

Article

Mechanical Performance and Durability of Concretes with Partial Replacement of Natural Aggregates by Construction and Demolition Waste

Thamires Alves da Silveira ¹, Rafaella dos Passos Nörnberg ², Marcelo Subtil Santi ², Renata Rabassa Morales ², Alessandra Buss Tessaro ¹, Hebert Luis Rosseto ³, Rafael de Avila Delucis ^{1,*} and Guilherme Hoehr Trindade ³

- ¹ Post-Graduate Program in Materials Science and Engineering, Federal University of Pelotas, Pelotas 96010-610, Brazil; thaamiresasilveira@gmail.com (T.A.d.S.); alessandrabuss@gmail.com (A.B.T.)
- ² Civil Engineering, Federal University of Pelotas, Pelotas 96010-610, Brazil; rafaellanornberg@gmail.com (R.d.P.N.); m.subtilsanti@outlook.com (M.S.S.); renatarmorales@yahoo.com.br (R.R.M.)
- ³ Graduate Program in Civil Engineering, Engineering Center, Federal University of Pelotas, Pelotas 96010-610, Brazil; hlrosseto@ufpel.edu.br (H.L.R.); guihoehr@hotmail.com (G.H.T.)
- * Correspondence: rafael.delucis@ufpel.edu.br

Abstract

This study investigated the mechanical performance and durability of concretes produced with varying proportions of recycled coarse aggregate from construction and demolition waste (CDW), ranging from 0% to 100% replacement of natural coarse aggregate, using recycled aggregates derived from crushed concrete and mortar debris, characterized by lower density and high water absorption (~9%) compared to natural aggregates. A key contribution of this research lies in the inclusion of intermediate replacement levels (20%, 25%, 45%, 50%, and 65%), which are less explored in the literature and allow a more refined identification of performance thresholds. Fresh-state parameters (slump), axial compressive strength (7 and 28 days), total immersion water absorption, sorptivity, and chloride ion penetration depth (after 90 days of immersion in a 3.5% NaCl solution) were evaluated. The results indicate that, up to 50% CDW content, the concrete maintains slump (≥ 94 mm), characteristic strength (≥ 37.2 MPa at 28 days), and chloride penetration (≤ 14.1 mm) within the limits for moderate exposure conditions, in accordance with ABNT: NBR 6118. Water absorption doubled from 4.5% (0% CDW) to 9.5% (100% CDW), reflecting the higher porosity and adhered mortar on the recycled aggregate, which necessitates adjustments to the water–cement ratio and SSD pre-conditioning to preserve workability and minimize sorptivity. Concretes with more than 65% CDW exhibited chloride penetration depths exceeding 15 mm, potentially compromising durability without additional mitigation. The judicious incorporation of CDW, combined with optimized mix design practices and the use of supplementary cementitious materials (SCMs), demonstrates technical viability for reducing environmental impacts without significantly impairing the structural performance or service life of the concrete.

Keywords: construction and demolition waste; durability; recycled aggregate; mechanical performance; water absorption; chloride ion penetration



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1. Introduction

The ever-increasing quantity of construction and demolition waste (CDW) poses a serious environmental challenge, as it requires ever-larger landfill areas and entails public

health risks. It is estimated that approximately 1 million tons of CDW are generated each year, much of which is disposed of untreated in sanitary landfills, contributing to the depletion of usable land and exacerbating local impacts [1]. However, a large fraction of this debris contains reusable components that, if managed through effective reuse and recycling policies, can substantially reduce the final waste volume [2].

Nonetheless, many of these materials contain recyclable fractions which, if properly processed, can substantially reduce the final volume of debris [2]. Recycling CDW into reclaimed aggregates (RA) for concrete has proven an effective strategy to both curb the extraction of natural resources and decrease the volume of waste sent to landfills [3,4]. A key component of this approach is selective demolition, which removes reusable materials in advance and can cut landfill-bound waste by up to 90%. Life-cycle assessments show that, compared with conventional demolition, selective demolition also reduces greenhouse-gas emissions, acidification, tropospheric ozone formation, eutrophication and heavy-metal contamination, although its uptake remains limited by cost and logistical hurdles [5,6].

In fact, recycled aggregates differ considerably from natural aggregates, typically exhibiting lower density, higher porosity, and greater water absorption due to the presence of adhered mortar. These characteristics tend to impair workability and mechanical strength, while also increasing sorptivity and chloride ingress, thus posing durability concerns for structural applications [3,7]. To overcome these drawbacks, numerous studies have explored pre-treatment techniques for recycled aggregates, as well as the incorporation of supplementary cementitious materials, aiming to mitigate the negative effects of old mortar and to refine the interfacial transition zone (ITZ).

Alongside experimental approaches, recent computational and artificial intelligence methods have provided deeper insights and practical tools for advancing recycled aggregate concretes (RAC). Mesoscale discrete element modeling (DEM) has demonstrated how the amount and quality of old mortar critically influence crack initiation and propagation, confirming that removing or weakening the adhered mortar can significantly improve RAC's mechanical performance [8]. In parallel, AI-driven mix design frameworks have been applied to optimize concretes with recycled aggregates, showing that intelligent algorithms can simultaneously enhance mechanical properties and sustainability. For instance, Yu et al. [9] developed an agile and scalable optimization framework for green concretes incorporating precast rejects, while Yu, Su & Wu [7] proposed a hybrid Bayesian and genetic algorithm approach to balance strength, cost, and carbon emissions, achieving reductions of up to 60%. Although initially focused on other concrete types, these methodologies are transferable to CDW-based concretes, pointing to promising future research opportunities where experimental data can be coupled with AI-assisted optimization to identify mix designs that reconcile performance and environmental impact.

Among CDW streams, concrete stands out due to its enormous global consumption—estimated at 11 billion tons per year, second only to water [10]. Extracting natural aggregates to meet this demand depletes geological resources, degrades ecosystems and generates pollutant emissions, while concrete demolition waste itself is largely under-utilized. Yet, there is growing demand for RA in a variety of applications: landscaping, road base and sub-base layers, asphalt pavements, mortars and structural concretes [1].

Physically and mechanically, RAs differ markedly from natural aggregates: they have lower bulk density and specific gravity, but higher water absorption, porosity and friability. These characteristics tend to reduce both workability and strength, especially because the residual cement paste adhering to recycled fragments increases surface roughness and geometric irregularity [3].

In the fresh state, Luo et al. [11] observed a slump reduction of 2–5 cm for every 25% RA substituted. Concurrently, mixture density decreased by 3–6%, and air content tended to

rise. These effects can, however, be mitigated by mix-design strategies such as pre-wetting RA to saturated surface-dry (SSD) condition and using high-efficiency superplasticizers, which help recover slump and control air content.

Silva et al. [1], compiling data from over 200 sources, found that the SSD bulk density of RA typically ranges from 2300 to 2450 kg/m³, compared with 2580 kg/m³ for natural aggregates. Water absorption of coarse RA averaged 4.7–5.0%, versus about 1.6% for natural aggregate. These factors correlate with strength losses, yet keeping RA content below roughly 30–40% by volume can limit strength reductions to 10–15% [1].

Numerous studies demonstrate that RA incorporation can lower concrete's compressive and tensile strengths, particularly at substitution levels above 30%. Nevertheless, mechanical properties remain adequate up to 30% RA if mix designs are properly optimized and supplemented with pozzolanic materials [3].

When coarse natural aggregates are partially replaced with RA, most research reports a moderate 10–15% loss in 28-day compressive strength at 30% RA, with more pronounced 10–20% drops at around 50% substitution [1,3]. Splitting tensile strength similarly decreases with increasing RA content—approximately 5–10% loss at 30% RA. However, adding fly ash or GGBS (35–50%) to mixes with up to 50% RA can partially offset this loss, improving splitting tensile strength by up to 7.3% compared to controls without admixtures [3]. Xiao et al. [12] observed that substituting up to 30% of cement mass with recycled fines (<45 µm) yielded minimal or even slightly positive compressive strength changes—about a 6% increase at 15% substitution [1,12]. Akbarimehr et al. [13] assessed unconstrained CDW-derived concrete and found 10–15% compressive-strength losses at 25–30% RA, 10–20% at 50% RA, and 28–42% in total substitution of coarse RA [13].

In the study by Wu et al. [14], recycled powders (RCP and RPP) from concrete waste were evaluated as substitutes for cement, fly ash (FA), and ground granulated blast furnace slag (GGBS). The RCP, when used as a total replacement, reduced the polymerization reaction and weakened the microstructure. In contrast, RPP showed better performance, maintaining good microstructural characteristics even at high replacement levels, especially up to 50%, without compromising the material's properties. Partial replacements (25–50%) produced satisfactory results with no significant loss of strength. RPP stood out by reaching 44.9 MPa of compressive strength at full replacement and proved to be more suitable than RCP, particularly for replacing FA rather than GGBS.

Mahmoud et al. [15] investigated the use of waste powders such as granite, marble, granodiorite, and ceramic, incorporating up to 9% as partial cement replacement. The study reported a 25% increase in compressive strength at 28 days for the mixture containing 7% granite powder. Additionally, the powders generally improved the workability of the concrete, except for marble powder, which caused a slight 6% reduction compared to the control mix. Overall, all waste powders contributed to an accelerated hydration process, enhancing the early-age performance of the concrete.

Regarding elastic modulus, full RA replacement reduced MOE by 18–40% for coarse aggregates and 28–38% for fines compared to reference concrete. Yet, when RAs undergo mechanical, chemical or thermal treatments to remove or strengthen the adhered mortar—and/or when supplemented with SCMs—losses in strength and MOE can be effectively eliminated or even reversed, matching or surpassing conventional concrete performance [11].

Durability of RA concretes is often compromised by their higher porosity and water absorption, which increase sorptivity and chloride permeability, exposing reinforcement to corrosion and reducing resistance to aggressive agents and freeze–thaw cycles [3]. Silva et al. [1] found water absorption of 6–8% in RA mixes versus ≤ 2% in conventional concretes, and a 10–20% increase in rapid chloride-permeability for RA contents above 30%; below

that threshold, the increase was only 5–10%, still acceptable for reinforced structures. Addition of pozzolanic materials (e.g., FA, GGBS, metakaolin) can cut chloride penetration and capillary absorption by up to 50%, yielding durability comparable to conventional concrete even at 50% RA content [1,3].

According to the study Thomas et al. [16] that evaluated different replacement levels of recycled concrete aggregate (RCA), it was concluded that substitution rates of up to 25% have no significant effect on concrete properties. However, when the replacement level exceeds this threshold, noticeable changes occur, particularly in compressive strength and elastic modulus. Regarding durability, it was observed to be inversely proportional to the RCA content, meaning that higher replacement levels reduce the durability of the concrete. Furthermore, improving concrete quality is closely associated with increasing the cement content, which enhances paste hydration and matrix density, leading to better overall performance.

Fattouh et al. [17] analyzed the influence of recycled aggregate particle size distribution on concrete properties. As expected, variations in gradation had a direct impact on workability. Mixtures with modified aggregate gradation showed a 22% reduction in slump, caused by changes in the proportion of particle sizes, which directly affected the fluidity of the concrete mix. Additionally, when the gradation was adjusted to favor larger particles (RCA2 and RCA3), both mixes achieved higher compressive strength, with gains of around 47%, and flexural strength, with increases of up to 44%, compared to the control mix at 28 days.

The microstructure of the concrete was also significantly influenced. Mixtures with modified gradation exhibited accelerated hydration, a reduction in portlandite content, and an increase in C-S-H formation, resulting in a denser and more interconnected cement paste matrix. These samples showed abundant C-S-H and refined interfacial transition zones (ITZs). Overall, the modified gradation of recycled aggregates likely created a more favorable environment for hydration, leading to improved C-S-H development and enhanced mechanical and microstructural performance [17].

Carbonation depths in RA concretes can be up to twice those of natural aggregate concretes, depending on composition and substitution level [18]. Nevertheless, the carbonation coefficient remains below 0.5 mm/year—a benchmark for good-quality concrete—and reinforcement passivity is preserved, even in mixes using blended RA or recycled-content cement [18]. Furthermore, pre-treatments of RA—such as immersion in $\text{Ca}(\text{OH})_2$ solution or controlled carbonation—have been shown to restore carbonation resistance to levels comparable with those of conventional concrete [11].

In this context, the present article aims to discuss the mechanical performance and durability of concretes produced with partial replacement of natural aggregates by CDW-derived RA. The novelty of this work lies in the detailed evaluation of several intermediate substitution levels, which are often overlooked in previous studies, thereby enabling a more precise determination of thresholds where performance and durability are still acceptable. By combining this approach with standardized mix design, the study contributes to practical guidelines for structural applications of CDW-based concretes.

2. Materials and Methods

2.1. Materials

The materials selected for this study were chosen to represent both conventional concrete and concrete incorporating recycled aggregates (RAs) derived from construction and demolition waste (CDW) with structural characteristics. The binder used was a high-early-strength Portland cement (CP V-ARI) with no pozzolanic additions, supplied by a locally certified producer in accordance with ABNT: NBR 16697 [19]. According to the

manufacturer's data, the CP V-ARI cement exhibited a minimum 28-day compressive strength of 53 MPa. Its typical chemical composition (Table 1) confirms a high clinker content, which is known to promote early-age strength development. Schack et al. [20] have likewise demonstrated the direct influence of clinker proportion on the early-strength gain in Portland cements.

Table 1. Chemical composition of cement CP V-ARI.

Oxide	Content (%)
SiO ₂	21.4 ± 0.3
Al ₂ O ₃	5.1 ± 0.2
Fe ₂ O ₃	3.1 ± 0.2
CaO	63.5 ± 0.5
MgO	2.2 ± 0.1
SO ₃	2.8 ± 0.2
K ₂ O	0.7 ± 0.1

Source: author.

The water used was potable municipal supply water, in accordance with ABNT: NBR 15900-1 [21]. The natural aggregates consisted of river sand with a fineness modulus of 2.4, a specific gravity of 2.60 g/cm³, and water absorption of 1.29%, and graded crushed stone (sizes 0 and 1) with specific gravities of 2.64 g/cm³ and 2.75 g/cm³, respectively, and water absorptions ranging from 1.25% to 1.70%. The recycled aggregates were produced by collecting, crushing, sieving, and homogenizing demolition waste composed predominantly of hardened concrete and mortar, yielding an average specific gravity of 2.16 g/cm³ and water absorption of approximately 9.0%.

To reduce the influence of the recycled aggregates' high porosity on workability and mechanical properties, the recycled aggregates were pre-saturated before mixing. This procedure was intended to minimize water uptake during mixing, as recommended by ABNT: NBR 15116 [22].

2.2. Concrete Mix Proportioning and Production

The concrete mixes were proportioned by adapting the dosing method of Helene and Terzian [23], with strict control of the water–cement ratio (w/c) and slump. A fixed cement content of 420 kg/m³ was used for all mixes to achieve structural concrete class C25/30.

Concrete mixtures were prepared with various levels of replacement of natural coarse aggregates by recycled aggregates from construction and demolition waste (CDW) at 0%, 20%, 50% and 100%, as well as intermediate levels of 25%, 45% and 65%. The inclusion of these intermediate proportions was deliberate, since the conventional scheme (0–20–50–100%) often provides limited resolution around the thresholds where mechanical strength and durability begin to deteriorate. By testing 25%, 45% and 65%, the study aimed to refine these boundaries and offer more detailed guidance for practical applications. All mixtures were designed for a water–cement ratio of 0.45, ensuring adequate workability for structural concretes cast and vibrated in formwork. Each mix targeted a slump of 80–120 mm and a minimum characteristic strength class of C25/30, in accordance with ABNT: NBR 8953 [24]. Table 2 details the proportions of the different concrete mixes used in this study.

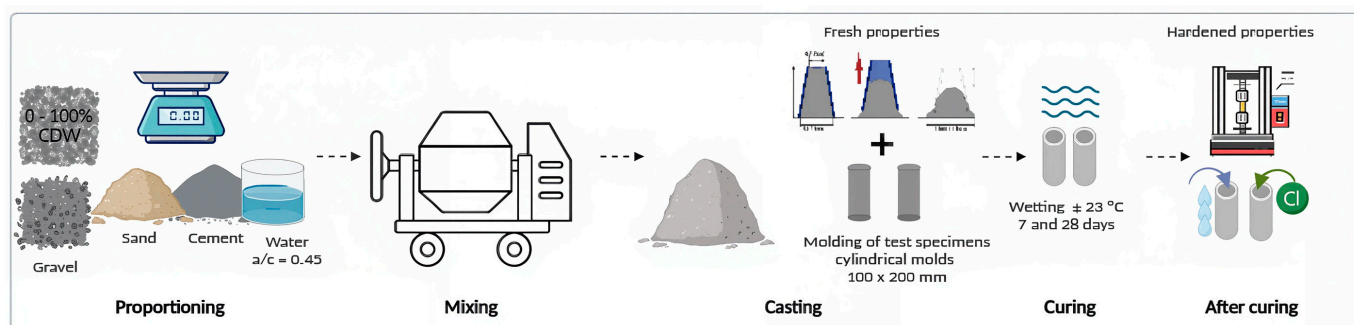
Table 2. Proportioning of the studied concretes.

Mix Proportion	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Natural CDW (kg/m ³)	Recycled Water (kg/m ³)	Water/Cement Ratio (w/c)
0% CDW	420	740	1050	0	189	0.45
20% CDW	420	740	840	210	189	0.45
25% CDW	420	740	788	262	189	0.45
45% CDW	420	740	578	472	189	0.45
50% CDW	420	740	525	525	189	0.45
65% CDW	420	740	368	682	189	0.45
100% CDW	420	740	0	1050	189	0.45

Source: author.

Concrete mixing was carried out in a vertical-shaft mixer with 40 L batch capacity. First, the dry constituents (sand, coarse aggregate, and/or recycled aggregates) were blended for 30 s. Next, the cement and 70% of the mixing water were added, and the mix was agitated for an additional 60 s. The remaining 30% of the water—together with the superplasticizer when used—was then introduced, and the mixture was homogenized for a further 60 s.

Immediately after mixing, cylindrical specimens (100 mm × 200 mm) were cast and consolidated using mechanical vibration on a vibrating table, in accordance with ABNT: NBR 5738 [25]. Demolding occurred after 24 h, and the specimens were subsequently cured in a humidity-controlled chamber at 23 ± 2 °C until the designated testing ages. Figure 1 illustrates the overall experimental workflow, from aggregate processing through to the final characterization of the concretes produced, thereby outlining the logical sequence of the experimental procedure.

**Figure 1.** Flowchart of the experimental process.

The density of the concretes was determined in both the fresh and hardened states. For the reference mixture (0% CDW), the fresh density ranged between 2350 and 2400 kg/m³, while the hardened density was between 2320 and 2380 kg/m³. As the CDW replacement ratio increased, a gradual reduction in density was observed due to the lower particle density and higher porosity of recycled aggregates. At 100% replacement, fresh density values varied from 2200 to 2280 kg/m³, and hardened density values from 2150 to 2250 kg/m³. These results confirm the influence of recycled aggregate characteristics on the unit weight of concrete.

2.3. Fresh-State Testing

The consistency test by the slump cone method was carried out in accordance with NM 67 [26]. For each mix, two specimens were prepared and the average slump value was taken as representative. The test involved filling a standardized metal frustum mold in three layers, compacting each layer with 25 taps of a standard metal rod.

Once filled and the surface leveled, the mold was lifted vertically and the slump was measured immediately—recorded in millimeters as the difference between the original mold height and the height of the concrete after settlement. According to ABNT: NBR 8953 [24], the target slump range of 80–120 mm partially corresponds to classes S50 ($50 < \text{slump} \leq 100$ mm) and S100 ($100 < \text{slump} \leq 160$ mm), which is ideal for conventional structural elements. This range ensures good workability and moldability for vibrated applications: slumps below 80 mm may indicate overly stiff mixes (risking poor compaction and high porosity), while slumps above 120 mm can lead to excessively fluid concrete and segregation.

In addition to measuring slump, cohesion and bleeding were observed immediately after testing. Any visible segregation (separation of mortar and coarse aggregate) or bleeding (formation of a water film on the surface) was noted to identify instability phenomena. These behaviors are critical in concretes with recycled aggregates, since the high porosity and water absorption of CDW-derived aggregates can adversely affect workability, mechanical strength, and long-term durability [1].

Although entrained air content was not systematically tested in this study, it was carefully controlled through appropriate fine-aggregate proportions and the use of superplasticizers known for minimal air entrainment. Such control is essential, as excessive entrained air can compromise mechanical strength, reducing structural capacity and durability [27].

2.4. Compressive Strength

The primary parameter evaluated was axial compressive strength, conducted in accordance with ABNT: NBR 5739 [28]. For each mix and testing age (7 and 28 days), at least three cylindrical specimens were cast, and results are reported as mean $\pm$ standard deviation. Tests were performed on a calibrated hydraulic press with a minimum capacity of 2000 kN. Specimen ends were capped with neoprene or high-strength mortar to ensure uniform load distribution. Loading rates were maintained at 0.45 ± 0.15 MPa/s as specified by the standard. Failure was defined by crushing of the concrete core and consequent loss of load capacity. The values reported correspond to the mean compressive strength of three specimens. References to characteristic strength (f_{ck}) follow the definition of ABNT NBR 6118 [29], and were only used when verifying compliance with structural class requirements.

2.5. Water Absorption by Immersion and Capillarity

Water absorption, an indicator of the open porosity of concrete, was determined in accordance with the procedures set out in ABNT: NBR 9778 [30] using two distinct test methods. These tests allow evaluation of pore connectivity, propensity for aggressive liquid transport, and potential resistance to degradation.

In total-immersion absorption, specimens were first dried in an oven at 105 ± 5 °C until constant mass was achieved—defined as a mass change of less than 0.2% over a 24 h period. They were then completely immersed in water for 24 h, after which the saturated mass was measured. Water absorption was calculated as the difference between saturated mass and dry mass, expressed as a percentage of the dry mass of the specimen. In capillary absorption, specimens were partially immersed in water so that only the bottom surface was submerged to a depth of 5 mm. Absorption was recorded at various time intervals (3, 6, 24, and 48 h). Capillary absorption was plotted against the square root of time, allowing calculation of the initial absorption rate, also known as sorptivity.

2.6. Chloride Ion Penetration

Durability against reinforcement corrosion was assessed indirectly by measuring chloride penetration. The test was based on methodologies adapted from ASTM: C1202 [31], with a modification for prolonged immersion. After 28 days of curing, specimens were immersed in a saline solution (3.5% NaCl) for 90 days. Upon completion of this period, the samples were transversely sectioned and a chloride indicator reagent (0.1 mol/L silver nitrate) was sprayed onto the freshly cut surface. The depth of the brown staining, corresponding to chloride presence, was measured at several locations. The average penetration depths were used as a qualitative indicator of the concrete's resistance to aggressive agent ingress.

3. Results and Discussion

3.1. Properties of Natural and Recycled Aggregates

The preliminary characterization of the constituent materials was carried out in order to ensure the reproducibility of the mixes and to provide a consistent comparative baseline among the concretes produced. The physical properties of the natural and recycled aggregates were determined, as shown in Table 3, considering that these characteristics influence the mechanical performance and durability of the concrete, especially in composites containing recycled aggregates [32].

Table 3. Physical properties of aggregates.

Property	Natural Sand	Natural Aggregate (0)	Natural Aggregate (1)	Recycled Fine Aggregate	Recycled Coarse Aggregate
Specific mass (g/cm ³)	2.60 ± 0.01	2.64 ± 0.02	2.75 ± 0.02	2.46 ± 0.02	2.16 ± 0.03
Water absorption (%)	1.29 ± 0.05	1.70 ± 0.08	1.25 ± 0.07	9.31 ± 0.15	9.00 ± 0.20
Fineness Modulus (Sand)	2.40 ± 0.05	—	—	2.30 ± 0.05	—

Source: author. Where: “Natural aggregate (0)” is fine aggregate and “Natural aggregate (1)” is coarse aggregate.

Recycled aggregates exhibited water-absorption values significantly higher than those of natural aggregates. The fine recycled aggregate ($9.31\% \pm 0.15\%$) absorbed about 5.5 times more water than natural aggregate 0 ($1.70\% \pm 0.08\%$). Likewise, the coarse recycled aggregate ($9.00\% \pm 0.20\%$) showed absorption approximately 7.2 times greater than that of natural aggregate 1 ($1.25\% \pm 0.07\%$), a behavior also noted in studies investigating the impact of aggregate moisture conditions on concrete performance [33].

This behavior underscores the need to pre-saturate recycled aggregates before mixing in order to maintain the concrete's workability within desired parameters. Moreover, the lower specific gravity of recycled aggregates compared to natural ones directly influences the density of the resulting concrete. Jia et al. [34] demonstrated that recycled construction and demolition waste aggregates have a lower saturated density (2300 kg/m^3) and significantly higher water absorption (7.82%) than natural aggregates, a difference attributed to the high porosity of recycled aggregates, which negatively impacts both the density and durability of concrete produced with this material.

3.2. Fresh-State Properties of the Concretes

The average slump results and cohesion observations are presented in Table 4. The slump of the concretes tended to decrease as the recycled concrete debris (CDW) content increased, reflecting the higher water demand needed to maintain workability due to the porosity of the recycled aggregates. This finding is corroborated by Ibrahim et al. [2], who observed that concrete workability decreases almost linearly with increasing recycled aggregate content: slump can drop by up to 37.5% when 100% recycled aggregate is used,

owing to the higher water absorption and surface roughness of the grains, which in turn increases the demand for superplasticizer to maintain the desired flow. Furthermore, pre-saturating the recycled aggregates significantly improves slump retention and reduces segregation, as it balances internal grain absorption without increasing the free water in the mix [2].

Table 4. Fresh properties of concrete.

Mix Proportion	Slump (mm)	Standard Deviation (mm)	Cohesion Observations
0% CDW	115	± 5	Good cohesion, no segregation
20% CDW	108	± 6	Slight exudation
25% CDW	105	± 5	Good cohesion, little exudation
45% CDW	98	± 7	Moderate exudation
50% CDW	94	± 6	Pronounced exudation
65% CDW	91	± 5	Incipient segregation
100% CDW	85	± 7	Clearly visible segregation and exudation

Source: author.

3.3. Compressive Strength at 7 and 28 Days

The compressive strength results for the various concrete mixes with aggregate replaced by recycled concrete debris (CDW) are presented in Figure 2, showing an inverse relationship between CDW content and mechanical strength. A progressive decrease in strength at both 7 and 28 days is observed as the percentage of CDW in the mix increases.

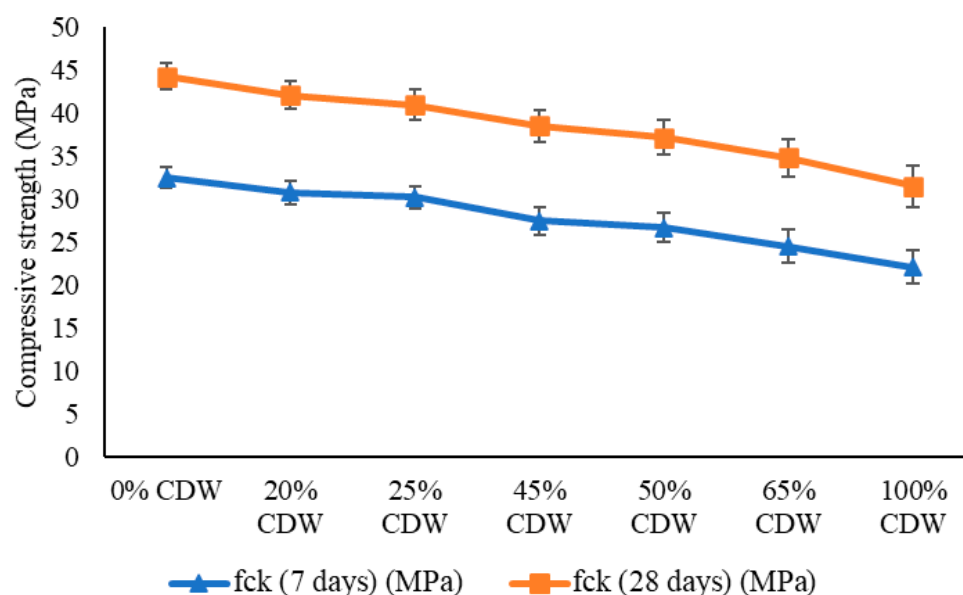


Figure 2. Compressive strength of concretes with varying CDW contents at 7 and 28 days, where “X% CDW” denotes the percentage of construction-and-demolition-waste recycled aggregate (RA) used to replace the natural coarse aggregate in the concrete mix, by mass.

The results shown in Figure 2 demonstrate an inverse relationship between R CDW content and mechanical strength, with a progressive reduction in compressive strength at both 7 and 28 days as the percentage of CDW in the mix increases. The reference concrete (0% CDW) reached 44.3 MPa at 28 days, whereas the 100% CDW blend achieved 31.5 MPa in the same period, representing an approximate 29% decrease.

Despite this progressive strength reduction with higher CDW content, all mixes containing up to 50% CDW met the minimum requirements for structural concrete

(class $\geq$ C25/30) according to ABNT: NBR 8953 [24]. In particular, the 50% CDW mix achieved 37.2 MPa at 28 days, exceeding the standard's minimum. Substitutions of up to 20% resulted in minimal impact on mechanical properties (only a 5.2% reduction in strength), maintaining excellent performance. It is also noted that the standard deviations increased progressively with higher CDW contents (from ± 1.5 MPa to ± 2.4 MPa), indicating greater variability in mechanical properties as the recycled-aggregate proportion rises. This behavior can be attributed to the greater heterogeneity and water-absorption capacity of recycled aggregates compared to natural ones.

Our results confirm trends observed by Silva et al. [1], Medina et al. [35] and Akbarimehr et al. [13], where compressive strength losses remained below 15% up to ~30% replacement, while higher reductions occurred at $\geq 50\%$. The inclusion of intermediate levels (45% and 65%) in our study refines these thresholds, showing that significant durability loss begins beyond 65% replacement.

Although the interfacial transition zone (ITZ) is recognized as important for material durability, its effect on mechanical performance proved secondary to that of the adhered residual mortar. Liang et al. [36] demonstrated via numerical simulations that the ITZ's influence on the elastic modulus of recycled-aggregate concrete is relatively limited, confirming that mechanical variability arises primarily from the properties of the residual mortar attached to the aggregates rather than from the characteristics of the interfaces within the system.

Similarly, Yu et al. [8] showed through mesoscale discrete element modeling that weak ITZ adhesion significantly reduces the mechanical properties of recycled-aggregate concrete, whereas strengthening the ITZ produces only minor improvements. Their study further highlighted that the amount and quality of the adhered mortar strongly govern crack initiation and propagation, with higher contents of old mortar leading to notable decreases in compressive strength and elastic modulus. It is important to acknowledge that these studies did not include microstructural analyses, such as porosity imaging or ITZ characterization, which could provide additional insights into the mechanisms governing the observed macroscopic behavior. Nevertheless, previous works Liang et al. [36] Yu et al. [8], De Brito e Saikia [37] have already described how the adhered mortar and porosity of recycled aggregates condition both mechanical performance and chloride transport. In line with these studies, our results can be interpreted as the macroscopic manifestation of these microstructural features. We recommend that future research combine experimental testing with micro-scale analyses to strengthen the understanding of recycled aggregate concrete performance.

3.4. Water Absorption

The average results of total-immersion absorption are presented in Figure 3. The analysis of the results reveals that total-immersion water absorption nearly doubles when moving from conventional concrete (0% CDW) to concrete with 100% recycled concrete debris (CDW), increasing from 4.5% to 9.5%. This pronounced behavior is largely due to the intrinsic porosity of the CDW and the presence of cement paste adhered to the surface of the grains, factors that enhance the water-retention capacity of recycled aggregates [38,39].

Up to approximately 25% CDW incorporation, the increase in water absorption is relatively moderate, rising from 4.5% to 5.5%. However, above 45% CDW, a pronounced acceleration of this increase is observed, reaching 9.5% at 100% replacement. This non-linear trend reflects not only the characteristic heterogeneity of recycled aggregates—with respect to particle-size distribution and varied surface textures—but also the variability in the amount of adhered mortar on each CDW fraction. Duan et al. [40] reported a similar

behavior in tests with thermally treated CDW, where absorption intensified significantly beyond intermediate replacement levels [40].

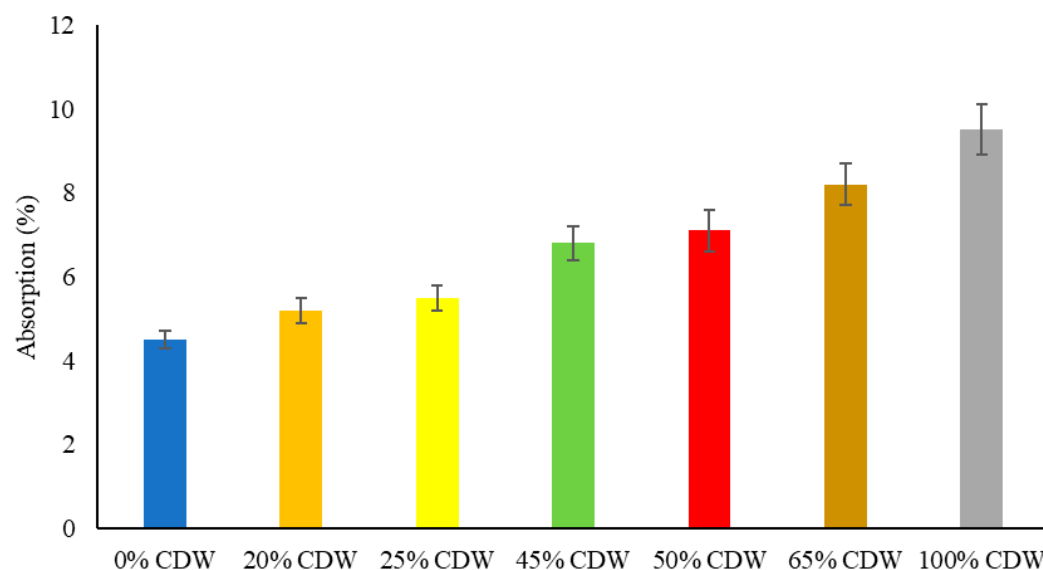


Figure 3. Water absorption of concretes with varying CDW contents at 7 and 28 days, where “X% CDW” denotes the percentage of construction-and-demolition-waste recycled aggregate (RA) used to replace the natural coarse aggregate in the concrete mix, by mass.

From a practical standpoint, the higher absorption means that recycled aggregates withdraw free water from the mix, reducing the effective water–cement ratio and compromising fresh-concrete workability. To maintain the desired consistency, it is common to add compensating water to the mix, but this must be done cautiously so as not to impair the hardened concrete’s strength and durability. In line with Dhir et al. [41], concretes containing up to 50% CDW exhibited immersion absorption of 6% to 8%, values consistent with those obtained for 45% and 50% CDW in this study [41].

3.5. Chloride Penetration

The average chloride penetration depths are presented in Figure 4. A progressive increase in chloride-ion penetration depth is observed as the content of recycled concrete debris (CDW) in the mix rises, from 10.2 mm at 0% CDW to 17.8 mm at 100% CDW. This increase is accompanied by a slight rise in standard deviation, indicating greater heterogeneity in chloride transport for mixes with higher CDW proportions.

Similar to the result obtained, Bao et al. [42] obtained an increase in chloride content and penetration depth as the RCA replacement ratio was increased, since the addition of RCA considerably increases the total porosity of the concrete [42]. At the microstructural level, the enhanced chloride penetration can be attributed to the higher porosity and pore connectivity in CDW, resulting from residual cement paste adhered to the aggregate and microcracks induced by the crushing process. Studies such as De Brito and Saikia [37] have shown that concretes with CDW exhibit greater sorptivity and permeability, which promotes ionic diffusion into the material [37]. Other authors have similarly reported that the aggregate-paste interfacial microstructure in CDW concretes conditions capillarity and facilitates chloride transport, especially at replacement levels above 40% [43,44].

Similar to Bao et al. [42], our findings showed that chloride penetration increases with CDW content, primarily due to higher porosity and adhered mortar. However, values for up to 50% CDW remain within acceptable limits, corroborating the conclusions of De Brito e Saikia [37] regarding safe use in moderate-exposure conditions.

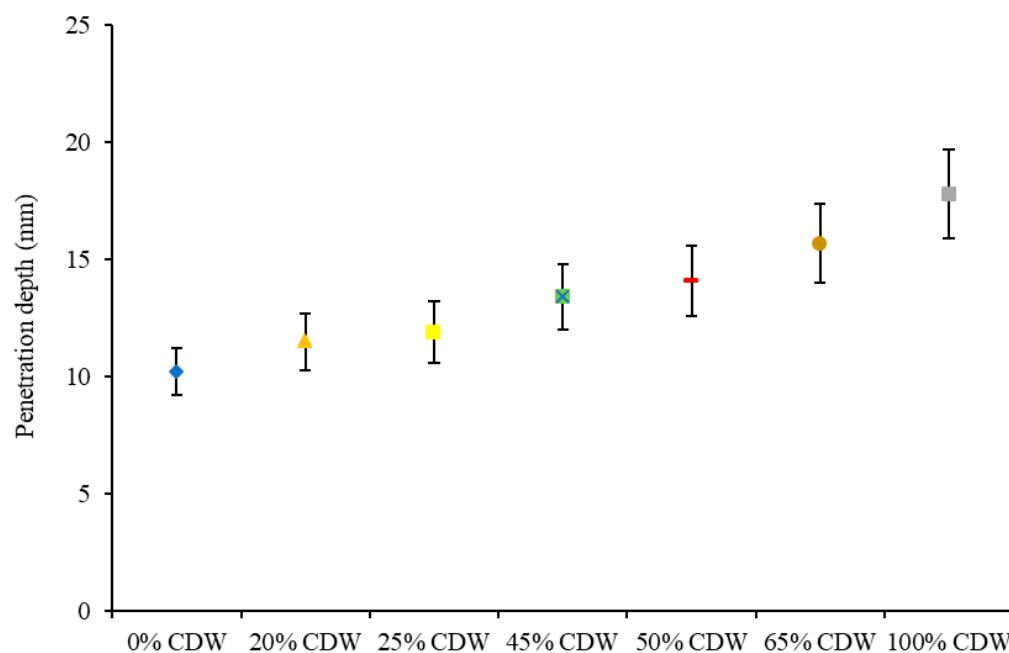


Figure 4. Chloride ion penetration of concretes with varying CDW contents at 7 and 28 days, where “X% CDW” denotes the percentage of construction-and-demolition-waste recycled aggregate (RA) used to replace the natural coarse aggregate in the concrete mix, by mass.

Despite this increase, penetration depths for up to 50% CDW (up to 14.1 mm) remain within the recommended limits for concrete in moderate-exposure environments according to ABNT: NBR 6118 [29]. It should be noted that the silver nitrate method adopted here differs from the ASTM C1202 RCPT standard, which measures electrical charge passed. Our approach, while qualitative, has been validated in previous studies as a reliable indicator of chloride ingress depth, allowing meaningful comparison of trends even if absolute values differ [45,46].

In such conditions, penetration depths below 15 mm are considered acceptable to ensure durability against chloride attack in reinforced-concrete structures. However, for CDW contents above 65%, depths exceed 15 mm—reaching 15.7 mm at 65% CDW and 17.8 mm at 100% CDW—which may compromise the service life of the structure if no mitigating measures are adopted.

4. Conclusions

This study demonstrated the technical feasibility of incorporating recycled aggregates derived from construction and demolition waste (CDW) into structural concretes by evaluating fresh-state properties, compressive strength, and durability. The results showed that, up to a 50% replacement level, the concretes maintained adequate slump (≥ 94 mm), compressive strength compatible with class C25/30 (≥ 37.2 MPa at 28 days), water absorption below 7.5%, and chloride penetration depth under 15 mm—all meeting the requirements for moderate exposure conditions as defined by ABNT: NBR 6118 [29].

The progressive reduction in mechanical performance and the increase in porosity and permeability—especially at replacement levels above 65%—underscore the need for compensatory strategies, such as pre-saturation of aggregates, use of high-range water-reducing admixtures, and incorporation of supplementary cementitious materials (SCMs), such as pozzolans. These practices can mitigate the adverse effects of CDW heterogeneity on concrete workability, strength, and long-term durability.

Importantly, the feasible replacement level of 50% identified here refers to the specific CDW used in this study, characterized by $\sim 9\%$ water absorption and density of 2.16 g/cm^3 .

Variations in CDW composition or quality may shift this threshold; therefore, these conclusions should not be generalized without further validation. Overall, partial replacement of natural aggregates by CDW—limited to 50%—is both technically viable and environmentally beneficial. The inclusion of intermediate replacement levels provides practical guidance on performance thresholds. This study has some inherent limitations that should be acknowledged. First, only one source of CDW was investigated, derived primarily from crushed concrete and mortar debris, which restricts the generalization of the findings to other waste streams with different compositions and properties. Second, the mechanical characterization focused exclusively on compressive strength, without assessing other critical structural parameters such as splitting tensile strength, flexural strength, and modulus of elasticity.

Future research should address the influence of multiple CDW sources, water–cement ratio variation, and microstructural characterization. Additionally, micro-scale tests (e.g., porosity imaging, ITZ analysis, and microcrack propagation) together with simulation studies and Life Cycle Assessment (LCA) analyses are promising directions to complement and expand these findings. Other important properties such as splitting tensile strength, flexural strength, and modulus of elasticity are also absent from this study, despite being highly relevant for the structural performance of concrete, and should be incorporated in future investigations.

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References

1. Silva, R.V.; De Brito, J.; Dhir, R.K. Properties and Composition of Recycled Aggregates from Construction and Demolition Waste Suitable for Concrete Production. *Constr. Build. Mater.* **2014**, *65*, 201–217. [\[CrossRef\]](#)
2. Ibrahim, M.; Alimi, W.; Assagaf, R.; Salami, B.A.; Oladapo, E.A. An Overview of Factors Influencing the Properties of Concrete Incorporating Construction and Demolition Wastes. *Constr. Build. Mater.* **2023**, *367*, 130307. [\[CrossRef\]](#)
3. Joseph, H.S.; Pachiappan, T.; Avudaiappan, S.; Maureira-Carsalade, N.; Roco-Videla, Á.; Guindos, P.; Parra, P.F. A Comprehensive Review on Recycling of Construction Demolition Waste in Concrete. *Sustainability* **2023**, *15*, 4932. [\[CrossRef\]](#)
4. Akhtar, A.; Sarmah, A.K. Construction and Demolition Waste Generation and Properties of Recycled Aggregate Concrete: A Global Perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. [\[CrossRef\]](#)
5. Roussat, N.; Dujet, C.; Méhu, J. Choosing a Sustainable Demolition Waste Management Strategy Using Multicriteria Decision Analysis. *Waste Manag.* **2009**, *29*, 12–20. [\[CrossRef\]](#)
6. Coelho, A.; de Brito, J. Influence of Construction and Demolition Waste Management on the Environmental Impact of Buildings. *Waste Manag.* **2012**, *32*, 532–541. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Yu, Y.; Su, J.; Wu, B. A Hybrid Bayesian Model Updating and Non-Dominated Sorting Genetic Algorithm Framework for Intelligent Mix Design of Steel Fiber Reinforced Concrete. *Eng. Appl. Artif. Intell.* **2025**, *161*, 112071. [\[CrossRef\]](#)

8. Yu, Y.; Zheng, Y.; Zhao, X.-Y. Mesoscale Modeling of Recycled Aggregate Concrete under Uniaxial Compression and Tension Using Discrete Element Method. *Constr. Build. Mater.* **2021**, *268*, 121116. [\[CrossRef\]](#)
9. Yu, Y.; Fang, G.-H.; Kurda, R.; Sabuj, A.R.; Zhao, X.-Y. An Agile, Intelligent and Scalable Framework for Mix Design Optimization of Green Concrete Incorporating Recycled Aggregates from Precast Rejects. *Case Stud. Constr. Mater.* **2024**, *20*, e03156. [\[CrossRef\]](#)
10. Pedroso, F.L. *Concreto: Material Construtivo Mais Consumido No Mundo*, 53rd ed.; IBRACON: São Paulo, Brazil, 2009; Volume XXXVII.
11. Luo, H.; Aguiar, J.; Wan, X.; Wang, Y.; Cunha, S.; Jia, Z. Application of Aggregates from Construction and Demolition Wastes in Concrete: Review. *Sustainability* **2024**, *16*, 4277. [\[CrossRef\]](#)
12. Xiao, J.; Ma, Z.; Sui, T.; Akbarnezhad, A.; Duan, Z. Mechanical Properties of Concrete Mixed with Recycled Powder Produced from Construction and Demolition Waste. *J. Clean. Prod.* **2018**, *188*, 720–731. [\[CrossRef\]](#)
13. Akbarimehr, D.; Eslami, A.; Nasiri, A.; Rahai, M.; Karakouzian, M. Performance Study of Sustainable Concrete Containing Recycled Aggregates from Non-Selected Construction and Demolition Waste. *Sustainability* **2024**, *16*, 2601. [\[CrossRef\]](#)
14. Wu, H.; Liu, X.; Wang, C.; Zhang, Y.; Ma, Z. Micro-Properties and Mechanical Behavior of High-Ductility Engineered Geopolymer Composites (EGC) with Recycled Concrete and Paste Powder as Green Precursor. *Cem. Concr. Compos.* **2024**, *152*, 105672. [\[CrossRef\]](#)
15. Mahmoud, A.A.; El-sayed, A.A.; Aboraya, A.M.; Fathy, I.N.; Abouelnour, M.A.; Tayeh, B.A.; Nabil, I.M. Investigating the Effects of Granite, Marble, Granodiorite, and Ceramic Waste Powders on the Physical, Mechanical, and Radiation Shielding Performance of Sustainable Concrete. *Ann. Nucl. Energy* **2025**, *216*, 111274. [\[CrossRef\]](#)
16. Thomas, J.; Thaickavil, N.N.; Wilson, P.M. Strength and Durability of Concrete Containing Recycled Concrete Aggregates. *J. Build. Eng.* **2018**, *19*, 349–365. [\[CrossRef\]](#)
17. Fattouh, M.S.; Abouelnour, M.A.; Mahmoud, A.A.; Fathy, I.N.; El Sayed, A.F.; Elhameed, S.A.; Nabil, I.M. Impact of Modified Aggregate Gradation on the Workability, Mechanical, Microstructural and Radiation Shielding Properties of Recycled Aggregate Concrete. *Sci. Rep.* **2025**, *15*, 18428. [\[CrossRef\]](#)
18. Sáez del Bosque, I.F.; Van den Heede, P.; De Belie, N.; Sánchez de Rojas, M.I.; Medina, C. Carbonation of Concrete with Construction and Demolition Waste Based Recycled Aggregates and Cement with Recycled Content. *Constr. Build. Mater.* **2020**, *234*, 117336. [\[CrossRef\]](#)
19. ABNT NBR:16697; Portland Cement—Requirements. Brazilian Association of Technical Standards (ABNT): São Paulo, Brazil, 2018; pp. 1–9.
20. Schack, T.; Strybny, B.; Haist, M. Improving the Early Age Strength of Eco-Efficient Mortar with Low Clinker Content Considering Binder Granulometry and Chemical Additives. *Materials* **2024**, *17*, 4509. [\[CrossRef\]](#)
21. ABNT NBR:15900; 1—Water for Mixing Concrete—Part 1: Requirements. Brazilian Association of Technical Standards (ABNT): São Paulo, Brazil, 2009.
22. ABNT NBR: 15116; Recycled Aggregates for Uses in Mortar and Concrete—Requirements and Test Methods. Brazilian Association of Technical Standards (ABNT): São Paulo, Brazil, 2021; pp. 1–20.
23. Helene, P.; Terzian, P. *Manual de Dosagem e Controle de Concreto*; Editoria Pini: Rio de Janeiro, Brazil, 1993; ISBN 8572660070.
24. ABNT NBR: 8953; Concrete for Structural Use—Density, Strength and Consistence Classification. Brazilian Association of Technical Standards (ABNT): São Paulo, Brazil, 2015.
25. ABNT NBR: 5738; Concrete—Procedure for Molding and Curing Concrete Test Specimens. Brazilian Association of Technical Standards (ABNT): São Paulo, Brazil, 2015.
26. NM AMDN NM 67; Hormigón—Determinación de la Consistencia Mediante el Asentamiento del Tronco de Cono. Brazilian Association of Technical Standards (ABNT): São Paulo, Brazil, 1998.
27. Carasek, H.; Araújo, R.C.; Cascudo, O.; Angelim, R. Parâmetros Da Areia Que Influenciam a Consistência e a Densidade de Massa Das Argamassas de Revestimento. *Matéria (Rio Janeiro)* **2016**, *21*, 714–732. [\[CrossRef\]](#)
28. ABNT NBR 5739:2018; Concreto—Ensaio de Compressão de Corpos de Prova Cilíndricos. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2018.
29. ABNT NBR: 6118; Projeto de Estruturas de Concreto. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2024.
30. ABNT NBR: 9778; Argamassa e Concreto Endurecidos—Determinação Da Absorção de Água, Índice de Vazios e Massa Específica. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2009.
31. ASTM C1202-19; Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration. American Society for Testing and Materials: West Conshohocken, PA, USA, 2019.
32. Kou, S.C.; Poon, C.S. Enhancing the Durability Properties of Concrete Prepared with Coarse Recycled Aggregate. *Constr. Build. Mater.* **2012**, *35*, 69–76. [\[CrossRef\]](#)
33. Poon, C.S.; Shui, Z.H.; Lam, L.; Fok, H.; Kou, S.C. Influence of Moisture States of Natural and Recycled Aggregates on the Slump and Compressive Strength of Concrete. *Cem. Concr. Res.* **2004**, *34*, 31–36. [\[CrossRef\]](#)

34. Jia, Z.; Cunha, S.; Aguiar, J.; Shi, C. Enhancing the Durability of Concrete with Construction and Demolition Waste Aggregate through Its Functionalization with Phase Change Materials (Paraffin). *Cem. Concr. Compos.* **2025**, *162*, 106135. [[CrossRef](#)]
35. Medina, C.; Zhu, W.; Howind, T.; Isabel, M.; Rojas, S. De Influence of Mixed Recycled Aggregate on the Physical e Mechanical Properties of Recycled Concrete. *J. Clean. Prod.* **2014**, *68*, 216–225. [[CrossRef](#)]
36. Liang, C.; Bao, J.; Gu, F.; Lu, J.; Ma, Z.; Hou, S.; Duan, Z. Determining the Importance of Recycled Aggregate Characteristics Affecting the Elastic Modulus of Concrete by Modeled Recycled Aggregate Concrete: Experiment and Numerical Simulation. *Cem. Concr. Compos.* **2025**, *162*, 106118. [[CrossRef](#)]
37. de Brito, J.; Saikia, N. *Recycled Aggregate in Concrete*; Green Energy and Technology; Springer London: London, UK, 2013; ISBN 978-1-4471-4539-4.
38. McNeil, K.; Kang, T.H.K. Recycled Concrete Aggregates: A Review. *Int. J. Concr. Struct. Mater.* **2013**, *7*, 61–69. [[CrossRef](#)]
39. Alharbi, Y.R.; Abadel, A.A.; Mayhoub, O.A.; Kohail, M. Effect of Using Available Metakaoline and Nano Materials on the Behavior of Reactive Powder Concrete. *Constr. Build. Mater.* **2020**, *269*. [[CrossRef](#)]
40. Duan, Z.; Zhao, W.; Ye, T.; Zhang, Y.; Zhang, C. Measurement of Water Absorption of Recycled Aggregate. *Materials* **2022**, *15*, 5141. [[CrossRef](#)]
41. Dhir, R.K.; de Brito, J.; Silva, R.V.; Lye, C.Q. *Sustainable Construction Materials*; Recycled Aggregates: Garland, TX, USA, 2019; ISBN 9780081009857.
42. Bao, J.; Li, S.; Zhang, P.; Ding, X.; Xue, S.; Cui, Y.; Zhao, T. Influence of the Incorporation of Recycled Coarse Aggregate on Water Absorption and Chloride Penetration into Concrete. *Constr. Build. Mater.* **2020**, *239*, 117845. [[CrossRef](#)]
43. Xiao, J.; Li, W.; Fan, Y.; Huang, X. An Overview of Study on Recycled Aggregate Concrete in China (1996–2011). *Constr. Build. Mater.* **2012**, *31*, 364–383. [[CrossRef](#)]
44. Otsuki, N.; Miyazato, S.; Yodsudjai, W. Influence of Recycled Aggregate on Interfacial Transition Zone, Strength, Chloride Penetration and Carbonation of Concrete. *J. Mater. Civ. Eng.* **2003**, *15*, 443–451. [[CrossRef](#)]
45. Nicula, L.M.; Corbu, O.; Iliescu, M.; Sandu, A.V.; Hegyi, A. Study on the Durability of Road Concrete with Blast Furnace Slag Affected by the Corrosion Initiated by Chloride. *Adv. Civ. Eng.* **2021**, *2021*, 16. [[CrossRef](#)]
46. Huang, K.S.; Yang, C.C. Using RCPT Determine the Migration Coefficient to Assess the Durability of Concrete. *Constr. Build. Mater.* **2018**, *167*, 822–830. [[CrossRef](#)]

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