Journal of Structural Engineering & Applied Mechanics Volume 9 Issue 1 (2026) 671

Contents lists available at https://www.goldenlightpublish.com/journals/jseam/1-toc

Journal of Structural Engineering & Applied Mechanics

Journal homepage: https://www.goldenlightpublish.com/journals/1/jseam

Mechanical activation of end-of-life building materials: grinding efficiency and potential for valorization

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https://doi.org/10.31462/jseam.2026.671

Received 22 January 2026; Revised 22 February 2026; Accepted 11 March 2026; Available online 30 March 2026

Keywords

Concrete waste
End-of-life materials
Mechanical activation
Recycling
Vertical stirred mills
Waste valorization

Abstract

Optimized grinding enhances material reactivity while reducing processing time and energy demand, supporting more sustainable and cost-effective construction. In this context, construction and demolition waste (CDW), widely landfilled due to its low reactivity, represents a promising candidate for upgrading. Accordingly, this study investigates the valorization potential of CDW-derived concrete waste (CW) as a value-added raw material. Vertical stirred mill was employed to investigate influences of grinding parameters, media filling ratio (MF = 50% and 70%) and grinding duration (5 min and 30 min), on features of CW. Particle size distribution (PSD) and specific surface area (SSA) were tested, while flow table and compressive strength tests were performed to investigate effect of CW on cementitious systems. Grinding reduced the median particle size (D50) from approximately 197 μm to 14–34 μm and increased the SSA by nearly 3–4 times. Replacing 20% of cement with untreated CW led to a significant reduction in workability and compressive strength, whereas ground CW mixtures exhibited improved mechanical performance. Although all CW mixtures remained below the reference, grinding enhanced compressive strength substantially compared to untreated CW. The effect of prolonged grinding varied with media filling ratio; while extended milling at 50% filling did not enhance performance, it contributed positively at 70%. The findings demonstrate that strength development is governed not only by fineness but also by agglomeration behavior and effective particle packing within the matrix.

1. Introduction

As a consequences of large-scale urban renewal projects, rising need for new buildings, and occurrence of severe natural disasters such as earthquakes and tsunamis, billions of tons of construction and demolition waste (CDW) are produced worldwide annually [1]. The content of this waste varies according to the building stock of the region where it is generated [2]. A study performed in the European Union (EU-27) using Material Flow Analysis resulted that, in 2020, the largest CDW fraction was concrete (56.2%), followed by brick-based materials (6.5%), and subsequently ceramics, tiles, steel, glass, wood, aluminum, and others [3,4]. Although recycling rates in developed countries are comparatively high (60–100%), CDW is yet to mainly employed in downcycling applications, such as filler material in road construction or backfilling, rather than being upcycled into higher-value secondary raw materials [1]. In developing or less developed countries, recycling rates are considerably lower. Given the massive amounts involved, the magnitude of the problem and the urgency of improving recycling practices become even more evident. CDW comprises about one-third of global solid waste [5,6]. While global estimates vary – because of inconsistent reporting or the lack of reliable data – annual CDW generation is projected to in the range of 3 to 10 billion-ton [7,8]. To demonstrate the scale, China produced about 1.7 billion tons of CDW in 2018, while the United States generated approximately 600 million tons [1]. Eurostat data for 2022 show that EU countries produced a total of 2,233 million tons of waste, around 38% of which was CDW [9]. Projections and data systematically demonstrate that these quantities will continue to increase in the following years [10,11]. Unless appropriate upcycling pathways are implemented within a circular-economy framework – facilitating CDW to be reintroduced into the supply chain as secondary raw materials – much of this waste will continue to be disposed of in landfills for extended durations. This yields to the loss of land resources that could otherwise serve agricultural or urban functions, as well as to air, soil, and water pollution [12]. Improving the recycling of CDW not

eISSN 2630-5763

only decrease the environmental impacts related to landfill disposal but also lower the need for natural resources.

Concrete waste (CW), which comprises the larger proportion of CDW-based materials, is mostly reused through the most practical and rapid way: its application as recycled concrete aggregate (RCA) in non-structural works such as road pavements, pavement sub-layers, and backfilling operations [13–15]. These applications are commonly applied because of simplicity and cost-effectiveness. Moreover, several studies have shown that RCA can also partially or fully replace natural aggregates in structural concrete, resulting promising performance [16,17]. RCA can be employed directly without any treatment; however, several enhancement techniques – such as accelerated carbonation, slurry coating, solution treatment, abrasion treatment, microbial treatment etc. – have been examined in the literature to mitigate disadvantages related to RCA, such as its highly porous inner structure, the presence of an inferior interfacial transition zone (ITZ), and existing cracks or microcracks [18–22]. The main motivation for these efforts can be attributed to the need to quickly handle the large quantity of CDW produced worldwide while simultaneously decreasing the construction sector's dependence on natural aggregates. Worldwide, the annual usage of natural aggregates is documented to vary between 20 and 50 billion tons, indicating the considerable environmental burden linked to their extraction and production [17,23–25].

In addition to employing as aggregate, CW has recently received considerable research attention as a supplementary cementitious material (SCM). Several studies have examined its performance when partially replacing cement at various replacement levels, investigating its effect on material properties [26–28]. Beyond these academic studies, a standardization effort has also resulted rapid development in this field: the introduction of EN 197-6:2023, a new standard that legally permits the utilization of recycled building materials-specifically recycled concrete [29,30]. With this standard, the way for incorporation CW into cement manufacturing has been officially opened, thereby encouraging the valorization of these wastes. As a result of these developments, research on utilizing CW as a value-added way has increased rapidly. These developments have collectively accelerated studies on the possibility of employing CW-based materials as mineral additives. Although some requirements governing the employing of CW in cementitious systems are defined in the standards, essential criteria for its application as an SCM contain its chemical composition, reactivity, and fineness, all of which critically affect its performance.

It is well known that grinding methods and operational parameters have a major effect on the features of powder materials. Therefore, the literature comprises diverse studies examining the influence of grinding parameters on the milling of waste materials, though still limited. In this context, Liu et al.[31] examined the influence of grinding time on the characteristics of waste glass. Obtained results demonstrated that grinding efficiency decreases as the process continues and becomes almost negligible after around 120 minutes. Increasing fineness improves the activity index, with 0–3 μm particles enhancing early-age reactivity and 3–10 μm particles contributing at later ages. 90 minutes was decided as the most optimal grinding time. In a separate study, Li and Hitch [32] examined the mechanical activation of mine waste using planetary, vibratory, and stirred mills. Results obtained indicated that extended milling in dry condition leads to particle agglomeration and a limit in crystallite size reduction, while wet stirred milling yields the highest surface area and dry vibratory milling results the most disordered structures. In another study, Mucsi et al.[33] examined the fine fraction of CDW and investigates how its reactivity can be improved through mechanical activation in a stirred media mill. Their systematic experiments showed that the reactivity of CDW fines can be controlled and enhanced through this mechanical activation process. In another study, Szabó et al.[34] investigated the fine fraction of CDW and examined how its reactivity can be enhanced through mechanical activation in a stirred media mill. It was found that mechanically activated CDW powder can partially replace Portland cement, though higher replacement levels reduce strength. Moreover, increased grinding fineness improved the pozzolanic reactivity, with the 10-minute milled CDW powder resulting a 51% enhancement in lime uptake compared to the untreated sample. Another study performed by Proenca et al. [35] examined several treatments-mechanoactivation, thermoactivation, and tannic acid exposure-on mixed – origin (MP) and concrete-origin (CP) CDW powders. It was found that mechanoactivation improved density and decreased particle size without causing chemical changes, and the authors suggested 0.5 h mechanoactivation for CP, while 1 h mechanoactivation was more appropriate for MP. In another study, Sinkhonde and Mashava [36] examined how increasing the mass of fragmented clay bricks fed into a ball mill influences the fineness of the obtained clay brick powder (CBP). It was reached that decreasing the feed mass resulted much finer CBP, which in turn lowered surface roughness. Adding these finer CBP particles into cement paste enhanced compressive strength without causing any notable change in mix density.

Considering given literature review, the present study was designed to contribute to a faster and value-added solution to the CDW problem. Although there are a few publications focusing on grinding parameters specifically for CDW, it is evident that much more detailed and extensive research is required in this field. Therefore, the effects of grinding parameters on CW – which constitutes a major portion of CDW – were examined in this study. The grinding process was performed using vertical stirred mills. Two different media filling (MF) ratios and two grinding durations were tested as the main grinding parameters. Changes in the properties of the concrete waste material were analyzed through particle size distribution and Blaine fineness measurements, and its effect within the cementitious matrix was investigated by replacing 20% of cement with CW, followed by flow table and compressive strength tests. The findings obtained from this study are expected to contribute to the current state of the art on this subject. Optimizing the grinding of CDW is considered beneficial not only in terms of economic efficiency but also in improving the effective use of these wastes as SCMs.

2. Experimental Program

2.1. Material details

The employed concrete waste (CW) in this study was collected as rubble form from urban demolition sites and crushed using a jaw crusher, adjusted to a 2 mm opening. After preparing a representative sample using a separator, the crushed CW was sieved on a 0.85 mm mesh; the 0.85 mm fraction was collected and used as the powder feed material. This <0.85 mm CW fraction was fed into the grinding process and also served as the reference sample for comparisons. This pre-procedure was carried out to control the particle size distribution (PSD) of the feed material. The physical appearances of these wastes are demonstrated in Fig. 1. To achieve a homogeneous distribution, the powder material obtained was subjected to three successive splitting steps via a sample splitter.

2.2. Grinding operation and parameters

The grinding process was performed using a laboratory-scale vertical stirred media mill equipped with a cylindrical chamber and a rotating shaft fitted with impellers. Spherical steel-alloy grinding balls with a diameter of 3.32 mm were employed as the grinding media. The grinding operations were conducted at two different media filling (MF) ratios – 50% and 70% of the chamber volume – while maintaining the material filling ratio at 100% (i.e., the interstitial spaces between the grinding media were fully filled with material). These MF levels were selected based on the operational ranges commonly reported in the literature [37–39]. Two grinding durations, 5 minutes and 30 minutes, were investigated. All experiments were performed under dry conditions at a constant impeller speed of 600 rpm. Prior to grinding, the powder materials were dried at 80 °C. Details of the vertical stirred media mill and the grinding balls used in this study are demonstrated in Fig. 2. The total internal volume of the grinding chamber was 1750 cm³ (1.75 L). The MF ratio (ϕm) represents the percentage of this chamber volume occupied by the grinding media (balls) and was set to 50% and 70%. For these conditions, the corresponding total media volumes were calculated as 875.0 cm³ and 1225.0 cm³, respectively. Based on the standard packing assumption that 60% of the media volume consists of solid balls, the solid ball volumes were determined to be 525.0 cm³ for 50% filling and 735.0 cm³ for 70% filling. The material volumes occupying the interstitial spaces between the balls were calculated accordingly as 350.0 cm³ and 490.0 cm³ for the respective MF ratios.

2.3. Testing methods

Experimental program was designed to examine the grinding performance. In this context, the characterization of the powder materials was first performed, and their PSD was measured using a laser diffraction analyzer with a sensitivity range of 0.02–2000 µm. The overall PSD curves, together with the D_{50} and D_{90} values, were employed for analysis. Moreover, the fineness of the powder materials was found using the Blaine fineness method in accordance with ASTM C204. In the second stage, the performance of the powders was examined by adding them into a cementitious system. Mortar mixtures were prepared with fixed water-to-binder and aggregate-to-binder ratios of 0.45 and 2.7, respectively, and a 20% cement replacement level was adopted for CW, following the provisions of ASTM C311. CEM I 42.5 R cement was used as the binder, and CEN standard sand (density: 2.50 g/cm³) was employed as the aggregate. The density of the CW was determined as 2.49 g/cm³. The CW powders produced under different grinding conditions were incorporated into the mixtures. In this scope, the flowability of the mortars was first investigated through a flow table test performed according to ASTM C1437-15. Compressive strength tests were then carried out using a hydraulic testing machine following the ASTM C109 standard, and the 7- and 28-day strength values were given as the average of three specimens.

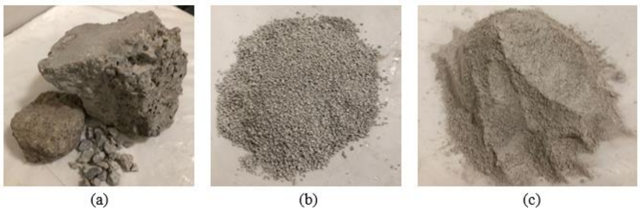


Fig. 1. Physical appearance of CWs a) Concrete Rubble, b) <2mm, c) <0.85mm

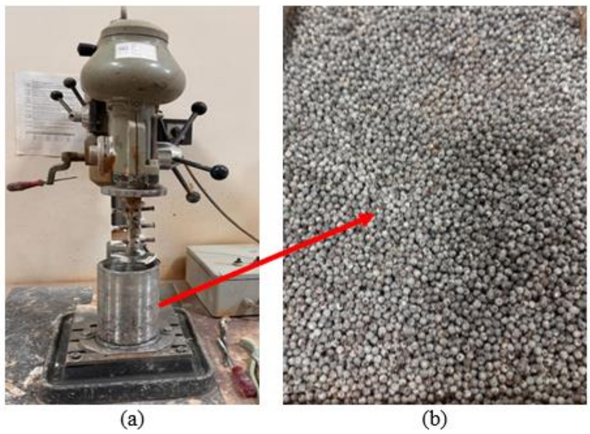
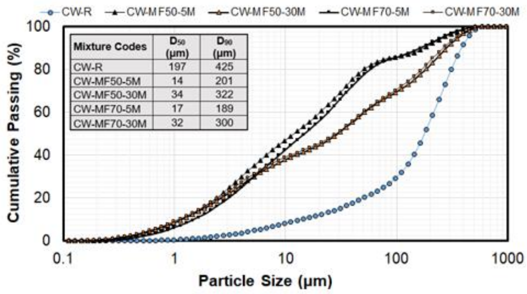


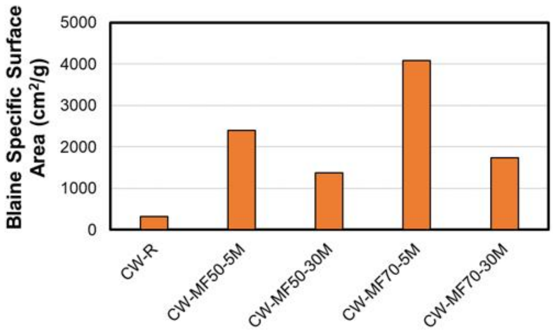
Fig. 2. Details of employed mill a) Vertical Stirred Mills, b) Grinding Media/Balls

Table 1. Grinding parameters and corresponding tests

Case ID	Media filling ratio (MF %)	Grinding duration (min)	Material filling	Powder tests	Mortar tests (20% replacement)
CW-R		No grinding		PSD & Blaine	Flow & Compressive Strength
CW-MF50-5M	50	5			
CW-MF50-30M	50	30	100%		
CW-MF70-5M	70	5			
CW-MF70-30M	70	30			



(a)



(b)

Fig. 3. a) Particle size distribution of CWs; b) Surface area of CWs

3. Results and Discussion

3.1. Physical characteristics of ground CW

To examine how the grinding process affects the physical properties of the CW powder, PSD analysis and Blaine fineness measurements were conducted on samples obtained from different grinding conditions. A total of five conditions were investigated. The CW-R sample, which was crushed, passed through a 0.85 mm sieve, and not subjected to any grinding, was prepared as the reference. For the remaining samples, two different media filling ratios were employed, MF50, where the grinding media occupied 50% of the mill volume, and MF70, where the media occupied 70, in combination with two grinding durations of 5 minutes (5M) and 30 minutes (30M). Powder samples obtained from these conditions were evaluated, and their PSD curves and Blaine fineness values are given in Fig. 3. As seen, all milled powders are markedly finer than the unground reference (CW-R: D50≈197 µm; D90 ≈ 425 µm), confirming the efficiency of the vertical stirred mill. After milling, the median size falls to the 14-34 µm range and the coarse tail to 189-322 µm. However, an analysis of the grinding parameters reveals that extending the duration from 5 to 30 minutes resulted in a coarser PSD for both MF ratio. This reversal is attributed to the excessive production of ultrafine particles, which significantly increases specific surface area and surface energy. These conditions strengthen interparticle attractive forces – specifically electrostatic and van der Waals forces – thereby promoting agglomeration [40–42]. Such agglomerates or secondary particles – formed through the clustering of very fine fragments – present as larger diameters in PSD measurements, thereby possibly giving the impression of decreasing grinding efficiency [31,42].

Furthermore, prolonged grinding may disrupt chemical bonds at the particlesurfaces, inducing microstructural changes and forming reaction layers. These surface products can coat fine particles, further stabilizing the agglomerates and enhancing their tendency to cluster [42].

A similar trend is seen in the specific surface area (SSA) results. SSA follows the same qualitative trend. Milling enhances SSA strongly relative to CW-R (≈3-4× or more), but 30 min does not yield higher SSA than 5 min, again consistent with agglomeration and partial pore blockage at long residence times. Although SSA enhanced substantially after grinding, extending the grinding time did not resulted in higher SSA values. Despite the absence of a noticeable difference in PSD between MF50 and MF70, the MF70 samples showed higher SSA. This can be explained by the higher media filling ratio, which enhances collision frequency, frictional interactions, and overall energy input inside the stirred mill. Under these conditions, surface abrasion becomes more dominant than particle breakage, especially at longer grinding times, as the system transitions from fracture-controlled to attrition-controlled grinding. Consequently, MF70 yielded greater surface roughening, resulting higher SSA even when the PSD curves seem similar.

3.2. Flowability performance of mortars incorporating ground CW

In addition to the investigations conducted on the powdered materials to evaluate the effects of grinding parameters, further analyses were carried out on cementitious mortar mixtures. At the initial stage, the fresh characteristics of the mixtures were examined using the flow table test. The obtained results are demonstrated in Fig. 4. The mixture coded as M-REF consists of 100% cement, whereas remaining mixtures contain a 20% replacement of cement with CW, derived from various grinding conditions. The results indicate that CW substitution negatively influenced the workability of the mixtures. This observation can be attributed to several factors, including the absorption of mixing water by the hydration products present on the surface and within the structure of CW particles and inherently porous, rough and irregular morphology of CW, which rises resistance to flow [43–46].

The M-CW-R mixture, in which CW was employed without any grinding and only sieved before cement replacement, showed a markedly greater loss in fresh properties compared to the mixtures incorporating ground CW. This pronounced reduction in workability may be associated with the angular, rough-textured fragments that persist without the edge-rounding/reshaping imparted by grinding, which raises interparticle friction and water demand [47,48]. In addition, the lack of newly generated fines eliminates the microfiller 'lubrication' and packing benefits typically provided by milled powders and coarse and non-reactive CW particles may remain undissolved within the matrix and yield to form agglomerates, resulting to heterogeneous dispersion [49].

The effect of grinding parameters on workability could not be distinctly differentiated, which may be attributed to the coexistence of competing mechanisms during the grinding process. Grinding reduces particle size and increases specific surface area, thereby enlarging the wetted surface and increasing water demand, which typically leads to reduced flowability [50,51]. This behavior is widely reported for finely ground supplementary cementitious materials [52]. Conversely, grinding also promotes the breakdown of porous clusters and weakly bonded agglomerates, leading to improved particle packing and a denser granular skeleton, which can reduce void water and make additional water available for lubrication within the matrix [53]. This refinement may release water previously trapped within voids or interparticle clusters, partially compensating for the increased surface-related water demand and contributing to improved flow behavior [54].

3.3. Compressive strength development mortars incorporating ground CW

In addition to fresh properties, the effect of grinding parameters on the mechanical properties was evaluated through mortar mixtures in which 20% of the cement was replaced with CW. The 7- and 28-day compressive strength results are provided in Fig. 5. The mixture coded as M-REF contains 100% cement, whereas all other mixtures include a 20% replacement of cement with CW derived from various grinding conditions. The obtained results show that the including of non-ground CW yields to a considerable reduction in compressive strength for each curing ages. This strength loss can be attributed to the formation of a porous and heterogeneous matrix, primarily caused by workability-related issues, as well as to the inability of CW to actively participate in the cementitious reactions, thus working as a non-reactive powder [43]. Previous studies have revealed that CW shows low activity when employed without any treatment or activation process, and similar behavior was recorded in the present study [44,46]. Furthermore, the large particle size and low specific surface area of the untreated CW may have increased this negative effect.

Regardless of the grinding parameters, mixtures incorporating ground CW showed significantly higher compressive strength compared to the mixture containing untreated CW, clearly indicating the beneficial role of grinding on the performance of the waste material. However, for all evaluated parameters, the CW-containing mixtures still resulted in lower 7- and 28-day compressive strength values than the reference mixture (M-REF). These findings highlight that grinding effectively improves the performance of CW, although it does not fully balance for the strength loss because of cement replacement. For mixtures produced with a MF of 50%, increasing the grinding time did not result in a positive effect on compressive strength. A similar trend was recorded in the fineness and specific surface area results, suggesting that prolonged grinding at this MF level promoted particle agglomeration, thereby limiting the effective contribution of the finely ground material. Although prolonged milling at MF 70 yielded a coarser apparent PSD and lower Blaine value, the mechanical response improved. This implies that at high media filling ratios, the benefits of intensified attrition, specifically edge rounding, enhanced particle packing, and superior ITZ continuity, dominated the nominal reduction in measured fineness. Additionally, this behavior can be attributed to optimized particle packing and improved microstructural continuity within the cementitious matrix. Furthermore, while increasing the MF ratio at a grinding duration of 5 minutes yielded a decrease in compressive strength, extending the grinding time to 30 minutes reversed this trend, leading to enhanced strength development. Across all conditions, the CW-involving mortars remained below the M-REF benchmark at 7 and 28 days. This trend reflects the dilution of clinker content and the limited early-age pozzolanic contribution of CW at the tested dosage. Overall, the results indicate that compressive strength is governed not by fineness alone, but by the interplay between grinding energy, agglomeration behavior, and effective microstructural packing.

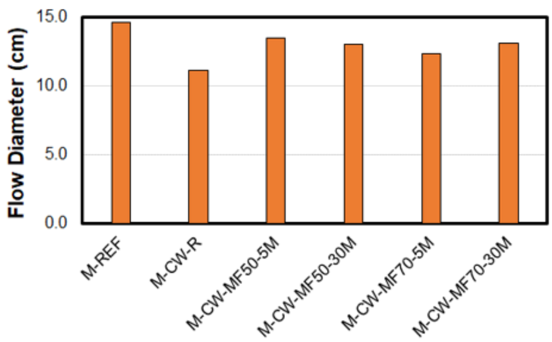


Fig. 4. Flow table test results

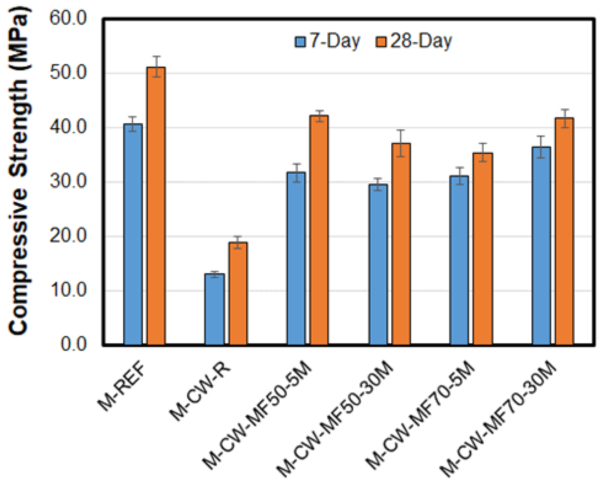


Fig. 5. Compressive strength test results

4. Conclusions

Within the scope of this study, the influences of grinding parameters on CW were evaluated, and the following findings were recorded:

- Grinding parameters considerably influenced the PSD and SSA of CW powder. Prolonged grinding yielded particle agglomeration, while increasing the MF ratio from 50% to 70% resulted in a slight positive effect, particularly in terms of SSA.
- In terms of fresh properties, mixtures containing ground CW showed enhanced workability compared to those incorporating untreated CW; however, they showed more viscous than the reference mixture. A similar trend was recorded in the compressive strength results, where grinding improved performance relative to untreated CW, yet the results remained below the reference level.
- The results show that the effect of grinding duration varies depending on the media filling ratio. By optimizing the grinding parameters, more effective grinding conditions can be obtained, leading to the production of more reactive CW powders. Although fineness and SSA are related to compressive strength, it is also emphasized that these are not the only determining parameters.
- Performance of CW in cementitious systems is strongly dependent on the optimization of grinding parameters, highlighting that mechanical activation must be carefully tailored to balance particle refinement, agglomeration behavior, and energy efficiency.
- The obtained results are specific to the CDW tested in this study, and it should also be noted that the results may also vary depending on the particle size of the feed waste added to the grinding process.
- The results indicate that while the inclusion of CW negatively affected fresh and hardened properties at the tested replacement level, appropriate balancing and optimization of grinding parameters could mitigate these effects, potentially achieving performance comparable to or even exceeding that of the 100% cement reference system.

Future research should focus on evaluating the grinding performance of CDW obtained from diverse sources and introduced at different feed size distributions. This would enhance the reliability, reproducibility, and broader applicability of the findings, thereby strengthening confidence in the practical use of ground CDW as a cementitious material. Furthermore, more comprehensive experimental investigations are needed to evaluate grinding performance (testing varied parameters) both at the material level and in terms of its influence on the behavior of cement-based systems.

Declarations

Conflict of interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This research received no external funding.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Use of generative AI and AI-assisted technologies

During the preparation of this work the author used AI in order to improve several important aspects of writing, such as readability, grammar, spelling, and tone of the text.

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