

Pozzolanic Potential of Recycled Aggregates for 3D Printed Concrete

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ABSTRACT

The emerging technology of 3D concrete printing enables faster construction, complex geometries, and reduced on-site injury risks. Despite its benefits, it still relies heavily on cement. Incorporating recycled aggregate powder offers a promising strategy to lower environmental impact, though it poses challenges. Assessing the pozzolanic reactivity of these materials is essential, as they may contribute to mechanical and durability properties or act as inert fillers that enhance rheology and setting. This study investigates the pozzolanic activity and hydration behavior of recycled aggregate powder used to replace 50% of the binder and cement by mass in 3D-printed concrete. The experimental program included X-ray diffraction (XRD), thermogravimetric analysis (TGA), Frattini and Chapelle tests, setting time measurements, and the Strength Activity Index (SAI). Results show that the recycled material lacks significant pozzolanic activity. However, its influence on hydration and setting provides insights into its role as a filler in sustainable printable cementitious formulations. These findings underscore the importance of evaluating recycled materials before their application in additive manufacturing.

KEYWORDS: 3D printed concrete; recycled aggregate; pozzolanic activity; additive manufacturing; binder replacement.

1.- INTRODUCTION

Recycled aggregate powder (construction and demolition waste) represents approximately 35–40% of the total solid waste generated globally, contributing significantly to environmental degradation due to the overuse of landfills and depletion of natural resources [1]. An increasingly adopted strategy to address this issue involves the recycling of fine aggregates, offering a sustainable alternative to natural aggregates in cement-based materials [2]. In addition to diverting materials from landfills, this practice helps reduce the exploitation of virgin raw materials and promotes circular economy principles in the construction sector [3]. In parallel with this sustainable shift, the construction industry has been undergoing a transformation through automation and digital manufacturing. Among the

most promising technologies is three-dimensional concrete printing, which enables the construction of structural elements without formwork, while significantly reducing labor, construction time, and material waste [4]. This method has also been recognized for its potential in emergency scenarios, such as natural disasters or armed conflicts, where rapid and adaptable construction solutions are essential [5].

The incorporation of recycled aggregate powder into printable cementitious mixtures presents both environmental benefits and technical challenges. Although mechanical properties such as compressive and flexural strength may slightly decrease compared to natural aggregate-based mixtures [6], optimized designs and treatments—like CO₂ curing—can enhance fresh-state behavior and structural performance [7]. Functional performance is highly dependent on rheological and mechanical characteristics, including flowability, extrudability, buildability, and interlayer bonding, all of which are influenced by particle morphology and water demand [6,8]. Recent studies confirm the technical feasibility of using recycled materials: ready-mix concretes with 25% recycled coarse aggregate achieved compressive strength around 36 MPa at 28 days with slump between 6–7 cm [9]; 3D printed concrete waste used as 10% cement replacement retained 93% of reference strength (49.5 MPa vs. 53.2 MPa), despite reducing spread flow due to angularity and absorption [10]; and structural concretes with up to 50% recycled aggregates reached 25–30 MPa when material quality was controlled [11]. Hence, this study aims to evaluate the pozzolanic activity and rheological behavior of recycled aggregate powder used as partial binder replacement in 3D-printed cementitious mixtures.

2.- METHODOLOGY

2.1.- Materials

The 3D printable cementitious pastes were formulated with CEM II/A-L 42.5R cement, concrete and demolition waste (CDW) powder (<0.125 mm or <0.063 mm), limestone filler (LMF), polycarboxylate ether-based superplasticizer (SP), and potable water, maintaining a fixed water-to-binder ratio of 0.2. LMF improved flow and reduced clinker demand, CDW replaced cement or total binder mass. All components were oven-dried and stored in sealed containers before use.

2.2.- Characterization of CDW powder and pozzolanic activity

CDW powder, was assessed through physical, chemical, and pozzolanic tests. The bulk density was determined by the pycnometer method. Sieving by the EN 933-1 [12], confirmed a fine fraction that can be suitable as binder. XRD and TGA revealed mineral phases and mass loss linked to hydration and carbonation. XRF showed major oxides (SiO₂, CaO, Al₂O₃). Pozzolanic activity was evaluated using Frattini test by EN 196-5 [13], Chapelle test according to AFNOR NF P18-513 [14], and strength activity index (SAI) following the EN 450-1 [15] standard, which verified the mechanical contribution of 25% cement replacement.

2.3.- Mixture Identification and Composition (Pastes)

Five cementitious paste formulations were prepared to evaluate the effects of recycled aggregate powder (CDW fines) on hydration and rheological behavior for 3D printing. Two replacement approaches were adopted: substitution of 25% or 50% of cement mass (C25, C50) and 25% or 50% of total binder mass (cement + limestone filler) (B25, B50). A CDW-free reference paste (REF) was used for comparison. Mixes were tested for setting time, Marsh funnel viscosity, and mini slump (Kantro cone) at 0, 30, 60, and 90 minutes to assess workability and setting kinetics, presented in Table 1.

Table 1. Dosage of raw materials in each paste formulation.

Mixture Code	Materials (Kg/m ³)					
	CEM II A/L	CDW	LMF	SFca	SP	Water
REF	1379.18	0.00	258.04	142.37	26.09	355.92
C50	1205.92	144.40	258.04	142.37	26.09	355.92
C25	1292.55	72.20	258.04	142.37	26.09	355.92
B50	1250.50	144.40	233.96	129.08	26.09	355.92
B25	1314.84	72.20	246.00	135.73	26.09	355.92

2.4.- Rheology and setting tests in pastes

All paste mixtures were prepared following the standardized protocol described in EN 196-3 [13]. The mixing process was carried out in a planetary mixer and consisted of three distinct stages: an initial 3-minute mixing at medium speed, a 1-minute rest period during which the internal walls of the mixer were manually scraped to ensure homogeneity, followed by a final 3-minute mixing at high speed. This procedure was adopted for all paste formulations (REF, C25, C50, B25, and B50), aiming to ensure repeatability and consistency in the fresh state characterization. The fresh-state behavior of the mixtures was evaluated through flowability, viscosity, and setting time tests. Workability was assessed using the mini-cone test based on the Kantro method, measuring spread diameter at 0, 30, 60, and 90 minutes, with gentle hand remixing prior to each test to simulate on-site reactivation. This allowed assessment of thixotropy and workability retention relevant to 3D printing. Flow time was evaluated using a Marsh funnel adapted from ASTM C939 [16], recording the discharge time of 1 liter of fresh paste at the same time intervals, enabling analysis of viscosity evolution. Initial and final setting times were measured with the Vicat apparatus in accordance with EN 196-3 [13], under standard conditions ($20 \pm 2^\circ\text{C}$; RH > 90%), identifying the moments of reduced needle penetration (<4 mm) and complete hardening, respectively. Together, these tests provided insight into the influence of CDW on paste consistency, buildability, and open time.

3.- RESULTS AND DISCUSSIONS

3.1.- Characterization of CDW Powder

The mineralogical composition was carried out by x-ray diffraction (XRD) with Rietveld refinement presented in Figure 1, showed that CDW powder is predominantly composed of calcite (53.8%), indicating carbonated cementitious residues. Minor phases include vaterite (0.4%) and dolomite (3.0%), confirming the heterogeneous nature of the recycled concrete. XRD analysis revealed quartz (20.2%) as the second most abundant phase, followed by feldspar (8.2%) and mica (4.1%), indicating natural aggregate origin. Ettringite (9.8%) and

hydrocalumite (0.2%) point to residual hydration, while small amounts of unreacted clinker phases—alite (0.3%), belite and brownmillerite (<0.1%)—suggest limited remaining reactivity. These findings confirm CDW's mineralogical heterogeneity and align with its low pozzolanic activity.

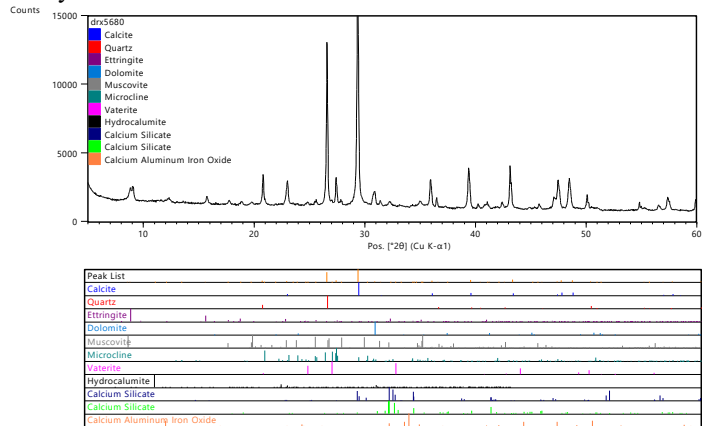


Figure 1. XRD pattern of the CDW powder with Rietveld refinement and identified crystalline phases.

X-ray fluorescence (XRF) analysis confirmed that CaO and SiO₂ are the dominant oxides in both CDW powder fractions, consistent with a cementitious origin. A slight increase in CaO and Fe₂O₃ content was observed in the finer fraction, while SiO₂ showed a corresponding decrease. Al₂O₃ remained relatively stable (~6.1%), and minor oxides, including MgO, SO₃, K₂O, and Na₂O, were consistently below 2%. The total oxide content surpassed 99%, demonstrating reliable quantification. The elevated loss on ignition (LOI), particularly in the finer fraction, points to the presence of hydrated or carbonated phases. Smaller losses at lower temperature ranges are associated with moisture evaporation and the decomposition of hydrated cementitious products. These results, detailed in Table 2, support the presence of both residual hydration products and carbonate-rich phases in the CDW.

Table 2. Thermogravimetric analysis results of CDW fractions.

Fraction	Moisture (%)	T250 (%)	T500 (%)	T950 (%)	Total Mass Loss (%)
AFR <0.125 mm	5.70	1.76	2.74	19.47	23.97
AFR <0.063 mm	6.79	1.92	2.99	20.37	25.28

Complementary thermogravimetric analysis (TGA) revealed that most of the mass loss occurred between 500 °C and 950 °C, indicating significant decarbonation of carbonate compounds such as calcite.

3.2.- Pozzolanic Reactivity of CDW Powder

Particle fineness greatly affects reactivity. The particle size distribution of the dry sieving revealed that most CDW particles (76.81%) were between 0.25 mm and 0.5 mm, with 52.83% retained on the 0.25 mm sieve and 23.98% on the 0.5 mm sieve. Only 0.46% passed the 0.063 mm sieve, indicating a very low proportion of ultrafine, cementitious-like particles, which may suggest low reactivity.

Fratтини Test results are presented in Figure 2, demonstrating both CDW fractions (<0.125 mm and <0.063 mm) had $[\text{OH}^-] \approx 57.0\text{--}57.6 \text{ mmol/L}$ and $[\text{Ca}^{2+}] \approx 10.9\text{--}11.0 \text{ mmol/L}$ at 8 and 15 days, remaining above the calcium hydroxide solubility curve. This indicates no significant $\text{Ca}(\text{OH})_2$ consumption, and thus, insufficient pozzolanic reactivity under the Fratтини test criteria.

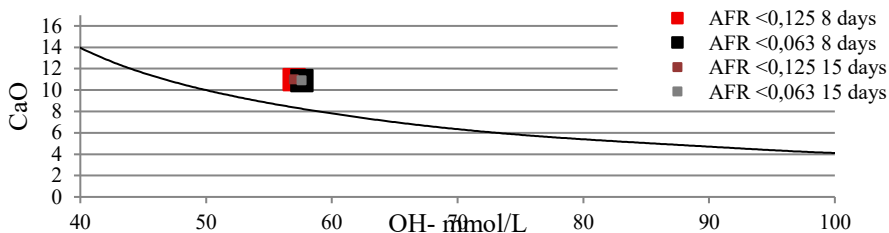


Figure 2. Fratтини test results for CDW powder samples (AFR <0.125 mm and AFR <0.063 mm) at 8 and 15 days of curing.

The Chapelle test results confirmed the limited pozzolanic reactivity of the CDW powder fractions. The fixed calcium hydroxide ($\text{Ca}(\text{OH})_2$) content was 94.5 mg/g for the AFR <0.125 mm sample and 98.5 mg/g for the AFR <0.063 mm sample. Values below 150 mg/g are considered indicative of low pozzolanic activity, which aligns with the results obtained for both fractions.

The SAI results are presented in Figure 3. The compressive strength of the mix with 25% CDW was 38.83 MPa at 28 days, compared to 62.12 MPa for reference. This resulted in a Strength Activity Index (SAI) of 65.20%, which is below the 75% minimum. Therefore, CDW cannot be classified as a pozzolanic material under these conditions.

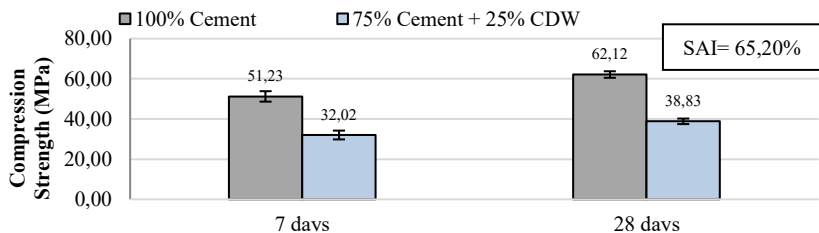


Figure 3. SAI results.

3.3.- Fresh-State Properties of Cement Pastes

The bulk density of the CDW showed a particle density of 2.608 Mg/m^3 (impermeable material, ρ_a), 2.251 Mg/m^3 (oven-dried, ρ_{rd}), and 2.387 Mg/m^3 (saturated surface-dry, ρ_{ssd}).

The 24-hour water absorption ($WA_{(24)}$) was 6.06%, indicating moderate porosity that may affect water demand and workability in cementitious systems using this material.

All mixtures exhibited a complete loss of self-flow, as evidenced by the absence of mini-slump spread across all formulations (Table 3). In the Marsh funnel test, flow performance varied significantly depending on the substitution strategy and CDW content. Mixtures incorporating high CDW levels, whether by total binder or cement replacement, showed early signs of flow obstruction, with loss in workability occurring within the first 15 minutes. In contrast, partial substitutions (25%) exhibit longer flow durations but still exhibited progressive loss in workability over time. These results underline the severe impact of CDW incorporation on fresh-state rheology, especially in terms of viscosity increase and reduced flow retention.

Table 3. Workability and Rheological Behavior: Mini-Slump and Marsh Funnel Tests.

Paste	Slump Flow @ 0 min (mm)	Marsh Flow Time @ 0 min (s)	Marsh Flow Time @ 30 min (s)	Flow Cessation Observation
REF	0	N/A	N/A	No flow at any age
B50 - CDW Max – Binder Substitution	0	N/A	–	Blocked at 820 s
C50 - CDW Max – Cement Substitution	0	284.84	544.97	Blocked at 990 s
B25 - CDW ½ Max – Binder Substitution	0	424.65	N/A	Blocked at 1260 s
C25 - CDW ½ Max – Cement Substitution	0	769.00	N/A	Blocked at 826 s

The setting time results, summarized in Figure 3, demonstrate the significant impact of CDW incorporation on the hydration kinetics of the pastes.

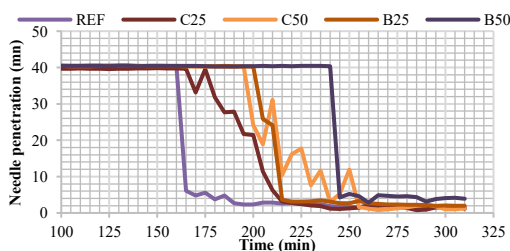


Figure 4. Setting time results.

Figure 4 presents the needle penetration results for all pastes. The reference mixture (REF) exhibited the earliest setting onset and completion (approximately 165–245 minutes), followed sequentially by C25, C50, B25, and B50. Partial cement substitutions with CDW (C25, C50) led to earlier setting compared to binder-based replacements (B25, B50), which showed a clear delay. This trend indicates that CDW incorporation affects the structuration kinetics differently depending on the replacement strategy, likely due to variations in particle packing, water demand, and residual reactivity.

4.- CONCLUSIONS

Characterization results confirmed the low pozzolanic reactivity of CDW, with XRD, TGA, Frattini and Chapelle tests indicating predominantly inert behavior. Despite this, its incorporation altered hydration kinetics and impaired fresh-state performance. Cement substitutions accelerated setting, while binder substitutions delayed it, with overall loss of workability and stability. These results highlight the need for optimized CDW content and granulometry to ensure viable rheological performance in applications such as 3D printing.

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