracking. Among the mitigation strategies proposed in the literature, the use of superabsorbent polymers (SAPs) as internal curing agents has proven to be particularly effective [25–27]. Parallel to performance-driven material design, sustainability considerations have become central to contemporary concrete technology. Circular economy approaches focused on the valorization of industrial and post-industrial waste have demonstrated strong potential to reduce environmental impacts while delivering high-performance cement-based materials [28–30].

Within this broader framework, the development of high-strength concretes incorporating HP-RCA represents a logical extension of circular economy concepts. By combining high-quality recycled aggregates derived from high-strength concrete waste with advanced mixture design strategies, it is possible to produce structurally efficient concretes with enhanced mechanical performance while reducing environmental impacts associated with natural aggregate extraction and waste disposal.

Accordingly, the present study investigates the influence of HP-RCA derived from high-strength concrete laboratory specimens on the fresh, physical, and mechanical properties of new high-strength concrete mixtures. Four mixtures are evaluated: a reference mixture and mixtures incorporating 10%, 20%, and 40% replacement of natural coarse aggregate by HP-RCA (by mass). Fresh properties are assessed through workability measurements, while physical properties related to microstructural quality and durability are evaluated using ultrasonic pulse velocity, total water absorption, and capillary absorption tests. Mechanical performance is analyzed through compressive strength, splitting tensile strength, and static modulus of elasticity at different curing ages.

The main contribution of this research lies in providing experimental evidence on the feasibility of using HP-RCA as a viable constituent for high-strength concrete, achieving not only comparable but, in some cases, enhanced mechanical performance at high replacement levels. From a sustainability perspective, this approach supports the valorization of high-quality C&DW, reduces the demand for virgin aggregates, and aligns with circular economy strategies and life-cycle-based environmental assessments promoted in the construction sector [1,31–33]. As such, HP-RCA represents a promising pathway toward the development of structurally efficient and environmentally responsible concrete mixes.

2. Methodology and Materials

This research was conducted in three major phases: Phase I—Materials Characterization, Phase II—Concrete Mix Composition and Preparation, and Phase III—Concrete Mixes Characterization (Figure 1). Phase I involved the characterization of cement, natural aggregates, recycled concrete aggregates (RCAs), and additives. Based on the results obtained in this phase, the concrete mix compositions and preparation procedures were developed in Phase II. Finally, in Phase III, the concrete mixes were characterized in both the fresh and hardened states through workability testing, ultrasonic pulse velocity measurements, total and capillary water absorption tests, compressive and splitting tensile strength tests, and the determination of the static modulus of elasticity. Further details on these methodological phases are provided in the following items.

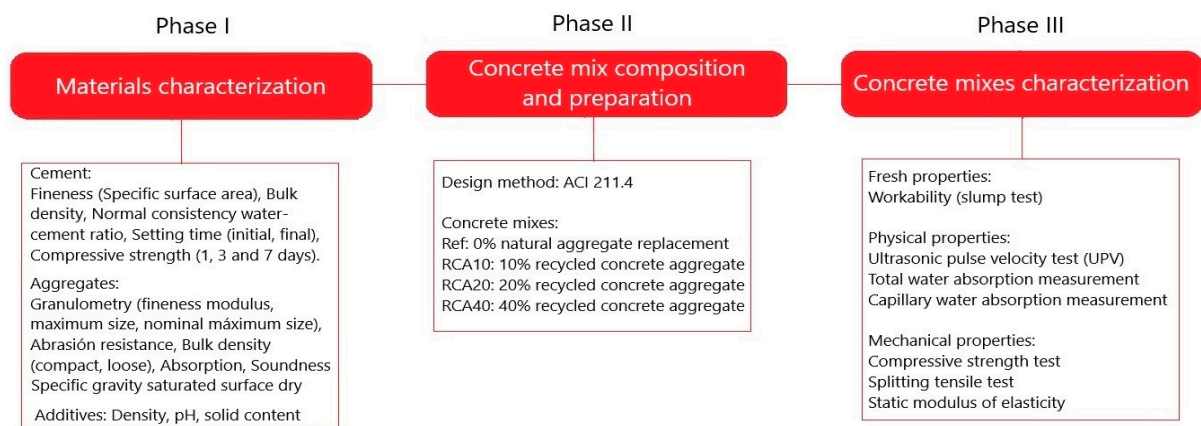


Figure 1. Three major methodological phases and the corresponding materials and tests.

2.1. Materials Characterization

2.1.1. Cement

A high-early-strength hydraulic cement (Type HS) was used, classified according to ASTM C1157-25 (Performance Specification for Hydraulic Cement). This cement was selected due to its widespread use and suitability in the production of high-strength concrete and precast structural elements. The cement was characterized through tests of fineness by air permeability, normal consistency, setting times, compressive strength, and density. A summary of the measured properties is presented in Table 1.

Table 1. Physical properties of cement.

Test		Unit	Result	Standard
Fineness (Specific Surface Area)		cm ² /g	4.875	ASTM C204-25
Specific Gravity		g/cm ³	3.14	ASTM C187-25
Normal Consistency		%	26.9	ASTM C191-21
Setting Time	Initial	h:min	1:30	ASTM C109-24
	Final	h:min	2:30	
Compressive Strength	1 d	MPa	12.5	ASTM C188-25
	3 d	MPa	20.8	
	7 d	MPa	27.7	

2.1.2. Aggregates

- **Fine Aggregate:** A medium river sand was used as the fine aggregate. The physical characterization results are presented in Table 2. The material complied with the

technical specifications required for concrete production. The full granulometric curves are presented in Figure 2 [34].

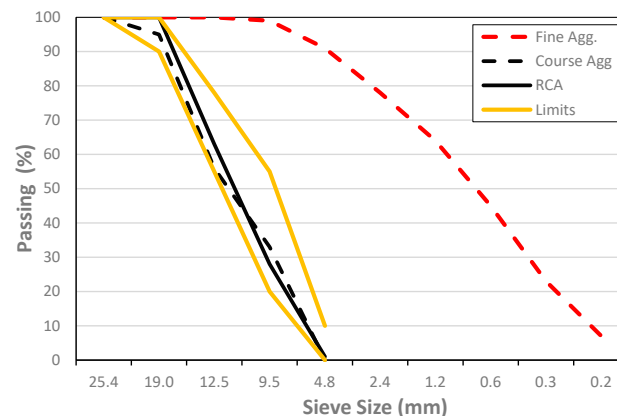


Figure 2. Particle size distribution of aggregates and valid limits for coarse aggregates in structural concrete mixes.

Table 2. Physical properties of river sand.

Test		Unit	Result	Standard
Granulometry	FM ¹	-	2.93	ASTM C136-25
	MS ¹	mm	9.5	
	NMS ¹	mm	4.75	
Bulk Density	Compact	kg/L	1.78	ASTM C29-23
	Loose	kg/L	1.62	
Organic Impurities		Range No.	3	ASTM C40-20
Specific gravity saturated surface dry		-	2.82	ASTM C128-25
Absorption		%	2.35	ASTM C128-25
Soundness		% Loss	32.7	ASTM C88-18

¹ MF: Fineness modulus; MS: Maximum size; NMS: Nominal maximum size.

- **Coarse Aggregate:** A crushed diabase gravel obtained from a local quarry was used as the natural coarse aggregate. A summary of its physical properties is provided in Table 3. The material exhibited high quality and met all technical specifications for structural concrete production. The complete granulometry curves are provided in Figure 2 [34].

Table 3. Physical properties of natural coarse aggregate.

Test		Unit	Result	Standard
Granulometry	FM ¹	-	6.69	ASTM C136-25
	MS ¹	mm	25.4	
	NMS ¹	mm	19.1	
Abrasion Resistance		%	17.3	ASTM C131-20
Bulk Density	Compact	kg/L	1.55	ASTM C29-23
	Loose	kg/L	1.44	
Specific gravity saturated surface dry		-	2.67	ASTM C127-25
Absorption		%	1.01	ASTM C127-25
Soundness		% Loss	1.18	ASTM C88-18

¹ MF: Fineness modulus; MS: Maximum size; NMS: Nominal maximum size.

- **Recycled Concrete Aggregate (RCA):** The raw material used to produce the course aggregate consisted of high-performance concrete specimens with compressive strengths

above 60 MPa, more than 28 days of curing and water-to-cement ratios below 0.35. The recycling process was carried out in two laboratory stages. First, large concrete blocks were pre-crushed using a compression press. Subsequently, the material was processed with a jaw crusher and sieved through a No. 4 mesh (Figure 3), obtaining a coarse aggregate with a nominal maximum size of 3/8 in. The complete granulometry curves are included in Figure 2 [34].

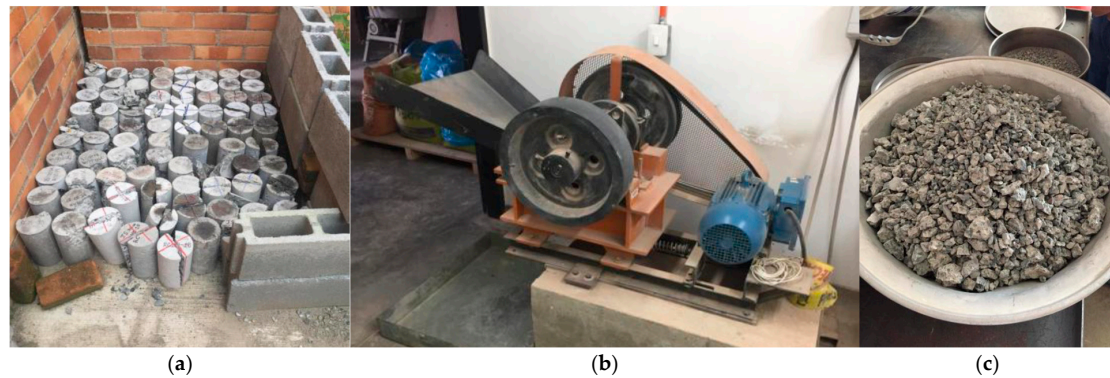


Figure 3. Production process of the recycled coarse aggregate: (a) tested high-strength concrete specimens; (b) laboratory jaw crusher; (c) produced recycled coarse aggregate.

The physical properties of the RCA are summarized in Table 4. The results indicate that the RCA exhibited high quality and performance, fulfilling the technical requirements for abrasion and soundness, with values comparable to those of the natural coarse aggregate.

Table 4. Physical properties of recycled concrete aggregate.

Test		Unit	Result	Standards Used
Granulometry	FM ¹	-	6.72	ASTM C136, 2025
	MS ¹	mm	25.4	
	NMS ¹	mm	19.1	
Abrasion Resistance		%	30.5	ASTM C131, 2020
Bulk Density	Compacted	kg/L	1.34	ASTM C29, 2023
	Loose	kg/L	1.25	
Specific gravity saturated surface dry		-	2.54	ASTM C127, 2025
Absorption		%	5.42	ASTM C127, 2025
Soundness		% Loss	7.56	ASTM C88, 2018

¹ MF: Fineness modulus; MS: Maximum size; NMS: Nominal maximum size.

2.1.3. Additives

A third-generation modified acrylic-based superplasticizer was used to produce concrete mixtures with low water-to-cement ratios. The physical properties of the admixture are summarized in Table 5. The admixture ensures extended workability retention, even under hot weather conditions. It is an aqueous solution of acrylic polymers (formaldehyde-free) capable of effectively dispersing cement particles and promoting a controlled hydration process.

Table 5. Physical properties of the superplasticizer additive.

Test	Unit	Result
Solid content	%	56.8
Density (Technical sheet)	g/cm ³	1.15
pH (Technical sheet)	-	7 ± 1

2.2. Concrete Mix Compositions and Preparation

Based on the material characterization results, the concrete mix proportions were established following the recommendations of Lopes [35] and ACI 211.4 [36]. The target compressive strength was set at 60 MPa, which corresponds to strength class C60/75.

To evaluate the influence of the recycled coarse aggregate on the concrete properties, partial replacements by weight of 10%, 20%, and 40% were adopted, along with a reference mixture (0%). These replacement levels were established based on the comparative analysis by Prajapati et al. (2019), which showed that untreated recycled concrete aggregate contents above 20% lead to a significant reduction in both compressive strength and elastic modulus [24]. Similarly, considering local public policy, the Cali Construye Sostenible certification from the Sustainable Construction Manual of Santiago de Cali proposes a 30% replacement in both structural and non-structural concretes, with performance verified through appropriate trial mixes [37]. On the other hand, to determine whether statistically significant differences existed among the experimental results for the mechanical properties, an analysis of variance (ANOVA) was performed for each concrete mixture at a 95% confidence level. Table 6 summarizes the mix composition and nomenclature of each mixture.

Table 6. Composition and parameters of the concrete mixes.

	Parameter	Ref	RCA10	RCA20	RCA40
Composition Data (kg/m ³)	Water (kg/m ³)	201	201	201	201
	Cement (kg/m ³)	550	550	550	550
	Fine Aggregate (kg/m ³)	610	610	610	610
	Coarse Aggregate (kg/m ³)	1100	900	880	800
	RCA	0	110	220	440
	SP Additive	3	3	3	6
Mix Parameters	Water/Cement ratio	0.37	0.37	0.37	0.37
	Coarse/Fine Agg. ratio	1.8	1.7	1.8	2.0
	Dry mortar (%)	51.3	51.3	51.3	51.3
	Water/Dry materials (%)	8.9	8.9	8.9	8.9

2.3. Concrete Mixes Characterization

2.3.1. Fresh Properties

The workability of each concrete mixture was evaluated using the slump test, according to ASTM C143-20. The slump consistency was maintained constant at 10 ± 2 cm for all mixtures by adjusting the dosage of the superplasticizer admixture.

2.3.2. Physical Properties

The physical properties evaluated were selected due to their relevance to mechanical performance and durability, including ultrasonic pulse velocity (UPV), total water absorption, and capillary water absorption. This non-linear behavior suggests that moderate HP-RCA contents may increase pore connectivity without sufficient additional hydration to compensate, whereas higher replacement levels promote matrix refinement and reduced permeability.

- **Ultrasonic Pulse Velocity:** This test was performed to assess the quality and uniformity of the hardened concrete. All specimens used for mechanical testing were also evaluated following ASTM C597-22 (Figure 4a). Each value reported represents the average of five readings per specimen.

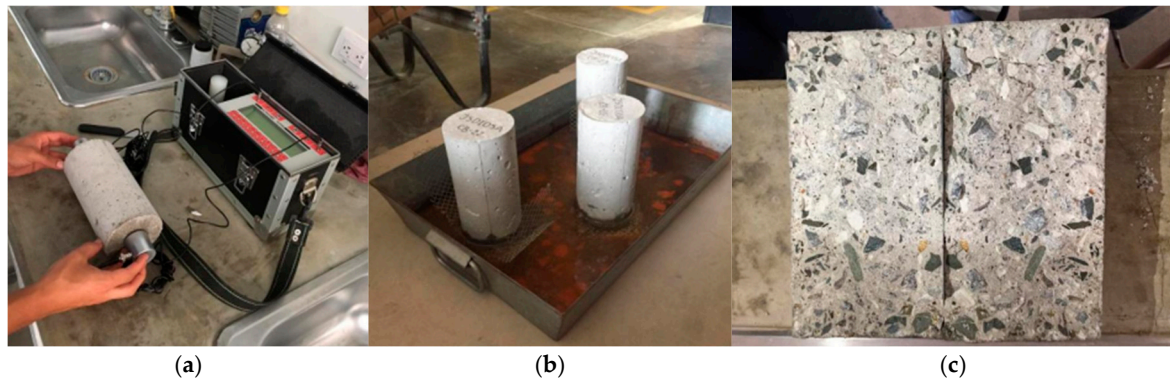


Figure 4. Physical property tests: (a) ultrasonic pulse velocity; (b) total water absorption; (c) capillary water absorption.

- **Total Water Absorption:** The apparent density, total absorption, and open porosity were determined in accordance with ASTM C642-21. Three specimens from each mixture were tested at 28 days of curing.
- **Capillary Water Absorption:** This test was conducted to evaluate the concrete's permeability and resistance to water penetration, which are closely related to durability. The procedure followed ASTM C1585-20 (Figure 4b). Three specimens from each mixture were tested at 28 days, and the capillary rise height was also measured for each sample (Figure 4c). This non-linear behavior suggests that moderate HP-RCA contents may increase pore connectivity without sufficient additional hydration to compensate, whereas higher replacement levels promote matrix refinement and reduced permeability.

2.3.3. Mechanical Properties

To evaluate the effect of incorporating recycled coarse aggregate (RCA), the following mechanical properties were studied at different curing ages: compressive strength, splitting tensile strength, and static modulus of elasticity:

- **Compressive Strength:** Cylindrical specimens were tested in accordance with ASTM C39-23 using a 1500 kN capacity hydraulic testing machine (Figure 5a). For each concrete mixture, four specimens were tested at 7, 28, and 56 days of curing.
- **Splitting Tensile Strength:** This property was determined following ASTM C496-17 (Figure 5b). For each mixture, three specimens were tested at 7 and 28 days to assess the tensile behavior of the concrete.

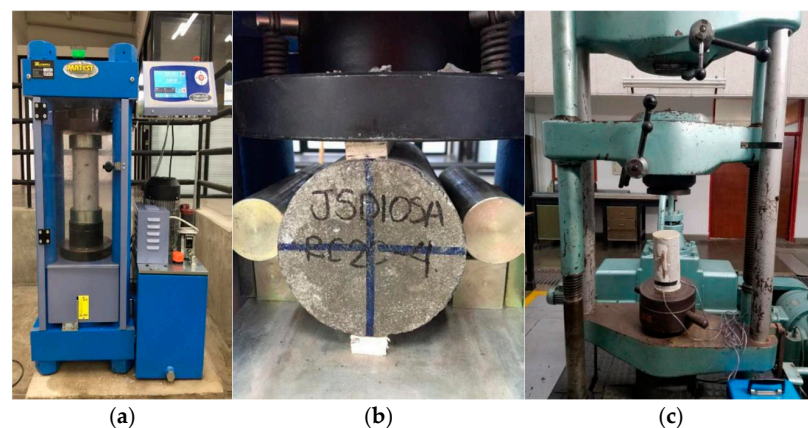


Figure 5. Mechanical property tests: (a) compressive strength; (b) splitting tensile strength; (c) static modulus of elasticity.

- **Static Modulus of Elasticity:** The modulus of elasticity was determined according to ASTM C469-22 (Figure 5c). The test was performed at 28 days, using the 40% of the ultimate compressive strength as the reference load. Two specimens per mixture were evaluated. Strain measurements were obtained using two electrical strain gauges attached directly to the concrete surface to ensure greater measurement accuracy.

3. Results

3.1. Fresh Properties

It is important to note that the reference mixture and those containing 10% and 20% RCA achieved the target slump range of 10 ± 2 cm using the same dosage of superplasticizer. The incorporation of recycled coarse aggregate did not significantly affect workability up to a replacement level of 20%, which is consistent with the findings of Hamad and Dawi [38]. However, for the mixture with 40% RCA, a higher amount of superplasticizer was required to achieve the target slump. This behavior can be attributed to two main factors: (i) the angular shape and rough surface texture of the recycled aggregates, and (ii) the partial absorption of mixing water and admixture by the RCA, since it was added in an air-dry condition. These characteristics likely reduced the effective water available for lubrication, resulting in lower workability. This condition was selected to represent realistic field conditions during concrete production. However, it has been reported by Bravo et al. (2017) that increasing superplasticizer dosage in concrete with high RCA content can retard hydration kinetics and reduce early strength, but it generally improves later-age strength and overall microstructural quality [39].

3.2. Physical Properties

3.2.1. Ultrasonic Pulse Velocity

Table 7 summarizes the ultrasonic pulse velocity (UPV) results obtained from the specimens tested for mechanical properties at 7, 28, and 56 days. The reference concrete showed a pronounced increase in velocity from 7 to 28 days, with only a slight change between 28 and 56 days. In contrast, concretes containing RCA exhibited a gradual increase in UPV over time. This trend may be attributed to the ongoing hydration of unhydrated cement particles present in the RCA, which generate additional hydration products and consequently reduce the overall porosity of the material.

Table 7. Average ultrasonic pulse velocity values for the tested concretes.

Mix	7 Days		28 Days		56 Days	
	Speed (m/s)	SD	Speed (m/s)	SD	Speed (m/s)	SD
Ref	4351.38	48.14	4679.26	13.37	4617.83	10.75
RCA10	4567.46	15.20	4639.51	45.47	4649.71	18.80
RCA20	4492.03	14.41	4595.54	11.05	4664.45	24.13
RCA40	4497.10	76.19	4676.18	95.54	4686.07	74.68

The obtained results are consistent with the behavior expected for high-strength concretes (HSCs) and align with the observations reported by González and Etxeberria [40].

3.2.2. Total Water Absorption

As shown in Table 8, the total water absorption values decreased with increasing RCA content at 28 days. Since the absorption percentage is generally considered an indicator of the overall porosity of the concrete, this reduction suggests that the incorporation of RCA may have promoted further cement hydration due to the presence of anhydrate cement

particles in the recycled material. This phenomenon is also reflected in the void ratio and correlates with the mechanical performance discussed later.

Table 8. Average total immersion water absorption results for concretes at 28 days.

Mix	Water Absorption		Dry Density		Permeable Pore Volume	
	(%)	SD	(g/cm ³)	SD	(%)	SD
Ref	4.97	0.10	2.37	0.01	11.34	0.22
RCA10	4.84	0.21	2.40	0.02	10.82	0.45
RCA20	4.75	0.20	2.38	0.01	10.54	0.46
RCA40	4.18	0.03	2.42	0.03	9.64	0.05

3.2.3. Capillary Water Absorption

The results for capillary water absorption are presented in Table 9. As expected, time was a key influencing variable. Capillary absorption occurs due to the surface tension of water acting within the concrete's pore network. This property, strongly related to durability, depends mainly on both the characteristics of the liquid and the microstructure of the solid, particularly pore radius, tortuosity, and connectivity. This non-linear behavior suggests that moderate HP-RCA contents may increase pore connectivity without sufficient additional hydration to compensate, whereas higher replacement levels promote matrix refinement and reduced permeability.

Table 9. Average capillary water absorption results for concrete cylinders at 28 d (g/cm²).

Mix	1 h		3 h		6 h		24 h		48 h		72 h		Penetration (cm)	
	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
Ref	0.16	0.05	0.23	0.06	0.30	0.06	0.42	0.07	0.59	0.09	0.67	0.10	5.38	0.20
RCA10	0.13	0.05	0.18	0.07	0.27	0.08	0.51	0.10	0.69	0.10	0.80	0.10	7.05	0.49
RCA20	0.14	0.01	0.23	0.01	0.32	0.02	0.59	0.03	0.76	0.03	0.87	0.03	7.49	0.45
RCA40	0.14	0.03	0.20	0.03	0.25	0.03	0.39	0.03	0.48	0.03	0.53	0.03	3.88	0.78

After 72 h, the reference mixture showed lower capillary absorption than RCA10 and RCA20. However, the mixture containing 40% RCA exhibited the lowest absorption, even lower than the reference mix. This result confirms the superior impermeability of the RCA40 concrete, consistent with the findings from the total immersion absorption test (Table 8). Moreover, the RCA40 mixture likely possesses a distinct pore structure, characterized by smaller and less interconnected pores, as evidenced by the lower penetration height and overall absorption. This behavior is consistent with the mechanical property trends discussed in the following section. This non-linear behavior suggests that moderate HP-RCA contents may increase pore connectivity without sufficient additional hydration to compensate, whereas higher replacement levels promote matrix refinement and reduced permeability.

3.3. Mechanical Properties

3.3.1. Compressive Strength

Table 10 presents the average uniaxial compressive strength values of the concretes at 7, 28, and 56 days. The ANOVA results indicated that the incorporation of up to 20% RCA did not produce a statistically significant difference in compressive strength compared with the reference concrete. However, at a 40% replacement level, the compressive strength increased on average by approximately 40% across all curing ages.

Table 10. Average compressive strength results for the tested concretes.

Mix	7 Days		28 Days		56 Days	
	(MPa)	SD	(MPa)	SD	(MPa)	SD
Ref	53.59	0.99	66.72	1.97	68.94	1.39
RCA10	56.82	1.82	64.28	1.91	69.37	2.28
RCA20	58.87	1.31	66.58	3.39	68.99	0.99
RCA40	75.92	2.14	94.71	1.24	94.99	4.06

When the ANOVA was applied separately at each curing age, significant differences were observed only at 7 days, where three distinct groups of concretes were identified. At this early age, mixtures containing 10%, 20%, and 40% RCA exhibited strength gains of approximately 6%, 10%, and 42%, respectively, compared with the control mixture. These findings suggest that the inclusion of RCA had a positive influence on early-age strength development. This indicates that HP-RCA contributes more significantly during early hydration stages, while long-term performance tends to stabilize. As expected, compressive strength increased with curing time. The reference mixture exhibited a strength gain of approximately 25% from 7 to 28 days and 3% from 28 to 56 days, while the other mixtures showed a similar trend (Figure 6). These results reinforce the conclusion that the incorporation of RCA enhances compressive strength, particularly at early ages. This also indicates that HP-RCA contributes more significantly during early hydration stages, while long-term performance tends to stabilize.

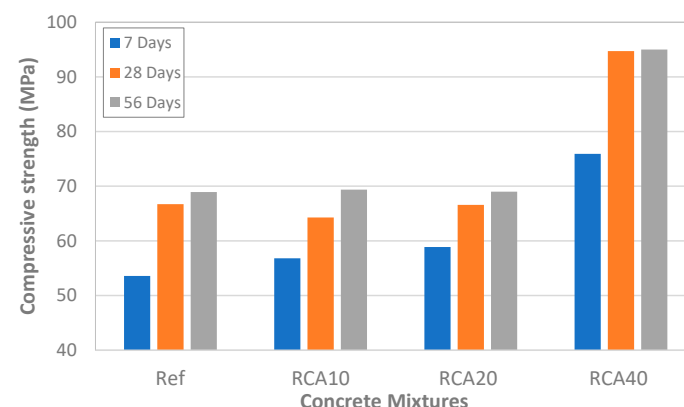


Figure 6. Compressive strength development of concrete mixtures using 0% (Ref), 10%, 20% and 40% recycled concrete aggregate coming from high-strength concrete (over 60 MPa).

The observed improvement can be explained by the presence of adhered high-strength cement paste on the recycled aggregates. This residual paste likely contained anhydrous cement particles due to the low water-to-cement ratio of the original high-strength concrete. Upon rehydration, these particles contributed to the formation of additional hydration products, improving the bond between the RCA and the new cement matrix and thereby enhancing the mechanical performance. This interpretation is consistent with the trends observed in the physical properties discussed earlier.

In addition, the recycled aggregates exhibited favorable results in tests related to mechanical durability, such as abrasion resistance and soundness, suggesting their high intrinsic quality. The rough surface texture and angular shape of the RCA likely improved the interfacial transition zone (ITZ) between the aggregate and cement paste, contributing to better stress transfer and higher compressive strength. Similar conclusions were reported by González and Etxeberria [40], who observed that rough RCA surfaces enhance the mechanical bond at the ITZ, leading to improved overall mechanical behavior of concretes incorporating recycled aggregates. The improvements in the above-mentioned parameters

further enhance, on a larger scale, the packing density and mechanical interlock of concrete mixes incorporating recycled aggregates derived from high-strength parent concrete. Recent findings by Jagadesh et al. (2024) [15] reported 15–20% increases in compressive strength in high-strength concrete incorporating recycled concrete aggregates. Likewise, Rezar et al. [16] observed a 5–8% improvement in tensile strength in mixes produced with recycled aggregates sourced from deconstructed high-strength concrete bridges.

3.3.2. Splitting Tensile Strength

Table 11 summarizes the average splitting tensile strength results for all mixtures. The overall ANOVA revealed statistically significant differences between the RCA40 and the reference concrete, indicating a notable increase in tensile strength for the mixture with the highest recycled aggregate content.

Table 11. Average splitting tensile strength results of concretes.

Mix	7 Days		28 Days	
	(MPa)	SD	(MPa)	SD
CBA	4.48	0.33	5.53	0.09
RCA10	4.70	0.36	5.03	0.23
RCA20	4.89	0.08	4.65	0.31
RCA40	5.12	0.26	5.68	0.40

At 7 days, a clear trend was observed: the incorporation of 10%, 20%, and 40% RCA resulted in strength increases of approximately 5%, 9%, and 14%, respectively, compared with the control mix. This improvement at early ages can be attributed to the continued hydration of the adhered high-strength cement paste on the surface of the recycled aggregates, which enhances the bond within the composite. These findings are consistent with those obtained for compressive strength, confirming the beneficial role of the RCA in early-age performance. This indicates that HP-RCA contributes more significantly during early hydration stages, while long-term performance tends to stabilize.

At 28 days, the trend became less pronounced. The reference concrete exhibited higher tensile strength than RCA10 and RCA20, but lower than RCA40. This behavior aligns with the results reported by González and Etxeberria [40] and Hamad and Dawi [38], who also observed that moderate replacement levels of RCA tend to have limited influence on tensile strength, while higher-quality or higher-content RCAs can produce comparable or even superior results.

3.3.3. Static Modulus of Elasticity

Table 12 presents the average results for the static modulus of elasticity. An increasing trend was observed as the RCA replacement level increased: the mixtures containing 10%, 20%, and 40% RCA exhibited gains of approximately 44%, 52%, and 119%, respectively, compared with the reference concrete.

Table 12. Average static modulus of elasticity of the concrete mixes after 28 curing days.

Mix	28 Days (GPa)	SD
Ref	24.53	1.86
RCA10	35.23	0.47
RCA20	37.31	3.17
RCA40	53.74	2.98

This trend differs from that reported by González and Etxeberria [40] and Hamad and Dawi [38], where such a marked improvement was not observed. Since the elastic modulus of concrete is largely governed by the type and stiffness of the coarse aggregate and the interfacial transition zone (ITZ) characteristics between the aggregate and the hydrated cement paste, these results suggest that the RCA used in this study exhibits superior mechanical quality and surface morphology compared to typical recycled aggregates.

The substantial improvement may be attributed to the rough and angular texture of the RCA, which enhances mechanical interlocking, packing and adhesion within the ITZ, as well as to the dense microstructure of the adhered high-strength paste. Consequently, the RCA used herein can be classified as a high-performance recycled aggregate (HP-RCA), suitable for the production of high-strength recycled concretes (HSRCs), due to its low porosity, high abrasion resistance, and its origin from high-strength concrete.

3.4. Relationships Between Mechanical Properties

This analysis was conducted using scatter plots to identify the proportional relationships between pairs of mechanical properties.

3.4.1. Compressive Strength vs. Splitting Tensile Strength

Although two functions, a power-law model and a linear model, were evaluated to describe the relationship between compressive strength (f_c) and splitting tensile strength (f_t), the linear model provided the best correlation, with an R^2 value of 0.629, which can be considered acceptable. However, this correlation was influenced by an outlier corresponding to the 7-day tensile strength value of the RC20 mixture, as shown in Figure 7. As expected, a directly proportional relationship was found between compressive and tensile strength. Considering the relevance of this relationship for the technological application of high-strength concretes incorporating recycled aggregates, further experimental research is needed to provide additional data and evidence.

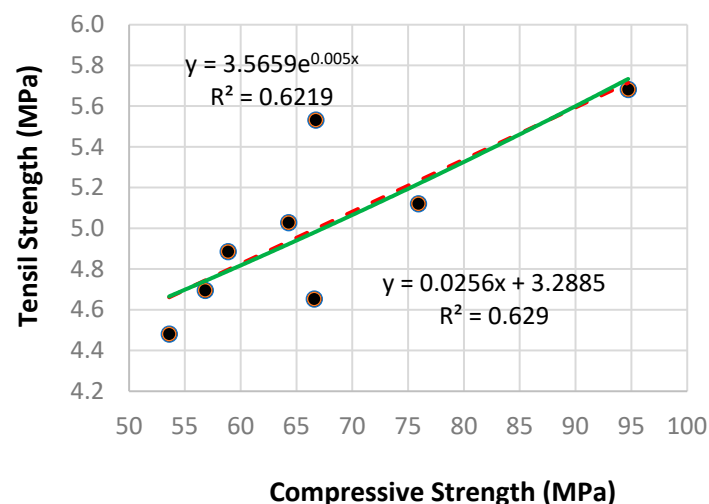


Figure 7. Correlation between experimentally obtained values of compressive strength (f_c , x-axis) and splitting tensile strength (f_t , represented in y-axis).

3.4.2. Compressive Strength vs. Ultrasonic Pulse Velocity

Figure 8 presents the scatter plot and the linear relationship between the experimentally obtained compressive strength and ultrasonic pulse velocity. As expected, the ultrasonic velocity increased with the compressive strength of the concretes, which aligns with the behavior of the studied mixtures. This technique effectively reflects the homogeneity and overall quality of the concrete. A strong direct correlation was found for the Ref,

RCA20, and RCA40 mixtures, with high determination coefficients (R^2). However, a weak relationship was observed for the RCA10 mixture, as its data did not exhibit a well-defined linear trend.

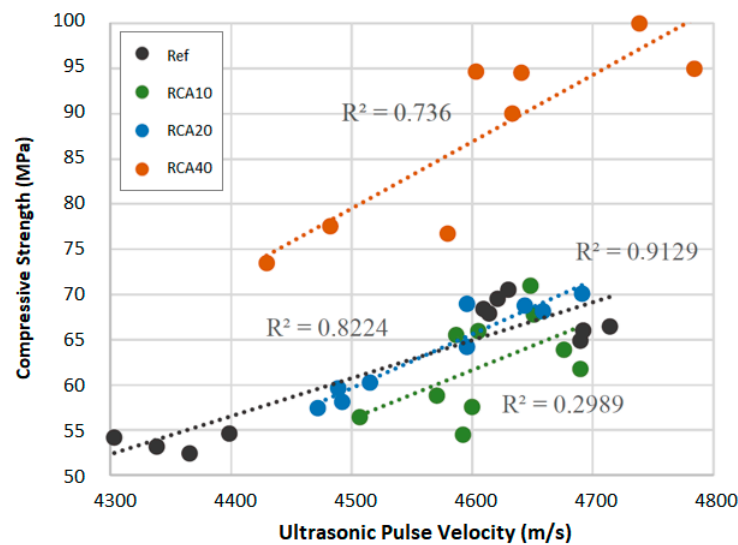


Figure 8. Correlation between experimentally obtained values of compressive strength and ultrasonic pulse velocity.

4. Conclusions

The findings of this research demonstrate the feasibility of producing high-performance recycled aggregates derived from high-strength concrete waste obtained from laboratory test specimens. These recycled aggregates can meet the technical requirements established by international standards for use in concrete and mortar production. The recycled aggregate is herein classified as a high-performance recycled coarse aggregate (HP-RCA) due to its low porosity, high abrasion resistance, and its origin from high-strength concrete.

Also, the results confirm that it is feasible to produce high-strength recycled aggregate concrete by partially replacing natural coarse aggregate with recycled concrete aggregate. Regarding compressive strength, the incorporation of RCA did not negatively affect this property. In fact, a 40% replacement level led to higher compressive strength values. This improvement can be attributed to the continued hydration of anhydrate cement present in the old high-strength paste within the RCA and the enhanced bond between the recycled aggregate and the new cement matrix due to its rough surface texture. Therefore, it is recommended that the production of high-strength recycled aggregate concrete includes the use of superplasticizers and pre-saturation of the RCA prior to mixing. Similarly, given the high quality of the recycled aggregate, a positive influence was observed on the static modulus of elasticity with increasing replacement levels.

Concerning physical properties which are related to durability, the use of RCA resulted in a reduction in void content and, consequently, in overall concrete porosity, which may positively influence the durability and service life of the material. Conversely, capillary absorption results indicated greater water ingress in the mixtures with 10% and 20% RCA replacement. This suggests a change in the pore structure of the concrete (pore radius, connectivity, and tortuosity) caused by the presence of the recycled aggregate. This non-linear behavior suggests that moderate HP-RCA contents may increase pore connectivity without sufficient additional hydration to compensate, whereas higher replacement levels promote matrix refinement and reduced permeability. Future research should further validate the mechanisms underlying the observed improvements in mechanical performance by incorporating additional porosimetry analyses and detailed SEM microstructural

characterization. Moreover, future studies should assess key durability indicators, such as chloride penetration and sulfate resistance, which are required by most international standards governing the use of recycled concrete aggregates.

Finally, this study promotes the use of high-performance recycled aggregates to produce various types of structural concretes. Within the framework of the circular economy, this approach supports the development of sustainable construction materials with high mechanical performance, contributing to the reduction in the environmental impact of the construction industry, the conservation of natural resources, and the achievement of global targets for construction and demolition waste valorization. Therefore, the results presented here were considered a case study that supports the use of recycled aggregates in high-strength concrete in the circular economy model included in the Cali Construye Sostenible Certification and the Manual de Construcción Sostenible de Santiago de Cali, both local public policies from Cali (Colombia) which promote sustainable construction.

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