

Article

Reutilization of Recycled CDW Sand in Mortars, Paving Blocks, and Structural Concrete

Ángel M. Pitarch , Ana Piquer , Lucía Reig ^{*} , Marta Roig-Flores , Vicente Albero ,
David Hernández-Figueirido  and Antonio Melchor-Eixea 

Department of Mechanical Engineering and Construction, Universitat Jaume I, 12071 Castellón de la Plana, Spain; pitarcha@uji.es (Á.M.P.); ana.piquer@uji.es (A.P.); roigma@uji.es (M.R.-F.); valbero@uji.es (V.A.); hernandd@uji.es (D.H.-F.); amelchor@uji.es (A.M.-E.)

^{*} Correspondence: lreig@uji.es

Featured Application: This study examines the technical viability of using industrially processed construction and demolition waste (CDW) with a limestone–ceramic composition, washed to remove sulphates, as a fine aggregate (sand) in mortars, paving blocks, and structural concrete.

Abstract: Reusing construction and demolition waste (CDW) as recycled aggregate reduces environmental impact and enhances resource efficiency. While previous research has mainly focused on the use of recycled aggregates (RAs) in concrete, this study evaluates the use of CDW-derived sand in mortars, paving blocks, and structural concrete. Natural and CDW aggregates were characterized, and samples were prepared with two types of Portland cement, replacing up to 100% of the natural limestone sand. Tests were conducted to assess workability, density, strength, and durability. CDW aggregates, primarily composed of limestone and ceramics, reduced sample density as their content increased. Workability improved in the mortars and concrete with higher CDW contents, peaking at 20% CDW in paving blocks. Although the permeability of concrete increased with CDW content, the developed recycled aggregate concrete (RAC) met structural code requirements for all the exposure classes. Despite the decline in strength with higher CDW content, the paving blocks maintained a relative tensile splitting strength above 80%, and the relative compressive strength of the mortars cured for 28 days exceeded 70%. The RAC compressive strength remained within the required range for reinforced concrete (>25–30 MPa). These results validate the feasibility of using CDW-derived sand in various sustainable construction applications with minimal strength loss. Furthermore, they contribute to the development of standardized guidelines for RAs in non-structural applications, fostering broader industry adoption and environmental benefits.

Keywords: construction and demolition waste; recycled aggregates; paving blocks; recycled aggregate mortars; recycled aggregate concrete; physico-mechanical properties



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1. Introduction

The reutilization of construction and demolition waste (CDW) as recycled aggregates (RAs) has been paid considerable attention in recent years for its potential to address environmental concerns and to enhance resource efficiency in the construction industry. Global urbanization and industrialization have led to an increasing demand for infrastructure and housing, which results in the generation of vast quantities of CDW. Over 3 billion tons of CDW waste are generated globally each year [1,2], and in the European Union,

CDW constitutes about one-third of the total waste produced annually [3]. According to Alhawamdeh et al. [4], the construction industry is responsible for approximately 36% of the global solid waste found in landfills. CDW can be classified into waste generated during the construction phase, and that generated during demolition, which typically accounts for over 50% of the total waste produced by the construction industry [5]. Additionally, the construction sector is a major consumer of natural resources, accounting for approximately 50% of all extracted materials, including metals, stones, gravel, sand, or wood. It is also responsible for the release of approximately 6 billion tons of CO₂ into the atmosphere [6]. Consequently, the development of sustainable practices to reduce the sector's environmental footprint is imperative. In this context, disposing of CDW in landfills is becoming increasingly unsustainable and necessitates the development of innovative waste management solutions that align with circular economy principles. These solutions should prioritize the reuse of CDW in higher-value-added applications, such as employing it as raw material in the production of new building materials, rather than restricting its use to lower-value applications like road sub-bases. To mitigate the environmental impact of CDW, researchers such as Trancone et al. [2] developed a sustainable bioleaching method to reduce the volume of concrete in CDW. This innovative approach offers an efficient and environmentally friendly strategy for CDW management, facilitating its reuse in the production of new building materials.

The RAs that derive from CDW are a promising alternative to natural aggregates (NAs) in construction applications, including recycled aggregate concrete (RAC), road construction, and embankments. Apart from reducing the volume of waste disposed in landfills, reusing CDW as RAs helps to keep natural resources and to mitigate the environmental impacts associated with resource extraction, habitat destruction, water pollution, and carbon emissions [7–10]. Although RA use can result in cost savings by decreasing the demand for natural materials and lowering waste disposal costs, the initial investment in processing facilities and equipment can be substantial. As highlighted by Vegas et al. [11], the implementation of landfill taxes could be crucial in promoting RA use by offsetting initial processing costs and improving the competitiveness of recycled materials compared to NAs.

The properties and performance of RAs have been extensively researched [12–14]. Recent studies have shown that, when appropriately processed, the properties of RAs can be comparable to those of NAs, which makes them a viable substitute in many structural and non-structural applications [10,13–18]. Elchalakani and Elgaali [12] observed that the impact of RAs on concrete strength is influenced more by the recycled material quality than by its quantity. Some studies have reported a reduction in compressive strength when NAs are replaced with RAs [8,19–21], but other research works have indicated that mechanical properties remain largely unaffected or even improve with the incorporation of RAs [22–26].

This variability in material properties, in addition to the perception of reduced quality compared to NAs, poses challenges of widespread RA adoption. Additionally, the potential for contamination in CDW-derived RAs is significant because materials like concrete, rubble, bricks, tiles, and asphalt, which are common components of CDW, can be processed into RAs. Consequently, the variability in the composition of CDW presents the challenges of ensuring the consistency and reliability of RAs, particularly in structural applications where material performance is critical [13]. To address these challenges, research has focused on optimizing processing techniques to enhance the quality and performance of RAs. Advanced crushing, sieving, and washing processes have been developed to remove contaminants, to reduce variability in particle size distribution, and to improve overall RA quality. In the present study, CDW-derived sand was subjected to multiple washing

cycles to reduce its sulphate content, along with pre-separation, controlled crushing, and sieving. Investigating the properties of this specific CDW and its behavior as raw material in the development of more sustainable building materials will contribute to expanding the current knowledge base and to advancing toward a more sustainable and circular construction industry.

Despite advancements made in processing and treatment, adopting RAs in the construction industry remains limited. One of the main obstacles for the widespread RA use is the perception that they are of lower quality than Nas, and they are, therefore, mainly used in landfills [27]. This perception is often reinforced by the absence of standardized guidelines and regulations that govern RA use in construction [28]. For instance, the Spanish Structural Concrete Code restricts RA use to those that exclusively derive from structural concrete, limiting their use to a maximum of 20% by weight of natural gravel. However, other European standards, such as DS 2426 from Denmark [29], NEN 8005 from the Netherlands [30], and NB 26 from Norway [31], allow the use of moderate and high-quality fine RAs. Additionally, Standard NF EN 206-1/CN from France [32] allows high-quality fine RA use, albeit with specific limitations [27]. To overcome these obstacles, it is important to conduct more studies that generate new knowledge and contribute to establishing consistent standards that guarantee the quality and safety of RAs. This will help to build trust and will encourage their use in a wider variety of applications because, although many studies have investigated CDW aggregate use in concrete [6], very few studies have examined their reutilization in non-structural elements, such as paving blocks or mortars. Previous studies by Ferro et al. [33] investigated mortars incorporating recycled sand with a particle size of less than 8 mm, primarily composed of calcite and quartz. The results indicated a slight reduction in both compressive and flexural strength. Borges et al. [16] developed mortars that replaced natural sand with RAs from CDW at rates of up to 100%. Although the results showed that higher RA content resulted in higher primary energy demand and greater water consumption, mortars containing 50% RA exhibited the best overall performance. This was characterized by higher carbon capture potential, improved compressive strength, and acceptable tensile adhesion strength. The mortars developed by Kepniak and Lukowski [34] reused recycled sand consisting of 88.5% concrete- or mortar-based materials, 4.7% natural stones and aggregates, and approximately 6.5% other compounds. These mortars also showed a positive environmental impact, particularly when replacing 40% to 60% of natural sand. Although a slight reduction in strength was noted, this was balanced by a significant conservation of natural resources. Poon et al. [17] investigated the use of RAs from CDW as replacements for coarse and fine aggregates in concrete bricks and blocks. The two types of RAs used consisted primarily of old concrete rubble, along with small amounts of natural stones, clay bricks, and other impurities such as wood, tiles, and metals. One RA was predominantly composed of concrete (98.8%), while the other contained 77.7% concrete and 21.8% natural stones. Their findings showed that replacing NAs with 25% or 50% RA had a negligible effect on compressive strength, whereas higher replacement levels caused a reduction in compressive strength. Additional tests, including assessments of shrinkage, skid resistance, and plant trials, yielded positive results. In later research, Chu et al. [18] identified particle packing as a key factor influencing the performance of concrete paving blocks. The appropriate packing optimization led to a significant increase in the compressive strength of concrete paving blocks made entirely with RAs, rising from approximately 30 MPa to 79 MPa. This strength was close to the maximum strength achieved in samples made with only NA, which was 84.8 MPa.

According to the report on a Sustainable Future for the European Cement and Concrete Industry [35], mortars and plasters comprise 24% of cementitious downstream products in Europe, while non-reinforced cement-based products represent 19%. Additionally, cur-

rently there are no standards that address the incorporation of CDW into non-structural elements. Therefore, this study aims to characterize one particular CDW RA and to evaluate its performance when used to partially replace natural calcareous aggregates in the manufacture of paving blocks, mortars, and structural concrete. The findings of this study aim to encourage the reuse of this particular CDW as raw material for high-value applications, thereby fostering a construction industry aligned with circular economy principles.

2. Material and Methods

2.1. Experimental Process

The experimental work conducted to explore the potential of reutilizing CDW RAs was divided into three primary stages:

1. Characterization of NA and RA;
2. Design, preparation, and characterization of mortars and paving blocks;
3. Design, preparation, and characterization of structural concrete.

2.2. Materials Used

The aggregates used in this study consisted of natural calcareous sand and one RA derived from CDW, supplied by the local company Hope and Effort S.L. The RA was pre-separated, control-crushed, and sieved, and it underwent multiple washing cycles to reduce its sulphate content. The treatments were conducted by the aggregate supplier, and the CDW RA sand was characterized and used as received, without any further processing.

Mortars and paving blocks were prepared with two different types of Portland cement (PC): CEM I 52.5R, Elite Cementos S.L. (Grao de Castellón, Spain) containing more than 95% clinker, to evaluate the potential for pozzolanic reactions that might enhance the interaction between aggregates and the cementitious matrix; and CEM II/B-M(Q-L) 42.5R, Elite Cementos S.L. (Grao de Castellón, Spain) a more sustainable option with a lower clinker content. Both PC types met the European Standard UNE-EN 197-1 [36] and were provided by Elite Cementos S.L. (Grao de Castellón, Spain). Mortars, paving blocks, and concrete were mixed and cured using tap water. Superplasticizer SKP380, supplied by SIKA (Madrid, Spain), was incorporated into all the prepared mixes.

2.3. Characterization of Aggregates

The aggregates were oven-dried at 100 °C for 24 h and subsequently characterized according to the test methods and standards summarized in Table 1. Each property was determined as the average of at least two tests. The Micro-Deval test was conducted by adapting the procedure outlined in Standard UNE 146404 [37]. During this test, a 500 g dry-weight sample was sieved and washed to obtain particle sizes between 0.125 and 2 mm. This sample was mixed with 2500 g of abrasive load (steel balls approximately 10 mm in diameter) and 2.5 kg of water, and then subjected to 1500 revolutions at 100 ± 5 rpm. After the test, the sample was sieved through an 8 mm sieve to collect the steel balls, and then through 250 micron and 63 micron sieves. The material retained in the last two sieves was then dried and weighed.

The chemical composition of the NA and RA was analyzed by X-ray fluorescence (XRF) in a Bruker S4 Pionner spectrometer (Bruker, Karlsruhe, Germany). Their mineralogical composition was examined through X-ray diffraction (XRD) in a Bruker AXS D4 Endeavor powder diffractometer with Cu K α radiation at 20 mA and 40 kV, covering 5° to 70° 2 theta degrees. Thermogravimetric (TG) analyses of the aggregates were conducted with a TGA/SDTA851e/LF/1600 by Mettler Toledo up to 1000 °C. Samples were heated at a rate of 20 °C/min in alumina crucibles in an air atmosphere.

Table 1. Properties analyzed, procedures, and standards used to characterize the aggregates.

Property	Test	Standard
Particle size distribution	Sieve analysis	UNE-EN 933-1 [38]
Percentage of fines (<0.063 mm)	Sieve analysis	UNE-EN 933-1 [38]
Assessment of fines	Sand equivalent	UNE-EN 933-8 [39]
Specific weight	Pycnometer	UNE-EN 1097-6 [40]
Water absorption	Sand absorption cone	UNE-EN 1097-6 [40]
Resistance to wear	Micro-Deval *	UNE 146404 [37]

* 500 g material, 2.5 kg stainless steel balls, 2.5 kg water, 1500 revolutions at 100 ± 5 rpm.

2.4. Design, Preparation, and Characterization of Mortars and Paving Blocks

After characterizing the natural and recycled sand, mortars and paving blocks were prepared to assess the suitability of the CDW aggregate as a partial replacement for natural sand in these applications. The applied mix proportions are summarized in Table 2. Both mortars and paving blocks were produced using two PC types: CEM I 52.5R and CEM II/B-M(Q-L) 42.5R. A reference mix (labeled “REF”) containing only natural limestone aggregates was prepared, while recycled CDW replaced up to 100% of the NA sand volume (vol.%). In addition to the reference mix, four natural sand replacement levels were investigated. Given the two analyzed cement types, there was a total of 10 series: 5 using CEM I 52.5R and 5 using CEM II/B-M(Q-L) 42.5R. For clarity, they are referred to as CEM I and CEM II, respectively, throughout this work.

Table 2. Mix proportions for mortars and paving blocks. (*) Note: this table applies to the series produced using both cement types (CEM I and CEM II).

Aggregate	Substitution Vol. %	Designation	Cement (*) kg/m ³	Effective Water, L	Effective w/c	NA kg/m ³	CDW kg/m ³
Limestone	0	REF				1757.8	0
	25	CDW25				1318.4	381.9
CDW	50	CDW50	586	264	0.45	878.9	763.8
	75	CDW75				439.5	1145.6
	100	CDW100				0	1527.5

All the mortar and paving block mixes were prepared at a constant cement-to-sand-to-water (c:s:w) weight ratio of 1:3:0.45, along with a constant amount of fluidizing agent SKP380, provided by Sika (1.46 kg/m³, equivalent to 0.25% by weight of cement). The total amount of water was adjusted to maintain consistent effective water content, which, as defined by UNE EN 206:2013 [32], is the water available for the cement hydration process, excluding the water absorbed by aggregates. In this study, the effective water-to-cement ratio (w/c) was kept constant in all the prepared samples (mortars, paving blocks, and concrete). To achieve this, all the mixes were designed by considering the weight of aggregates saturated with a dry surface, and the water absorption coefficient and humidity content of the aggregates were contemplated to calculate the total amount of water required for each mix. To simulate real fabrication conditions, the packing block aggregates were used with their natural moisture content. In contrast, to minimize the influence of aggregate moisture and to achieve better control over the effective w/c ratio, the aggregates used for mortar production were pre-dried.

The mortar samples were mixed using an automatic mortar mixer, following the specifications of Section 6.2 of Standard UNE EN 196-1 [41]. Each designed mix was cast into molds with three cavities, each measuring $40 \times 40 \times 160$ mm³. The molds were filled in two layers, with each layer compacted using an automatic horizontal jolting table, applying

60 drops at a rate of one per second. The paving blocks were cast in molds measuring $400 \times 400 \times 40 \text{ mm}^3$, each with eight cavities of $100 \times 200 \times 40 \text{ mm}^3$, as shown in Figure 1.

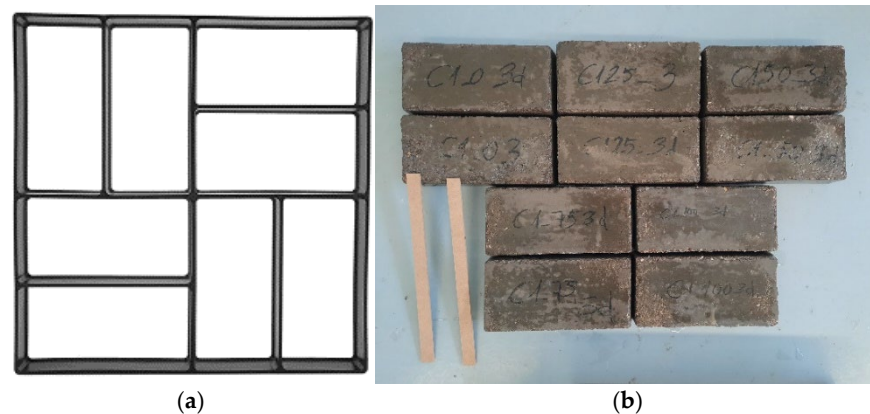


Figure 1. Paving blocks made with the NA and CDW aggregates: (a) molds; (b) developed paving blocks.

Paving blocks were prepared using a mortar mixing rod, with a total mixing time of 9 min. Initially, the aggregates were mixed with cement, followed by the addition of water for 1 min. Mixing continued for 4 min before incorporating the fluidizing additive. The mixture was then mixed for a further 4 min. Finally, the samples were compacted on a vibrating table, as depicted in Figure 2.

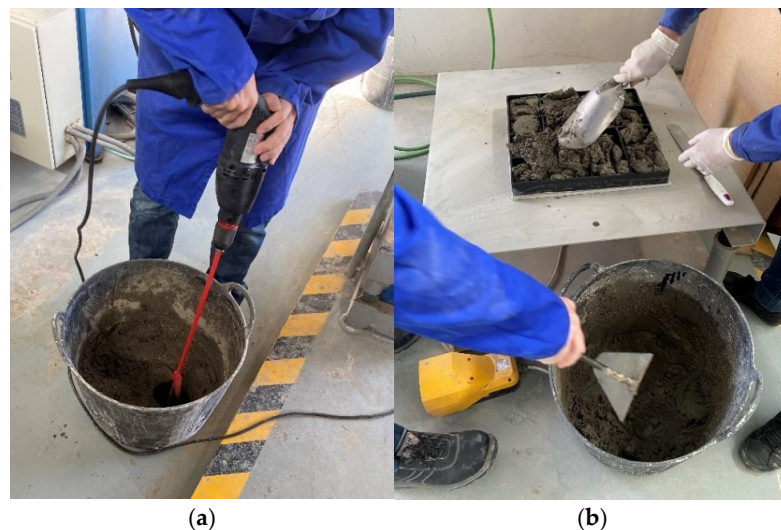


Figure 2. Preparation of paving blocks made with NA and CDW sand: (a) mixing; (b) compaction.

Both paving blocks and mortars were cured for up to 28 days at 20°C and 100% relative humidity in a controlled temperature and humidity chamber until the testing age.

The density of the mortar and paving block samples was determined by weighing and measuring them. Their workability was evaluated by adapting the procedure outlined in Standard UNE-EN 1015-3 [42], using Vicat test molds with a truncated cone shape and a bottom diameter of 80 mm. The molds were first moistened and filled in two layers. Each layer was compacted with 10 strokes, applied at a constant frequency of one stroke per second, using a circular tamper (40 mm diameter, 200 mm long, and a mass of $250 \pm 15 \text{ g}$). After 30 s, the mold was lifted vertically and slowly, and the plate was tapped 15 times, at a rate of one tap per second. Workability was assessed in two perpendicular directions by measuring the diameter of spread on a glass plate. For the mortars, workability was

measured immediately after mixing (4 min and 30 s after mixing began). For the paving blocks, workability was measured immediately after mixing (10 min) and once again 20 min after mixing commenced. The water absorption of the paving blocks was assessed according to Annex E of Standard UNE EN 1338:2004 [43]. The specimen was first conditioned at a temperature of 20 ± 5 °C. It was then submerged in water for at least 3 days until it reached a constant mass. After this, the specimen was dried in an oven at 105 ± 5 °C for a minimum of 3 days, until a constant mass was attained. The water absorption of each specimen was calculated as the mass loss relative to the dry mass.

The compressive strength of the mortar samples was assessed in a universal testing machine MEH-3000PT/W by Ibertest (Madrid, Spain), after 7 and 28 curing days, in accordance with Standard UNE EN 196-1 [41]. Six samples per mix and curing age were tested. The splitting tensile strength of the paving blocks was measured after 3, 7, and 28 curing days using the same equipment, but following Annex F of Standard UNE EN 1338:2004 [43], as illustrated in Figure 3. Two samples per mix and curing age were tested.

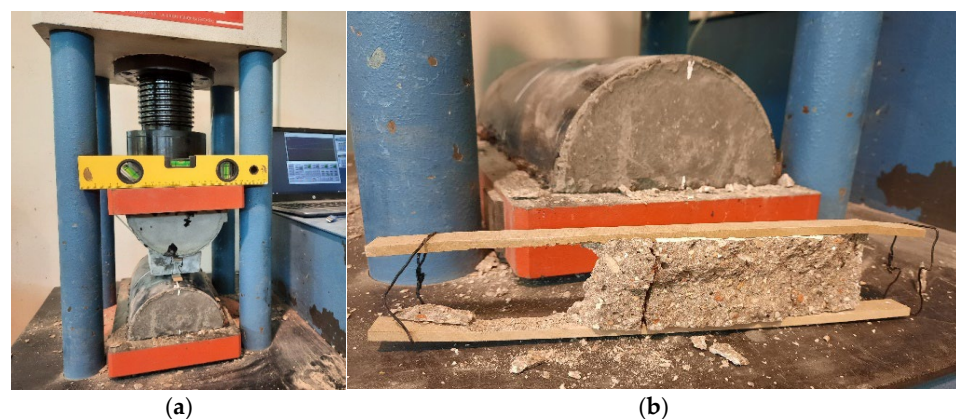


Figure 3. Splitting tensile strength testing of the paving blocks made with NA and CDW aggregates: (a) equipment used; (b) fragments after the test.

2.5. Design, Preparation, and Characterization of Structural Concrete

The mix proportions for the concrete samples designed to evaluate the influence of CDW recycled sand on the performance of structural concrete are summarized in Table 3. Mixes were prepared using the CEM II/B-M(Q-L) 42.5 cement. Consistently with the preparation of the mortars and paving blocks, the amount of PC (370 kg/m^3) and superplasticizer (SKP380 provided by Sika, 0.7% by weight of cement, equivalent to 2.59 kg/m^3) and the effective w/c ratio (0.50) were left constant across all the concrete mixes. The CDW volume used to replace NAs varied. The total amount of water in the mix was adjusted according to the water absorption and humidity of aggregates in order to have constant effective water. A reference mix with no CDW sand (labelled “REF”) was also prepared, and 50 vol.% and 100 vol.% of natural sand were replaced with recycled CDW.

Table 3. Mix proportions for structural concrete.

Aggregate	Subs. Vol. %	Desig.	Cement kg/m^3	Effective Water, L	Effective w/c	Gravel NA kg/m^3	Sand	
							NA kg/m^3	CDW kg/m^3
Limestone	0	REF	370	185	0.5	890	890	0
CDW	50	CDW50					445	386.7
	100	CDW100					0	773.5

Concrete mixes were prepared using a concrete pan mixer. The workability, density, compressive strength, shrinkage, and permeability of the developed concrete were evaluated. Workability was determined using the Abrams cone test in accordance with Standard UNE-EN 12350-2 [44], with measurements taken 10 and 30 min after mixing started. For compressive strength testing, eight cubic specimens with dimensions of $100 \times 100 \times 100 \text{ mm}^3$ were used. Two prismatic specimens measuring $100 \times 100 \times 300 \text{ mm}^3$ were employed for shrinkage testing, while three cylindrical specimens, each 150 mm in diameter and 300 mm high, were employed for permeability testing. The utilized molds met Standard UNE-EN 12390-1 [45]. The concrete specimens were cured for up to 28 days in a temperature and humidity-controlled chamber at 20°C and 100% relative humidity.

Density was determined by weighing the cylindrical specimens after 28 curing days. Compressive strength was evaluated using the cubic specimens, cured for 7 and 28 days, in accordance with Standard UNE-EN 12390-3 [46]. Testing was conducted with a hydraulic press by applying a load rate of 0.6 MPa/s until failure. Four specimens per concrete mix and curing period were tested, and the mean compressive strength values, along with their corresponding standard deviations, were calculated. The relative strength (RS) of the concrete containing CDW was calculated as the ratio of the strength of the RAC to that of the REF mix.

The shrinkage of the concrete samples was measured according to Standard UNE-EN 12390-16 [47], using prismatic specimens (dimensions of $100 \times 100 \times 200 \text{ mm}^3$). Measurements were taken at 1, 7, 14, 18, and 28 curing days, using reference points placed on two faces of samples, as illustrated in Figure 4. In accordance with Standard UNE-EN 12390-16 [47], which specifies a relative humidity range of $50\text{--}70\% \pm 5\%$, these concrete specimens were cured in a temperature and humidity-controlled chamber, at 20°C and 70% relative humidity.



Figure 4. Concrete samples for shrinkage measurements. Reference points marked with red circles.

To assess the durability of the concrete mixes, water penetration tests were performed in accordance with Standard UNE-EN 12390-8 [48]. This procedure involves applying pressurized water at 500 kPa (5 bars) on the lower hardened concrete surface for 72 h. After this period, samples were split in half under indirect tensile stress, as depicted in Figure 5. Both the maximum and average water penetration depths were then measured, following the method detailed in Annex A of the standard.

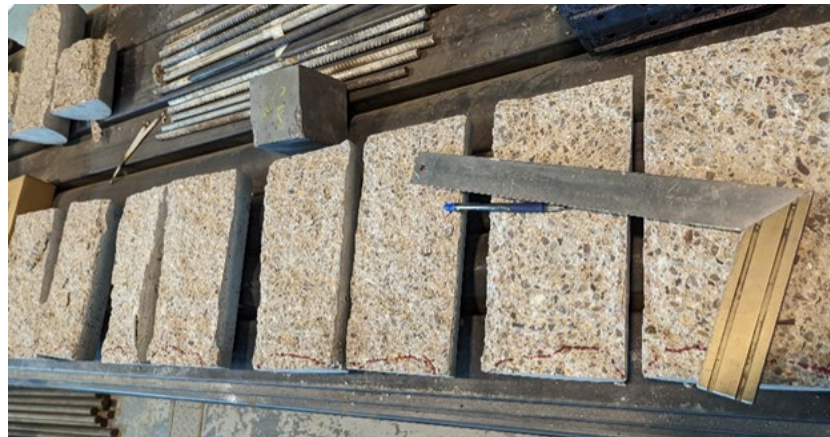


Figure 5. Concrete samples after water penetration depth measurements.

3. Results and Discussion

3.1. Properties of Aggregates

3.1.1. Morphology and Chemical and Mineralogical Composition of Aggregates

The morphology of the natural calcareous sand and recycled CDW sand used in the study is illustrated in Figure 6. Both sand types exhibited irregular particles characterized by rough surfaces and sharp edges.



Figure 6. Aggregates used in this study: (a) natural calcareous; (b) CDW.

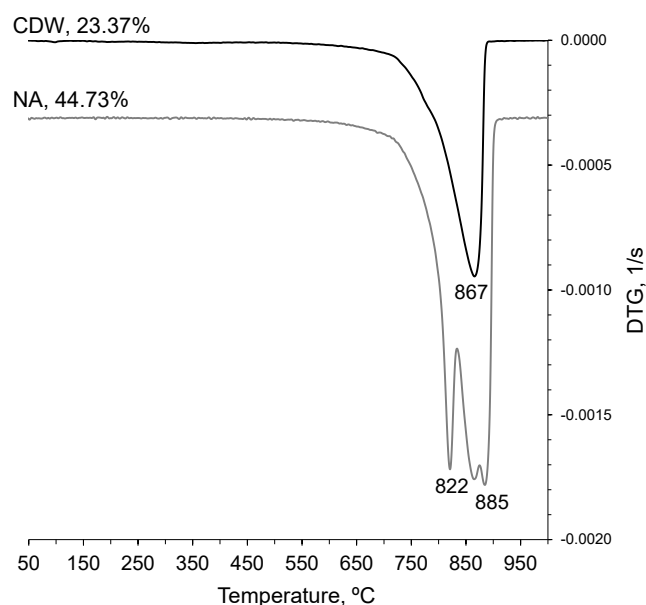
The chemical composition of the NA and CDW aggregates is listed in Table 4. The CDW sand primarily consisted of SiO_2 and CaO , with relatively large amounts of Al_2O_3 , and low contents of Fe_2O_3 , Na_2O , MgO , and K_2O . The total amount of SiO_2 , Al_2O_3 , and Fe_2O_3 was 41.3%, which is less than 70%, the value established by Standard UNE EN 450-1:2013 [49] for other pozzolanic materials commonly used in concrete, such as fly ashes. Additionally, to present pozzolanic activity, Standard UNE EN 450-1:2013 [49] establishes that loss on ignition (LOI) must be below 5% of the total composition. Therefore, the CDW sand was not expected to exhibit pozzolanic activity, or at least not significantly, and behaved more like an inert aggregate. Although this aggregate size is too large to exhibit pozzolanic activity with PC, pozzolanic behavior could enhance the aggregate–matrix interface. The X-ray fluorescence tests (XRF) did not detect significant amounts of sulfur.

Table 4. Chemical composition of the recycled CDW aggregate, weight % (wt.%).

	Al ₂ O ₃	SiO ₂	CaO	MgO	K ₂ O	Na ₂ O	Fe ₂ O ₃	SO ₃	Other	LOI *
CDW	8.2	32.1	30.5	1.8	1.1	1.1	1.0	0.5	0.4	23.4

* Determined at 1000 °C.

The LOI was determined at 1050 °C for 45 min and closely matched the obtained thermogravimetry results, as shown in Figure 7 (total weight losses expressed as a percentage). The calcareous aggregate exhibited significant weight loss between 630 °C and 920 °C, and reached approximately 45%, which is attributed to the decomposition of CaCO₃ and MgCO₃. Although this mass loss generates several overlapping peaks that cannot be separately evaluated, previous studies [50] indicate that the first band is associated with the decomposition of magnesium carbonate, and the second with calcium. The mass loss observed in the CDW aggregate (23.4%) is primarily attributed to the decomposition of limestone (CaCO₃), as it predominantly occurred between 650 °C and 900 °C. The lower mass loss observed in the CDW waste, compared to the natural dolomitic limestone, is attributed to its lower limestone content, as the CDW waste was mixed with other materials, primarily ceramics. Notably, no mass loss related to the decomposition of cement hydrates was observed. The dehydration of calcium silicates (CSH) or ettringite (AfT) would generate a band between 100 °C and 180 °C, while calcium aluminates (CAH) or calcium aluminosilicates (CASH) would generate a band between 180 °C and 240 °C [51]. Similarly, no mass loss associated with portlandite dehydration, which typically occurs between 520 °C and 600 °C, was observed. These results indicate that the quantity of the concrete waste in the CDW recycled sand was minimal. Thermogravimetric results indicate that the recycled CDW aggregate was expected to show improved stability at high temperatures. Finally, although ceramic residues typically experience minimal mass losses up to 1000 °C, their presence in the sample was confirmed by the X-ray diffraction analysis, as depicted in Figure 8.

**Figure 7.** DTG curves for the NA and CDW aggregates.

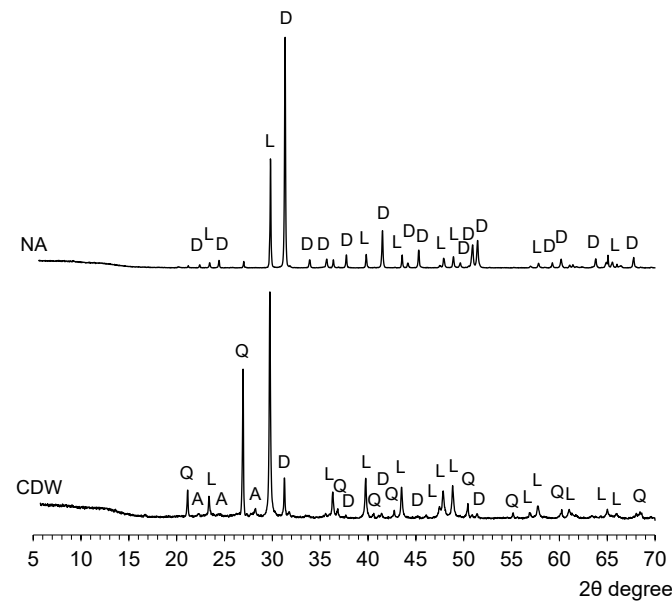


Figure 8. X-ray diffractogram of CDW and calcareous NA sand. D: dolomite ($\text{CaMg}(\text{CO}_3)_2$); L: limestone (CaCO_3); Q: quartz; A: albite ($\text{NaAlSi}_3\text{O}_8$).

The diffractogram of the CDW aggregate, shown in Figure 8, reveals the presence of quartz (Q, SiO_2 , PDFcard 46-1045), limestone (L, CaCO_3 , PDFcard 83-578), and magnesium carbonate dolomite (D, $\text{CaMg}(\text{CO}_3)_2$, PDFcard 75-1760). This suggests that the CDW aggregate is composed of natural limestone and ceramic products. Traces of sodium feldspar albite (A, $\text{NaAlSi}_3\text{O}_8$, PDFcard 9-466), a phase commonly found in ceramic products, were also identified. However, mullite, a crystalline compound typically found in ceramics sintered at high temperatures, was not detected. This indicates that there was a small amount of ceramic products in the CDW recycled aggregate. Consistent with the thermogravimetric analyses, no peaks attributed to portlandite, a typical compound of hydrated cement, were identified, confirming that the RA used did not contain significant amounts of concrete. Additionally, neither aggregate type showed deviation from the baseline within the 15–30 degrees 2θ range, which confirms a minimal presence of amorphous phases that could react with portlandite during PC hydration. As a result, the CDW aggregate was expected to have limited pozzolanic activity. Although it may be suitable as an RA, its low reactivity when used as a partial PC replacement would likely reduce binder strength. Consistently with the XRF and TG results, no crystalline phases associated with sulfur compounds were detected.

The morphology and chemical and mineralogical composition of both the natural and CDW aggregates analyzed were similar. Therefore, the CDW sand characterized in this study has the potential to be effectively reused in the production of sustainable construction materials. This reuse would help reduce environmental impact and enhance resource efficiency.

3.1.2. Particle Size Distribution of Aggregates, Percentage and Quality of Fine Particles

The particle size distribution and percentage of fines in the NA and CDW aggregates, determined by sieving according to Standard UNE-EN 933-1 [38], are presented in Figure 9. The recommended particle size distribution range from the previous Structural Concrete Instruction EHE-08, as defined in the comments of Article 28.4.1, is also included in the figure for reference. Although this reference range is not incorporated in the current Spanish Structural Code, it remains a useful granulometric reference for fine aggregates. At the upper limit of the 0.063 mm sieve, a cumulative retained percentage of 16% was considered,

which, according to Article 30.4.1 of the Structural Code, corresponds to limestone crushed aggregates intended for use in structural concrete exposed to general non-aggressive exposure classes (X0 and XC, as defined in Article 27). The particle size distribution of both the NA and CDW aggregates falls within the reference limits established by EHE-08. This indicates that, based on their particle size distribution, both NA and RA would be suitable for use in structural concrete. However, it is important to note that, since the RA used in this study was not sourced from concrete waste and pertains to a fine aggregate fraction rather than a coarse aggregate fraction, it falls outside the scope of the current Spanish Structural Code.

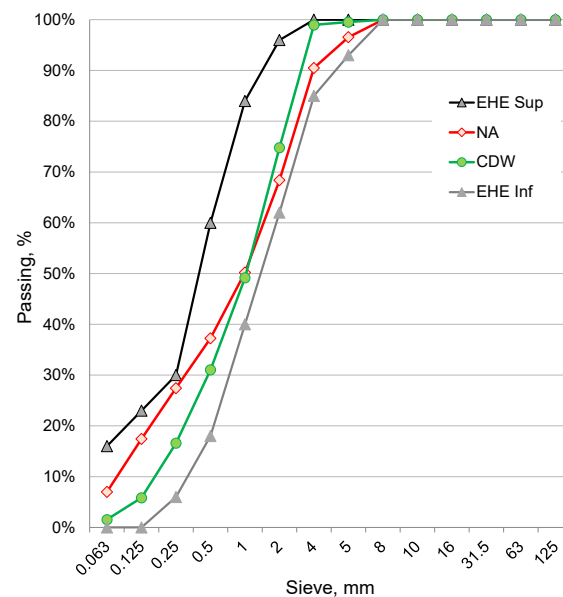


Figure 9. Particle size distribution of natural limestone and CDW aggregates.

The percentage and quality of fine particles, as well as the fineness modulus (FM) of the aggregates, are presented in Table 5. Below 1 mm, the CDW particles were larger than the NA particles (see Figure 9), which was due to the repeated washing to remove sulphates. However, both aggregate types had a similar FM (3.1–3.2), because within the 1–4 mm range, NA particles were coarser than those of the recycled CDW, which balanced the overall modulus value. Slightly higher FM values are reported by Pitarch et al. [52] for natural sand (3.64) and recycled sand obtained from ceramic tiles (3.76), sanitaryware (3.84), and red clay bricks (4.04) intended for use in structural concrete.

Table 5. Particle size distribution, percentage, and quality of fine particles.

Property	NA	CDW
FM	3.1	3.2
Percentage of fine particles, wt. %	14.4	4.4
Sand equivalent	53	73

Article 30.4.1 of the Spanish Structural Code specifies the environmental conditions under which aggregates can be used based on their maximum fine content. Thus, according to the percentage of fines, the CDW recycled sand is suitable for use in structural concrete exposed to the following classes: X0 (no carbonation risk), XC (carbonation-induced corrosion), XS (chloride-induced corrosion from seawater), XD (chloride-induced corrosion not from seawater), XA (chemical attack), XF (freeze–thaw), or XM (erosion). These classifications correspond to non-calcareous aggregates with a fine content below 6%. In contrast,

the calcareous sand is restricted to use in X0 or XC environments because its fines content exceeds 16%, which makes it unsuitable for structural concrete exposed to more severe exposure classes.

When assessing the quality of fines by the sand equivalent test (Annex A of Standard UNE-EN 933-8 [39]), certain particles in suspension were identified. Additionally, the observation of black particles during the oven drying of the CDW recycled aggregate suggests the presence of organic matter. According to the requirements established in Article 30.4.2 of the Structural Code, the recycled CDW aggregate is suitable for use in structural concrete exposed to general classes X0 (no risk) or XC (carbonation), because the sand equivalent value exceeded 70. However, it is unsuitable for structural concrete exposed to specific classes, such as XS, XD, XA, XF or XM, because the obtained sand equivalent value was below 75.

Although the sand equivalent value of limestone sand was below 70, its suitability for use in structural concrete would depend on the methylene blue test results. Additionally, both sand types could be employed in roadbed layers, because the sand equivalent requirements are lower (>30–40, depending on the vehicle weight category) according to the Spanish PG-3 General Technical Specifications for Road and Bridge Works.

3.1.3. Physico-Mechanical Properties of Aggregates

Table 6 summarizes the physico-mechanical properties of both the NA and CDW aggregates. The CDW particles exhibited lower specific weight than the NA sand, which indicates higher porosity and water absorption for the recycled sand versus the NA calcareous particles. This difference is attributed to the presence of ceramic particles in the CDW recycled sand. Pitarch et al. [52] observed significant variation in water absorption values among different types of ceramic materials. They report water absorption values of 0.69%, 6.28%, and 15.76% for the fine ceramic sand obtained from ceramic sanitaryware, ceramic tiles, and red clay bricks, respectively. Medina et al. [25] also report water absorption values ranging from 2.0% to 17.2% for fine recycled aggregates derived from different types of ceramic tiles, which they used in concrete.

Table 6. Physico-mechanical properties of the NA and CDW aggregates.

Property	NA	CDW
Specific weight, kg/m ³	2808.9	2441.2
Water absorption, wt. %	2.01	5.62
Resistance to wear, wt. %	29.2	23.9

The natural sand meets the maximum water absorption requirement outlined in the Spanish Structural Concrete Code for NAs used in structural concrete (5% for both fine and coarse aggregates, as per Article 30.6). According to Article 30.8.3.1. Physical-mechanical conditions of recycled aggregates, the water absorption of the recycled coarse aggregate must not exceed 7%, while that of the natural coarse aggregates to be mixed with should remain below 4.5%. Although the Spanish Structural Code does not contemplate recycled sand use, the CDW RA would meet the requirements established for coarse RAs in structural concrete.

As shown in Table 6, the CDW recycled aggregate exhibited slightly better wear resistance compared to natural limestone, as indicated by the lower mass loss after the Micro-Deval test. These results were due to the presence of ceramic particles in the CDW, which may be harder than calcareous aggregates. A study by Medina et al. [25] also indicates greater resistance to fragmentation, measured by the “Los Angeles” test, in RAs obtained from ceramic sanitaryware compared to NAs.

The results indicate that the properties of the analyzed CDW aggregate are comparable to those of the NA limestone and suggest its suitability for use in structural concrete exposed to environmental classes X0 (no carbonation risk) and XC (carbonation-induced corrosion). However, the current structural code permits RA use in structural concrete only if sourced from concrete, with a maximum replacement of natural coarse aggregates limited to 20% by weight. Removing sulfates at the source before CDW disposal could facilitate the production of aggregates with larger particle sizes. Nevertheless, these aggregates would still remain ineligible for concrete applications under current regulations, which restrict the use of RAs to those derived from concrete. While RAs from non-concrete sources are currently excluded from structural concrete, further research is essential to assess their potential and to extend their reuse opportunities. Additionally, this CDW recycled aggregate could be considered for non-structural applications, such as mortars or paving blocks.

3.2. Properties of the Developed Mortars

3.2.1. Workability and Density of the Mortar Samples

Figure 10 illustrates the workability and density of the developed mortars. Workability (Figure 10a) was assessed immediately after mixing, 4 min and 30 s after starting the mixing process. It was slightly better in the mortars prepared with CEM I 52.5R and improved with increasing CDW content, but the overall the results were similar. The density of the mortar samples (Figure 10b) ranged between 2.10 g/cm³ and 2.35 g/cm³ and decreased as CDW content increased. The density values were slightly lower in the mortars made with CEM II/B-M(Q-L) 42.5R compared to CEM I 52.5R, which implies that the CEM I 52.5R mixes were more compact.

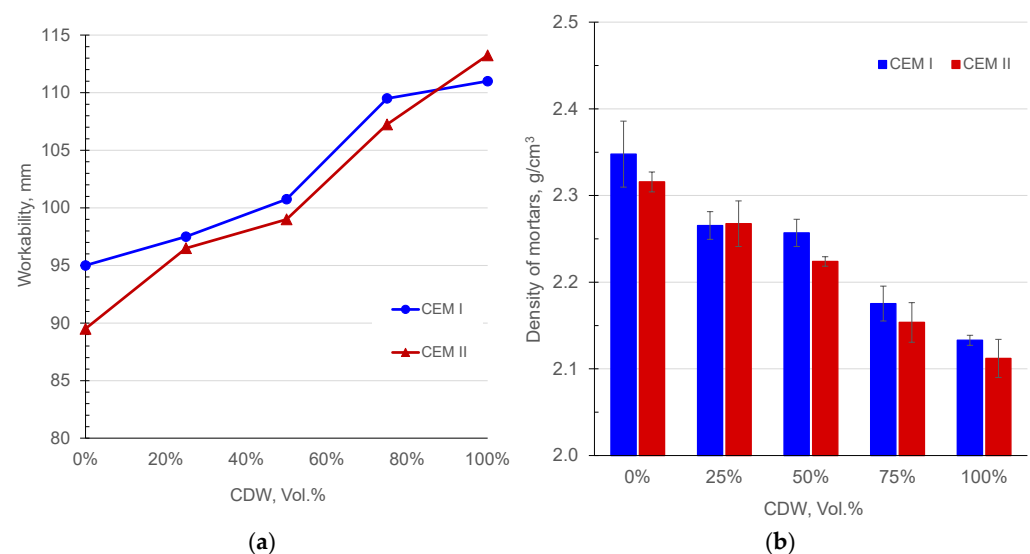


Figure 10. Properties of the mortars made with the NA and CDW aggregates: (a) workability; (b) density.

3.2.2. Compressive Strength of the Mortar Samples

Figures 11a and 11b present the compressive strength and RS of the developed mortars, respectively. Compressive strength progressively decreased as the CSW content increased. The RS remained above 80% with NA substitutions of up to 50 vol.% regardless of curing age, and above 70% for all the mortars cured for 28 days, which indicates a strength loss of less than 30%.

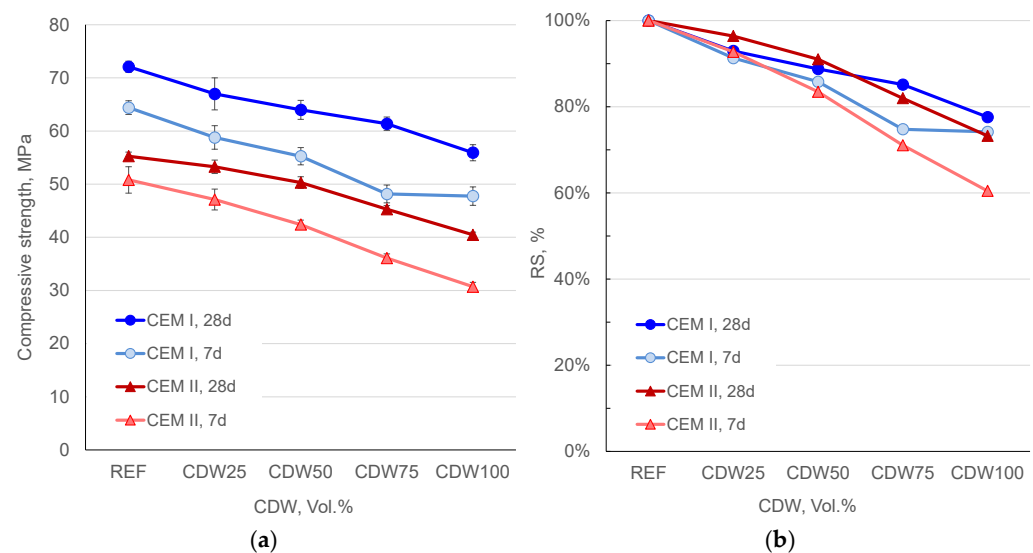


Figure 11. Compressive strength of the mortars made with NA and CDW aggregates: (a) compressive strength; (b) relative strength.

The results obtained in this study differ from those reported by Borges et al. [16], who prepared mortars using RAs composed of 46% old mortar, 32% ceramics, and 22% basaltic coarse aggregates. While Borges et al. [16] observed a slight increase in the 28-day compressive strength at replacement rates of 25% and 50%, the compressive strength of the reference mix in their study was significantly lower, approximately 2 MPa. In contrast, the results obtained by Kępnia and Łukowski [34] were more consistent with those of the present study, showing a progressive decrease in both compressive and flexural strength as the replacement rate of RAs increased. Although they used recycled sand of a different composition (primarily recycled concrete), the compressive strength of the reference mortar (52 MPa) was closer to that of the mortars prepared in this study using CEM II/B-M(Q-L) 42.5R (~55 MPa). A more pronounced decrease in compressive strength was observed by Ferro et al. [33], who employed recycled sand predominantly composed of calcite and quartz, with traces of cement compounds. This reduction is partly attributed to a significant decrease in the mix's consistency.

3.3. Properties of the Developed Paving Blocks

3.3.1. Workability of Paving Blocks

Figure 12 illustrates the workability of the developed paving blocks. Those produced with CEM II/B-M(Q-L) 42.5R generally showed greater workability compared to those made with CEM I 52.5R. This improvement in workability can be attributed to the larger particle size of the former cement type and the presence of limestone filler, which enhanced workability and delayed the onset of initial chemical reactions. Workability generally decreased with increasing mixing time. A slight improvement was observed with 25 vol.% CDW, but workability progressively decreased with higher CDW RA contents. This reduction is attributed to the higher water absorption of the RA, which caused water retention during mixing. This issue could be addressed by pre-saturating the aggregates.

These findings contrast with those observed in the mortar samples (Figure 10a), which exhibited slightly higher workability with CEM I 52.5R than with CEM II/B-M(Q-L) 42.5R, with values progressively improving as CDW content increased. These differences are attributed to the higher standardization of the mortar preparation process, whereas paving blocks were produced by a more manual method (mixing, mold filling, and compaction). Additionally, minor variations in the total w'/c ratio may have occurred because, to

minimize the influence of aggregate humidity and to better control the effective w/c ratio, aggregates were dried before mortar preparation, whereas sands were used with their natural moisture content for paving block production. Furthermore, given the faster hydration reactions and higher heat of hydration of CEM I 52.5R compared to CEM II/B-M(Q-L) 42.5R cement, the differences in testing times likely contributed to the observed variations in workability. Specifically, mortar workability was measured after 4 min and 30 s, whereas it was assessed after 10 and 30 min for the paving blocks.

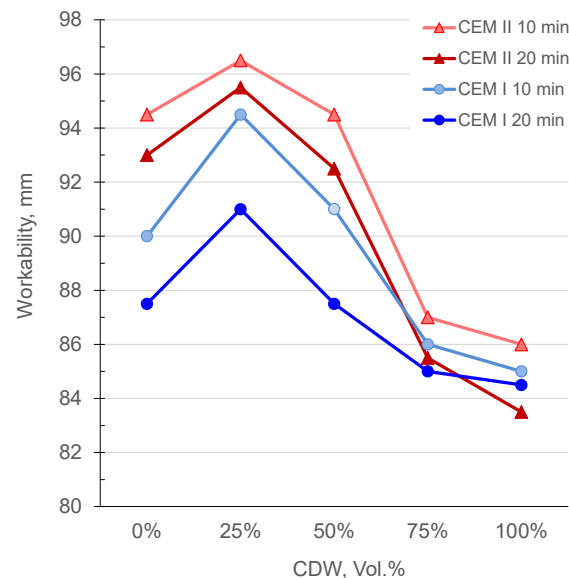


Figure 12. Workability of the paving blocks made with the NA and CDW aggregates.

3.3.2. Density and Water Absorption of Paving Blocks

Similar to the results obtained for the mortars, the density of the paving blocks generally decreased with increasing CDW aggregate content; see Figure 13a. A slightly lower density was observed in the paving blocks made with CEM II/B-M(Q-L) 42.5R compared to those prepared with CEM I 52.5R. However, this difference was insignificant, as all the values ranged between 2.11 g/cm³ and 2.32 g/cm³. The high deviation observed in the density of the paving blocks, compared to the variation seen in the mortar results (Figure 10b), is attributed to differences in the preparation process, which was more manual for the paving blocks than for the mortars. Additionally, the dimensional variability of the paving blocks was significantly greater. Specifically, the volume of each paving block was determined as the average of three measurements for each dimension: length, width, and thickness. In contrast, the mortar samples were assumed to have a constant volume of 40 × 40 × 160 mm³.

As expected, the water absorption coefficient was higher for the paving blocks made with CEM II/B-M(Q-L) 42.5R than for those prepared with CEM I 52.5R, which is attributed to the lower clinker content. As shown in Figure 13b, the coefficient progressively increased with the CDW RA content, with values ranging from 8.94% to 12.05%. According to the specifications outlined in Table 4.1 of Standard UNE EN 1338:2004 [43], the produced paving blocks should be classified as Type A, for which water absorption measurement is not required. Regardless of the aggregate used, all the water absorption values exceeded 6%, the threshold to be classified as Class 2 with a B marking. Consequently, these paving blocks would not be suitable for use in areas prone to frost.

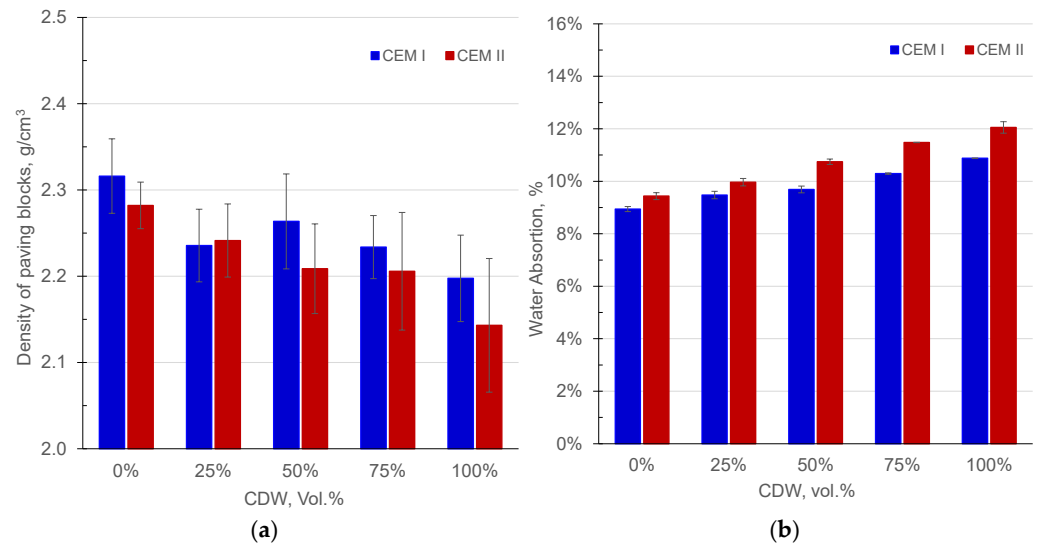


Figure 13. Properties of the paving blocks made with the NA and CDW aggregates: (a) density; (b) water absorption.

3.3.3. Splitting Tensile Strength of Paving Blocks

Figures 14–16 illustrate the splitting tensile strength of the developed paving blocks. Figure 14 presents the splitting tensile strength (Figure 14a) and breaking load (Figure 14b) of the paving blocks produced with CEM I 52.5R, incorporating increasing amounts of CDW. Figure 15 depicts these properties for the paving blocks made with CEM II/B-M(Q-L) 42.5R. According to Section 5.3.3.2 of Standard UNE EN 1338:2004 [43], the splitting tensile strength of paving blocks must exceed 3.6 MPa, with no individual values falling below 2.9 MPa. Additionally, breaking load must be above 250 N/mm of breaking length (184.1 ± 0.9 mm). These minimum thresholds are indicated in the figures. The paving blocks produced with CEM I 52.5R met these specifications after only 3 curing days, regardless of the percentage of CDW recycled sand used. However, those made with CEM II/B-M(Q-L) 42.5R generally met these requirements only after 28 curing days. The wide variability in the results is primarily attributed to the sample preparation process and the testing methodology.

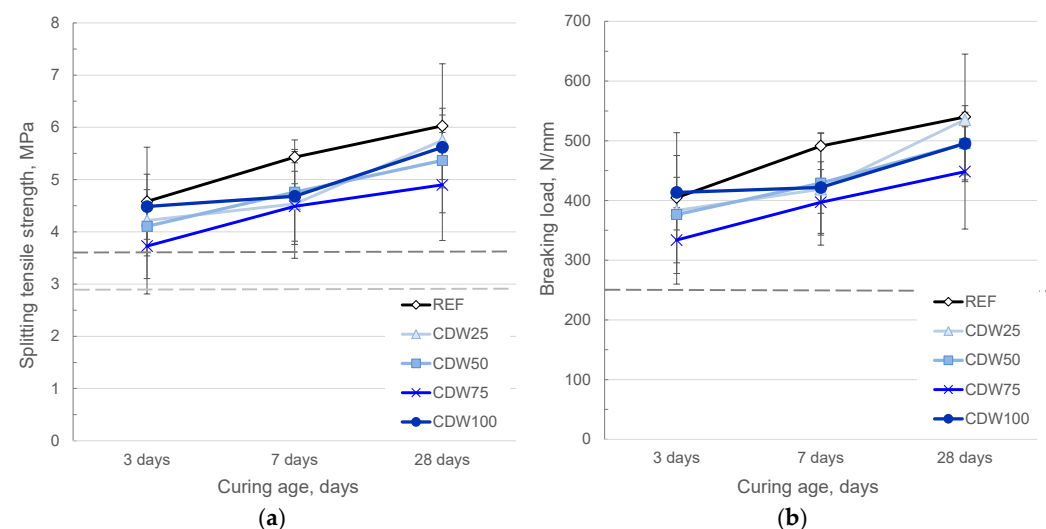


Figure 14. Splitting tensile strength of the paving blocks developed with CEM I 52.5R and increasing amounts of CDW: (a) splitting tensile strength; (b) breaking load. Limits established by Standard UNE EN 1338:2004 [43] indicated with striped lines.

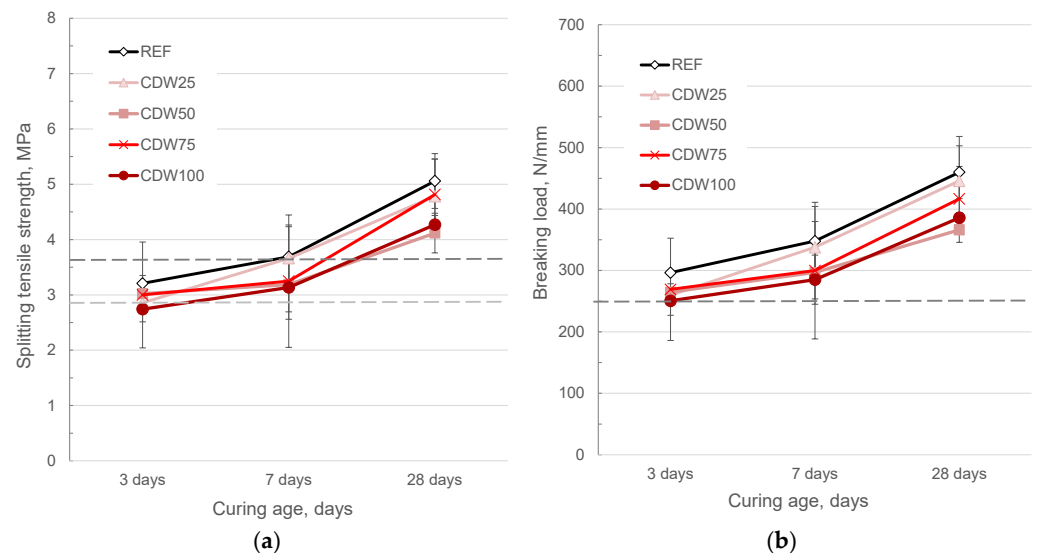


Figure 15. Splitting tensile strength of the paving blocks developed with CEM II/B-M(Q-L) 42.5R and increasing amounts of CDW: (a) splitting tensile strength; (b) breaking load. Limits established by Standard UNE EN 1338:2004 [43] indicated with striped lines.

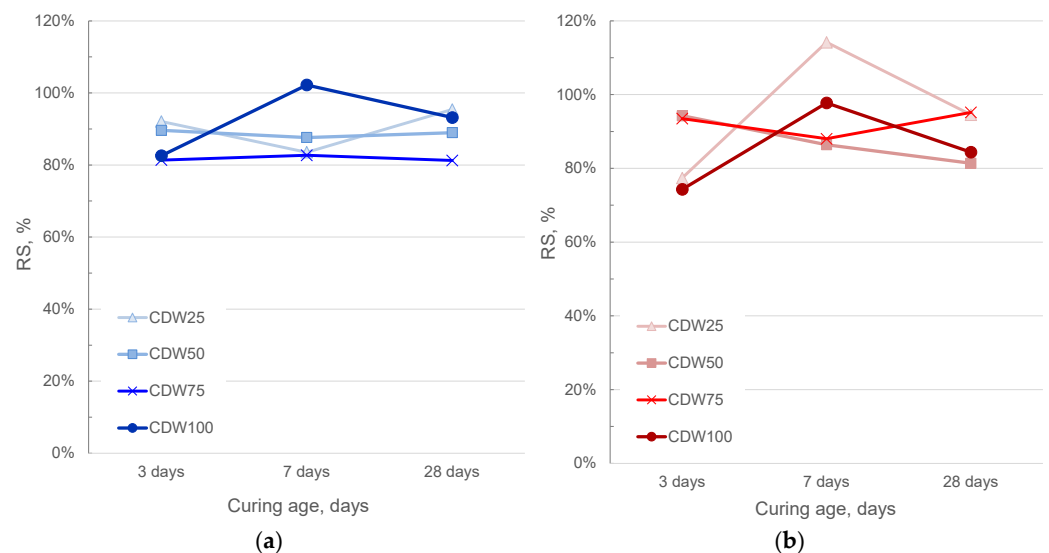


Figure 16. Relative splitting tensile strength between the paving blocks incorporating CDW RA and the REF paving blocks: (a) CEM I 52.5R; (b) CEM II/B-M(Q-L) 42.5R.

Figure 16 illustrates the RS ($RS = R_{CDW} / R_{REF}$) between the paving blocks that incorporated CDW aggregates and the REF samples, made with 100% natural calcareous aggregates. Although no significant variation was observed with increasing CDW aggregate content, the RS values generally ranged between 80 and 100%, which denotes a maximum 20% strength reduction compared to the REF samples.

Both the mortars and the paving blocks generally exhibited a progressive strength reduction with increasing CSW content. This trend was more pronounced in mortars than in paving blocks (see Figure 11, Figure 14 and Figure 15), with mortars displaying greater homogeneity and less variation in the strength results. This is attributed to the higher uniformity and standardization of the mortar preparation process, and also to the more precise testing methodology. Figure 17 illustrates the correlation between the strength of the paving blocks and mortars, which enables paving block splitting tensile strength based on mortar compressive strength, and vice versa, to be estimated. The relatively wide data dispersion ($R^2 = 0.74$) is due primarily to the variability in the paving blocks results, which

can be attributed to their manual preparation process and the challenges associated with adjusting the splitting tensile strength testing method.

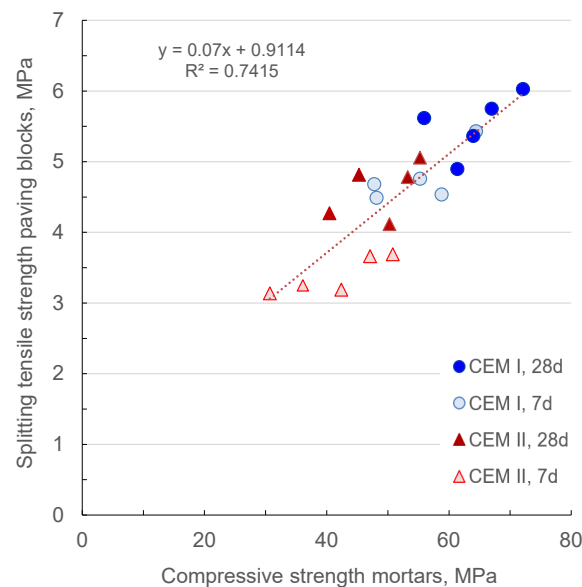


Figure 17. Correlation between the splitting tensile strength of the paving blocks and mortars with increasing CDW content.

The results differ from previous research on concrete blocks [17], where the replacement of natural sand with recycled aggregates (RAs) led to only slight reductions in compressive strength, particularly at replacement rates of 25% or 50%. However, at higher replacement rates, an increase in transverse strength was observed. These discrepancies may be attributed to the higher strength of the reference mixes used in the present study, as well as variations in the type and particle size distribution of the RAs employed in both studies.

3.4. Properties of the Developed Concrete

3.4.1. Workability

Table 7 summarizes the workability of the developed concrete as measured by the Abrams cone test. An improvement in workability was observed in the concrete samples containing CDW recycled sand. As the total water content in the mixes was adjusted based on the water absorption capacity and moisture content of the aggregates, similar workability values were expected. The observed variations can be attributed to differences in the rate of water absorption by aggregates and the additional water added to compensate for this absorption. Furthermore, the mixing process, which affects particle dispersion and consequently influences workability, also played a role.

Table 7. Workability of concrete mixes.

Designation	Cone, mm
REF	100
CDW50	190
CDW100	170

Despite a slight reduction in workability in sample CDW100 compared to CDW50, all the mixes had a fluid (100–150 mm) or liquid (160–210 mm) consistency in accordance with the classification in Chapter 8 of the Structural Code (Table 33.5.a). Previous studies on RAC, in which the amount of water was also adjusted based on that absorbed by

aggregates [8,20,23,53], also report similar or slight variations in slump test values. In contrast, other studies [26,54] maintain the water content constant across all the concrete mixes, regardless of the amount of RA used. This method usually results in a reduction in RAC consistency as the proportion of RAs increases due to the higher water absorption typically exhibited by recycled particles.

3.4.2. Density and Compressive Strength of the Developed Concrete Samples

Table 8 summarizes the density and compressive strength of the developed concrete samples. RAC density decreased by 4.2% with the 50 vol.% substitution and by 6.8% with the 100 vol.% replacement of NA with CDW. This reduction is attributed to the lower density of the CDW particles (see Table 6), which led to a smaller RA mass for a given substitution percentage in volume. These findings are consistent with previous studies about RA use in concrete [23,25,52,55], which report a gradual decline in the density of hardened concrete as the proportion of RAs rises. Our results also align with a previous study by Pitarch et al. [52], in which natural limestone aggregates are replaced with various types of ceramic materials (bricks, tiles, and sanitaryware) in RAC. This substitution led to a reduction in density of up to 3.3% when incorporating up to 30% ceramic waste.

Table 8. Density and compressive strength of the developed concrete samples.

	Compressive Strength						
	Density, kg/m ³	7 Days			28 Days		
		Mean MPa	Std. Deviation MPa	RS %	Mean MPa	Std. Deviation MPa	RS %
REF	2343.4	37.2	0.8	-	45.7	1.8	-
CDW50	2245.3	28.9	0.5	77.7	39.0	1.7	85.3
CDW100	2184.9	24.9	1.5	66.9	33.7	2.1	73.7

The compressive strength of the concrete samples decreased as the percentage of CDW increased, Figure 18, with minimal variability in the results. The RS of the RAC cured for 28 days exceeded 70%, which indicates that strength loss was less than 30% when completely replacing natural sand with the CDW recycled sand. These findings, along with the higher workability observed in the CDW concrete samples, are consistent with the results obtained for mortars (Figures 10 and 11, mortars with CEM II/B-M(Q-L) 42.5R). Despite having a lower density, the CDW aggregate exhibited slightly higher wear resistance than NA (see Table 6). Consequently, the lower RAC strength cannot be attributed to lower RA particles quality, but may have resulted from the reduced fine content of the CDW aggregate, which might have led to a less compact matrix, along with a delay in PC hydration caused by the gradual release of water absorbed by the aggregates.

The RS of the developed concrete improved with curing time. Previous studies using ceramic materials as RAs in concrete have attributed this improvement to a pozzolanic reaction between the fine ceramic particles and portlandite formed during PC hydration, which enhances the interface between the aggregate and the cementitious matrix [8,52,56]. However, the chemical composition and LOI of the CDW used in this study (see Section 3.1.1) suggest only limited pozzolanic activity. The improvement in RS with curing time herein observed is attributed mainly to greater CDW aggregate absorption. This likely facilitates a slower release of water, which results in more gradual PC hydration over time.

Previous studies into RAC demonstrate that the compressive strength of concrete is significantly influenced by the type of aggregate used. Consistently with the results obtained in this study, several researchers [8,19–21,55] report decreased compressive strength when using RAs in comparison to samples with NAs. Conversely, some studies, like those

by Cachim [23], Medina et al. [25], and López et al. [57], observed improved compressive strength when incorporating ceramic RAs. Roig-Flores et al. [58] investigated the use of RAs from stoneware ceramic tiles and report a slight reduction in strength when replacing natural limestone sand. However, when 20% to 100% (by volume) of natural coarse aggregates were substituted, strength was either maintained or slightly improved. Similar studies by Malesev et al. [24] and Evangelista and de Brito [22] report only minor enhancements in compressive strength when replacing NAs with recycled concrete aggregates.

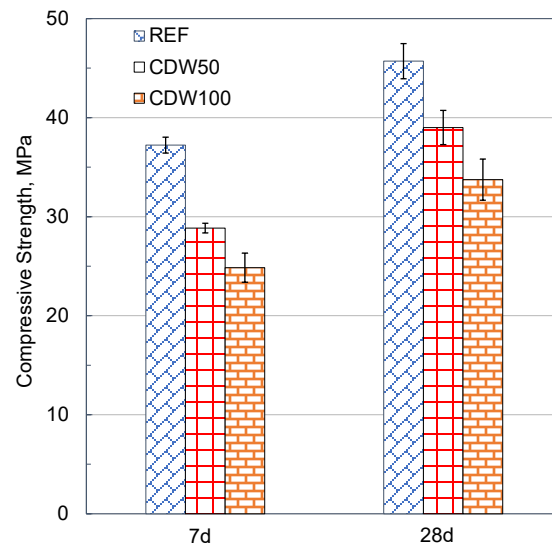


Figure 18. Compressive strength of the developed concrete samples.

As reviewed by Xiao et al. [7], RAC typically exhibits lower mechanical properties than traditional concrete. This limitation is likely one of the primary reasons why the Spanish Structural Code for Concrete restricts the use of RAs to those that derive from concrete, allowing a maximum replacement of 20% by weight of natural coarse aggregates. For higher replacement levels or the incorporation of different RA types, additional studies are required. Despite the reduction in compressive strength observed with the incorporation of the CDW recycled sand herein employed, the obtained strength values still meet the minimum requirements for reinforced concrete production. These findings suggest that the CDW recycled sand has the potential for use as RA in structural concrete applications.

3.4.3. Concrete Shrinkage

Linear shrinkage is presented in Figure 19. The CDW50 concrete exhibited the highest shrinkage values, which surpassed those of the REF sample. In contrast, the CDW100 concrete displayed the least shrinkage, with even lower values than those observed in the REF concrete. As the employed CDW primarily consisted of limestone and ceramic particles, the variation in the shrinkage values among mixes can be attributed to differences in aggregate type, the absorption ratio, and the specific surface of the CDW sand compared to natural sand. As previously reported by Zhang et al. [59], these factors significantly influence concrete shrinkage. Furthermore, the higher porosity of RAC may have also influenced the results. The greater shrinkage observed in the CDW50 series compared to the REF mix can be attributed to the increased porosity (indicated by higher permeability) of RAC, which resulted in fewer restrictions in movement or shrinkage. In the CDW100 samples, slight expansion was measured one day after demolding, which suggests a minor delay in hydration reactions due to the gradual release of water absorbed by aggregates. In the CDW50 samples, this expansion was not recorded, likely because it occurred before the first measuring date. Nevertheless, greater shrinkage should have also been observed in the CDW100 series given

its higher permeability. Therefore, shrinkage should be further investigated, particularly at early ages, to better understand the underlying causes of this behavior.

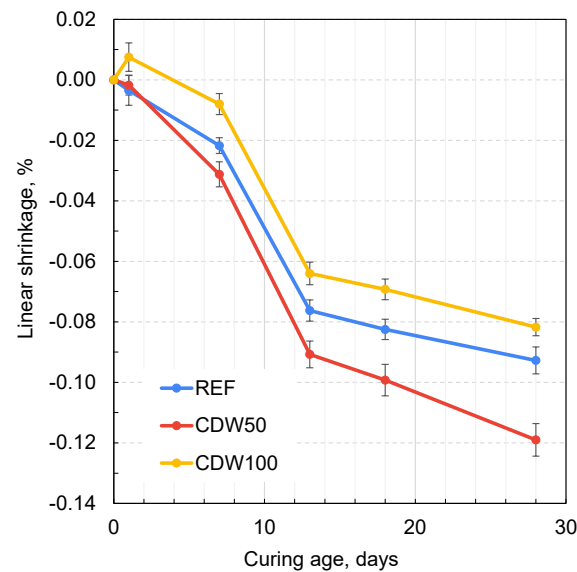


Figure 19. Linear shrinkage of the developed concrete at various curing ages.

3.4.4. Concrete Permeability

Figure 20 shows the maximum and average water penetration depths, measured in accordance with Annex A of UNE-EN 12390-8 [48]. Consistent with the compressive strength values, which decreased as CDW content increased, concrete permeability results showed a slightly more permeable matrix with the incorporation of CDW sand. Both the maximum and the average water penetrations increased with CDW recycled sand incorporation, with a respective rise from 18 mm to 26 mm and from 10.2 mm to 19.5 mm. Despite the increase, the penetration values remained below the limits specified in Table 43.3.2 of the Structural Code for concrete. This code establishes that, for any concrete exposed to highly aggressive environments XS3 (marine corrosion in tidal zones) and XA3 (highly aggressive chemical attack), the maximum water penetration must be less than 30 mm and the average penetration less than 20 mm.

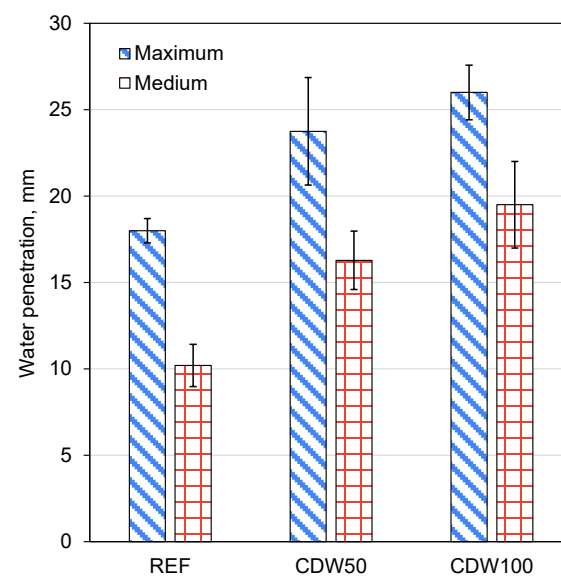


Figure 20. Average and maximum water penetration depths.

4. Conclusions

This study evaluates using CDW-derived sand as RA in mortars, paving blocks, and concrete. The key findings are as follows:

- The CDW aggregate was composed of mainly limestone and ceramics, with low sulfur content, lower fine content, and no pozzolanic activity. It was slightly harder than natural limestone, and had lower density and higher water absorption. The similar properties of NA and RA suggest that the CDW sand can be effectively reused in sustainable construction materials.
- The workability of paving blocks slightly improved with 20 vol.% CDW, but decreased with higher content, while mortars and concrete showed improved workability with the CDW sand.
- The density of all the samples decreased as CDW content increased, and ranged from 2.35 g/cm³ in the REF sample to 2.10 g/cm³ with 100% CDW recycled sand.
- The water absorption in the paving blocks increased with the CDW content, limiting their suitability to non-frost areas. Water permeability was higher in RAC, but the water penetration values met the Structural Code limits for all the environmental exposure classes.
- The paving blocks made with CEM I 52.5R met splitting tensile strength requirements after 3 curing days, while those with CEM II/B-M(Q-L) 42.5R met the standard after 28 curing days.
- Compressive strength generally decreased with higher CDW content. The RS of the mortars with up to 50 vol.% CDW remained above 80% at all curing ages, and the RS of all the mortars cured for 28 days exceeded 70%, regardless of the CDW content. The compressive strength of the RAC samples met the minimum requirements for reinforced concrete.

The use of RAs is a key strategy for sustainable construction because it reduces environmental impacts and improves resource efficiency. This study confirms that the CDW-derived sand used can effectively replace natural limestone sand in both structural and non-structural applications. Although regulatory restrictions limit the use of RAs in structural concrete, the study highlights opportunities for reusing this significant waste material, with the optimal replacement percentage determined by specific application requirements. The results support the development of standardized guidelines for RAs in non-structural applications, encouraging broader industry adoption and providing environmental benefits. Further research, along with supportive policies and economic incentives, is essential to overcome the current challenges of using RAs and to promote circular construction practices.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CDW	Construction and demolition waste
NAs	Natural aggregates
PC	Portland cement
RAs	Recycled aggregates
RAC	Recycled aggregate concrete
Vol. %	Percentage in volume
Wt. %	Percentage in weight
WA	Water absorption
w/c	Effective water-to-cement ratio
w'/c	Total water-to-cement ratio
RS	Relative strength
XRD	X-ray diffraction
XRF	X-ray fluorescence
TG	Thermogravimetric analysis
LOI	Loss on ignition
FM	Fineness modulus

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