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Influence of Recycled Ceramic and Concrete Fine Aggregates on the Mechanical Properties and Freeze–Thaw Resistance of Low-Carbon Cement Mortars

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Featured Application

The cementitious composites containing recycled aggregates and ceramic waste powder proposed herein may be considered for use in sustainable low-carbon mortars and concretes, subject to further application-specific validation. One potential application could be their use in railway infrastructure projects. In particular, recycled materials obtained from the demolition or modernization of railway stations may be reused as secondary raw materials in new cement-based composites. This approach supports closed-loop material circulation, reduces the consumption of natural resources, and enhances the waste valorization potential of railway station construction and renovation projects. Another potential application for these mixtures is in building projects that involve the demolition of ceramic materials and concrete. However, their use in railway infrastructure has not yet been validated under field conditions or assessed against railway-specific technical, quality-control, or regulatory requirements. Therefore, railway infrastructure should be regarded only as a potential area of application requiring further investigation.

Abstract

The reuse of construction and demolition waste in cementitious materials supports the development of sustainable low-carbon composites and circular economy strategies. This study investigated the influence of recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA) on the mechanical properties, freeze–thaw durability, pozzolanic potential, and environmental performance of cement mortars prepared with different cement types. Mortars containing 20% and 40% replacement of natural sand with recycled aggregates were evaluated through strength testing and freeze–thaw resistance assessment, while SEM analysis and pozzolanic potential were assessed on separate mortars in which 25% of the cement binder was replaced with the recycled materials, alongside carbon footprint calculations based on global warming potential (GWP), using the recycled materials directly after the crushing process without additional grinding. The results showed that mortars containing recycled concrete fine aggregate generally maintained satisfactory mechanical performance and freeze–thaw resistance, particularly at the 20% replacement level. In contrast, 40% RCerFA reduced mechanical performance and freeze–thaw resistance. Neither recycled material demonstrated confirmed pozzolanic reactivity in its unground state. Although one RConFA mixture exceeded the 75% compressive strength index criterion, this result alone was insufficient to confirm a chemical pozzolanic reaction. Environmental assessment demonstrated that cement type had a greater influence on carbon footprint than recycled aggregate incorporation. The study confirms the potential

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applicability of recycled fine aggregates in sustainable low-carbon cement mortars and explores their possible use as low-energy supplementary cementitious components.

Keywords: recycled fine aggregates; low-carbon cement mortars; freeze–thaw durability; pozzolanic potential; carbon footprint

1. Introduction

The construction sector is under increasing pressure to reduce its environmental impact while maintaining the mechanical performance and durability of cement-based materials. Concrete and mortar are among the most widely used construction materials worldwide, but their production is associated with high consumption of natural resources, intensive extraction of aggregates, and considerable CO_2 emissions from cement manufacturing [1–3]. Therefore, the development of low-emission binders and the incorporation of recycled constituents have become key strategies for reducing the carbon footprint of cementitious composites.

One of the most promising approaches is the partial replacement of Portland clinker with supplementary cementitious materials (SCMs) or the use of multicomponent cements containing limestone, fly ash, slag, natural pozzolans, or other mineral additions. Such binders can significantly decrease CO_2 emissions while maintaining adequate mechanical and durability performance [4–6]. However, the availability of traditional SCMs, especially fly ash and blast-furnace slag, is expected to decline due to changes in energy and metallurgical sectors, which increases the need to identify alternative locally available materials [7–9].

In parallel, construction and demolition waste (CDW) represents a major environmental challenge and an important material resource. The recycling of CDW into aggregates, fines, or powders supports circular economy principles by reducing landfill use and limiting the extraction of natural aggregates [10–12]. Recycled aggregates and recycled fines can be used in cement mortars and concretes as partial substitutes for natural aggregates, although their performance depends strongly on origin, particle-size distribution, adhered mortar content, porosity, and processing method [13–15].

Fine recycled fractions are particularly relevant for mortars, where natural sand is one of the main constituents. Several studies have demonstrated that recycled concrete aggregates, mixed recycled aggregates, and construction waste fines can be incorporated into masonry and rendering mortars, although their influence on workability, strength, shrinkage, porosity, and durability is not uniform [16–18]. Some authors reported satisfactory mechanical performance at moderate replacement levels, while higher content may lead to reduced density, higher water demand, or lower strength due to increased porosity and weaker interfacial transition zones [19,20].

Ceramic waste is another CDW-derived material with high potential for sustainable cementitious composites. It is produced during ceramic manufacturing, demolition, tile cutting, and renovation works. Depending on its mineralogical composition, firing temperature, fineness, and amorphous phase content, ceramic waste may act as a filler, fine aggregate, or pozzolanic material [21–23]. Previous studies have shown that moderate ceramic powder content may densify the microstructure, reduce permeability, and improve selected durability properties, whereas excessive replacement can reduce mechanical performance [24–26].

Recycled concrete fines and recycled concrete powders have also been investigated as alternative materials in cementitious systems. These materials contain residual hydrated

cement paste and in some cases unhydrated clinker particles, which may contribute to filler effects, nucleation, and limited secondary hydration [27–29]. However, the performance of recycled concrete fines depends on fineness, composition, and replacement mode. When used at moderate levels, they may improve pore structure and transport properties, but excessive incorporation can increase porosity and weaken the matrix.

The combination of recycled aggregates with low-carbon binders is especially attractive from an environmental perspective, but it also introduces additional complexity. Blended cements based on slag, limestone, fly ash, or multicomponent systems differ from ordinary Portland cement in hydration kinetics, pore structure development, and durability mechanisms [30,31]. As a result, the interaction between recycled ceramic or concrete fines and the cement type may determine whether the recycled material improves packing and durability or instead increases water absorption and degradation susceptibility.

Durability remains one of the most important criteria for the practical application of recycled materials in cement mortars. Recycled aggregates and fines may modify water absorption, capillary suction, chloride penetration, carbonation resistance, sulfate resistance, and freeze–thaw durability [32–34]. Among these properties, freeze–thaw resistance is particularly important in cold and temperate climates, where cyclic freezing and thawing may cause internal cracking, scaling, mass loss, and progressive strength reduction.

Previous research has shown that the frost resistance of cementitious composites containing recycled constituents can vary significantly. In some cases, recycled ceramic powder improved freeze–thaw durability due to pore refinement and matrix densification, while in other cases, high replacement levels increased porosity and accelerated deterioration [26,30]. Similar variability has been observed for recycled concrete materials, where treatment methods such as carbonation, limewater soaking, and optimized processing can improve aggregate quality and durability performance [35–37].

Environmental assessment studies further confirm that the use of recycled materials may reduce the overall environmental burden of cementitious composites, provided that transport, processing energy, and replacement efficiency are properly considered [38–40]. The environmental benefits are particularly significant when local waste streams are used and when the replacement does not cause substantial performance loss.

Despite the large number of studies on recycled aggregates, ceramic waste, and low-carbon binders, several research gaps remain. First, many investigations focus on either mechanical properties or selected durability parameters, while long-term freeze–thaw performance is less frequently analyzed. Second, studies often consider one cement type only, although the binder composition may strongly affect the response of mortars containing recycled fines. Third, the comparative behavior of recycled ceramic and recycled concrete fine aggregates in low-emission mortars is still insufficiently documented. Finally, the optimal replacement level remains unclear, particularly when mechanical performance and frost durability are considered simultaneously.

Therefore, this study investigated the influence of recycled ceramic and recycled concrete fine aggregates on the mechanical properties and freeze–thaw durability of cement mortars prepared with different cement types, including ordinary Portland cement and low-emission blended cements. The experimental program included the characterization of recycled fine aggregates, determination of bulk density and particle-size distribution, assessment of flexural and compressive strength, evaluation of the pozzolanic potential of the recycled materials used as partial cement replacements, and freeze–thaw resistance testing after 50, 100, and 150 cycles. The main objective was to determine how the type and amount of recycled fine aggregate affect mortar durability and to identify replacement levels that provide a balance between sustainability, mechanical performance, and resistance to cyclic freezing and thawing.

The novelty of this work lies primarily in the systematic comparison of recycled ceramic and recycled concrete fine aggregates as partial replacements for natural sand across four cement types, with particular emphasis on freeze–thaw durability. Several recent studies have investigated related aspects of recycled fine materials in cementitious mortars, but typically within a narrower scope than the present work. Algourdin et al. [41] examined mortars containing 10–50% recycled cement under freeze–thaw cycling, but considered a single binder type and did not include aggregate replacement or an environmental assessment. Rutkowska et al. [42] evaluated fine recycled concrete aggregate as a sand replacement (25–100%) in mortar, including freeze–thaw resistance and microstructure, but used a single reference cement and did not consider ceramic-derived fines or cement-type effects. Yu et al. [43] investigated recycled aggregate concrete containing ceramic waste powder under freeze–thaw exposure, but focused on a single mix design rather than a systematic comparison across cement types. In contrast, the present study combined both recycled ceramic and recycled concrete fine aggregates, evaluated as both aggregate and cement replacements, across four cement types differing in clinker content, under an extended freeze–thaw regime (up to 150 cycles) with a parallel carbon footprint assessment. As an additional, complementary test, the same recycled materials were also evaluated, without additional grinding, for their potential as partial cement replacements, providing preliminary insight into whether they could be reused directly after crushing without the added energy cost of grinding. Together, these findings support the primary aim of establishing recycled ceramic and concrete fines as viable partial substitutes for natural sand in low-carbon mortars, while also indicating a possible secondary pathway for their reuse as a supplementary cementitious material. This study was conceived as a preliminary, screening-level investigation focused on the macro-scale mechanical, durability, and environmental performance of the recycled materials. Detailed physicochemical and mineralogical characterization of the recycled fractions is planned as a subsequent stage of this research.

2. Materials and Methods

The experimental program was designed to investigate the influence of recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA) on the physical, mechanical, durability, microstructural, and environmental properties of cement mortars prepared with different cement types. The research methodology consisted of several consecutive stages, including raw material characterization, specimen preparation, mechanical and durability testing, microstructural observations, and carbon footprint assessment.

Initially, the physical properties of the raw materials were determined by particle-size distribution analysis and bulk density measurements. Subsequently, standard mortar mixtures were prepared and mixed in accordance with EN 196-1 [44], using 450 g of cement, 225 g of water, and 1350 g of aggregate. Natural aggregate was partially replaced with recycled aggregate at replacement levels of 20% and 40% by weight. These replacement levels were selected based on a preliminary literature review and pilot trials conducted in the authors' laboratory, representing a moderate substitution level expected to preserve adequate performance and a higher level likely to reveal the onset of significant property deterioration. The water content was kept constant across all mixtures, and the recycled aggregates were not pre-saturated prior to mixing. Consequently, the higher water absorption of the recycled materials relative to natural sand may have resulted in a lower effective water-to-cement ratio in mixtures containing higher recycled aggregate content. The prepared mortars were cast into prismatic specimens and cured for 28 days. The samples were designated according to the type of cement used, the percentage of recycled aggregate replacement, and the type of recycled aggregate. For example, the

designation CEM_I_42.5R_40%_CER refers to a mortar prepared with CEM I 42.5 R cement and 40% replacement of natural aggregate with recycled ceramic fine aggregate, whereas CEM_I_42.5R_20%_CON denotes a mortar containing 20% recycled concrete fine aggregate as a replacement for natural aggregate.

After the curing period, the specimens were subjected to flexural and compressive strength tests. Durability was assessed through freeze–thaw resistance evaluation after exposure to repeated freezing and thawing cycles. Additionally, the pozzolanic potential of recycled mineral additives was evaluated using the pozzolanic potential index (PPI), and the microstructure of these same cement-replacement specimens was further characterized by scanning electron microscopy (SEM) analysis. Finally, the environmental impact of the developed mixtures was assessed by estimating their carbon footprint based on global warming potential (GWP).

2.1. Materials

2.1.1. Cement

Four commercially available cements supplied by Holcim were used in this study: CEM I 42.5 R, CEM II/A-M (S-LL) 52.5 N, CEM II/A-LL 42.5 R, and CEM V/A (S-V) 42.5 N-LH/HSR/NA. All cements complied with the requirements of relevant PN-EN standards [45] and differed in terms of composition, hydration characteristics, early strength development, and environmental performance.

2.1.2. Standard Sand

Standard quartz sand conforming to PN-EN 196-1 [44] was used as fine aggregate. The material was supplied in bags of 1350 $\pm$ 5 g with a particle-size distribution ranging from 0 to 2 mm and moisture content below 0.2%.

2.1.3. Recycled Ceramic Fine Aggregate (RCerFA)

Recycled ceramic fine aggregate was obtained from recycled ceramic waste, mainly crushed bricks and roof tiles. The material was characterized by a red-brown color. The material was used both as partial fine aggregate replacement and, without additional grinding, as partial cement replacement in pozzolanic potential assessment. The material originated from construction and demolition waste of unspecified provenance and was processed to remove contaminants, retaining only ceramic debris (bricks and roof tiles) representative of the mixed-origin recycled ceramic fractions commonly encountered in engineering practice.

2.1.4. Recycled Concrete Fine Aggregate (RConFA)

Recycled concrete fine aggregate was obtained from recycled hardened concrete originating from demolition waste. The material consisted mainly of mineral aggregate particles and residual cement paste and was used as a recycled mineral additive. The material was also evaluated as a partial cement replacement material without additional grinding treatment. The parent concrete was of unspecified provenance. The material was processed to remove contaminants, retaining only concrete debris representative of the mixed-origin recycled concrete fractions commonly encountered in engineering practice.

2.1.5. Distilled Water

Distilled water was used during specimen preparation to eliminate the influence of impurities and ensure repeatability of the obtained results.

2.2. Experimental Program

2.2.1. Particle-Size Distribution of Aggregates

Particle-size distribution analysis was performed according to EN 933-1 [46] using a sieve set with mesh sizes of 0.125, 0.25, 0.5, 1, 2, and 4 mm.

Prior to testing, all materials were dried at 110 ± 5 °C until a constant mass was achieved. Three samples of each aggregate type (standard sand, RCerFA, and RConFA), each weighing 500 g, were prepared. The material was manually sieved for at least 1 min. Each separated fraction was subsequently weighed and recorded.

2.2.2. Bulk Density of Aggregates

Bulk density measurements were performed according to EN 1097-3 [47]. Three samples of each aggregate type were dried at 110 ± 5 °C until constant mass.

The bulk density values in loose and compacted states were calculated using the following equations:

$$\rho_l = (m_2 - m_1)/V \ [kg/m^3] \quad (1)$$

$$\rho_c = (m_3 - m_1)/V \ [kg/m^3] \quad (2)$$

where ρ_l is the loose bulk density, ρ_c is the tapped bulk density, m_1 is the mass of the empty cylinder in kg, m_2 is the mass of the cylinder with loose material in kg, m_3 is the mass of the cylinder with compacted material in kg, and V is the cylinder volume in m^3.

2.2.3. Flexural and Compressive Strength of Mortars

After 28 days of curing, specimens were removed from water and tested according to EN 196-1 [44]. The specimens were positioned on supporting rollers and loaded centrally at a loading rate of 50 ± 10 N/s until failure. Flexural strength was calculated as:

$$R_f = (1.5 \cdot F_f \cdot l)/b^3 \ [N/mm^2] \quad (3)$$

where R_f is flexural strength in N/mm^2, F_f is fracture load in N, b is specimen side length in mm, and l is support spacing in mm.

The final result was expressed as the average value of three measurements.

The compressive strength test was conducted according to EN 196-1 [44] using specimen halves obtained after flexural testing. The load was applied at a rate of 2.4 ± 0.2 kN/s until specimen failure. Compressive strength was calculated as:

$$R_c = F_c/1600 \ [N/mm^2] \quad (4)$$

where R_c is compressive strength in N/mm^2 and F_c is the failure load in N.

The final result was calculated as the arithmetic mean of six measurements.

2.2.4. Freeze–Thaw Resistance of Mortars

Freeze–thaw resistance was assessed according to PN-B-06265 [48] in a climate chamber (Toropol, Warsaw, Poland). As no dedicated freeze–thaw resistance standard exists for cement mortar beams, the procedure prescribed by PN-B-06265 for concrete was adopted by analogy, applied directly to the mortar specimen geometry described in Section 2.2.3. For each evaluation point (50, 100, and 150 cycles), half of the fully water-saturated specimens (three beams 40 × 40 × 160 mm) were exposed to freeze–thaw cycles, while the remaining specimens (three beams 40 × 40 × 160 mm) were stored as reference samples in water at a temperature of 18 ± 2 °C. One cycle consisted of:

- freezing in air at −18 ± 2 °C for 4 h;
- thawing by immersion in water at 18 ± 2 °C for 2 h.

The evaluation was performed after 50, 100, and 150 cycles. At each evaluation point, the same number of cycled and reference specimens was tested. The cycled and reference specimens were obtained from the same batch and were of the same age on the test date. The samples subjected to cyclic freezing and thawing, together with the reference samples, were tested for strength in accordance with Section 2.2.3, yielding six compressive strength results for the frozen and thawed samples and six results for the reference samples. A specimen was considered destroyed, and therefore unsuitable for strength testing, when it disintegrated (crumbled) during handling or removal from the climate chamber. Freeze–thaw resistance was assessed based on the strength loss, expressed as the freeze–thaw resistance coefficient. The freeze–thaw resistance coefficient was calculated as:

$$C_n = (f_{cn}/f_{c0}) \times 100\ [\%] \quad (5)$$

where f_{cn} is compressive strength after n freeze–thaw cycles in N/mm^2 and f_{c0} is compressive strength of the reference specimen in N/mm^2.

2.2.5. Pozzolanic Potential of Recycled Materials Used as Partial Cement Replacements

Pozzolanic potential of recycled ceramic material and recycled concrete material was evaluated according to EN 450-1 [49]. This supplementary test was conducted to evaluate the effect of unground recycled ceramic and concrete materials on mortar strength and to assess their potential for partial cement replacement without additional energy-intensive grinding. In this part of the study, the investigated recycled materials were used directly as obtained after the crushing process without any additional grinding treatment and incorporated as partial cement replacements rather than fine aggregate replacements. Although originally obtained as recycled fine aggregates, the investigated recycled materials were additionally evaluated as partial cement replacement components for pozzolanic potential assessment. This approach was adopted to evaluate the potential pozzolanic activity of recycled materials in their original post-processing condition, reflecting possible practical industrial application without additional energy-intensive grinding. Mortar specimens containing 25% replacement of cement binder with recycled material were prepared and tested according to the same procedure used for mechanical strength assessment. The sample designation system applied in this stage of the study was based on the type of recycled material followed by the cement type. For example, the designation 25%_CER_CEM_I_42.5R refers to a mortar in which 25% of the cement binder was replaced with recycled ceramic material in a mixture prepared with CEM I 42.5 R cement, whereas 25%_CON_CEM_V/A(S–V)_42.5N denotes a mortar containing 25% recycled concrete material used with CEM V/A (S–V) 42.5 N cement.

The pozzolanic potential indices were used to assess the pozzolan potential and were determined as the ratio between the mechanical strength of mortars containing recycled materials and the corresponding reference mortars prepared only with cement binder. The activity indices for flexural and compressive strength were calculated using the following equations:

$$R_{pozz,1} = (R_{f,pozz}/R_{f,ref}) \times 100\ [\%] \quad (6)$$

$$R_{pozz,2} = (R_{c,pozz}/R_{c,ref}) \times 100\ [\%] \quad (7)$$

where $R_{f,pozz}$ is flexural strength of samples with 25% replacement in N/mm^2, $R_{f,ref}$ is flexural strength of reference samples (only with cement binder) in N/mm^2, $R_{c,pozz}$ is compressive strength of samples with 25% replacement in N/mm^2 and $R_{c,ref}$ is compressive strength of reference samples (only with cement binder) in N/mm^2. $R_{pozz,1}$ and $R_{pozz,2}$ refer to pozzolanic potential.

A strength activity index of at least 75% of the reference compressive strength at 28 days was adopted following the principle defined in EN 450-1. The same numerical threshold was also applied to the flexural strength index as an author-defined comparative benchmark to facilitate a consistent comparison of the relative flexural and compressive performance of the investigated mortars. However, the 75% threshold for flexural strength is not specified in EN 450-1 and should not be interpreted as a normative criterion for pozzolanic activity. In both cases, the calculated indices are treated as screening-level indicators of strength contribution rather than direct confirmation of a chemical pozzolanic reaction.

2.2.6. Scanning Electron Microscopy Analysis

Scanning electron microscopy (SEM) was used to characterize the morphology and microstructure of the investigated materials. SEM observations were performed on mortar specimens prepared for the pozzolanic potential assessment, in which recycled materials were used as partial cement replacements without additional grinding. SEM investigations provided detailed information regarding surface morphology, pore structure, particle morphology, and microstructural features of the investigated materials. The structure of the hardened mortar samples after 28 days of curing was analyzed using a Tescan Vega 3 scanning electron microscope (Brno, Czech Republic). Prior to observation, specimens were dried at room temperature and examined without conductive coating using the low-vacuum mode of the microscope with a backscattered electron (BSE) detector to minimize surface charging effects. Images were acquired at a magnification of 1.00 kx (277 μm field of view) with a working distance of 15.00 mm. The micrographs presented in Figure 7 were selected as representative of the observed microstructure.

2.2.7. Carbon Footprint Assessment

The environmental impact of the investigated cement mortars was assessed through carbon footprint analysis using the life cycle assessment (LCA) approach. The calculations were based on the global warming potential (GWP) indicator, expressed as carbon dioxide equivalent emissions (kg CO_2 eq), according to EN 15804: Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products [50]. The carbon footprint analysis was conducted using OneClick LCA software (One Click LCA© version 0.30.0, database version 7.6, Helsinki, Finland) [51].

The assessment considered only the product stage (A1–A3), assuming that the construction stage, use phase, and end-of-life stage would remain identical for all investigated mortar compositions. This represents a simplification, as it does not account for differences in service life or replacement frequency arising from the durability differences observed between mixtures (Section 3.4), particularly for compositions exhibiting severe freeze–thaw deterioration at high replacement levels. Consequently, the reported GWP values should be interpreted as a per-unit-mass production footprint rather than a full indicator of environmental performance over the service life of the material, and a service-life-normalized functional unit is recommended for future comparative assessments. Therefore, the analysis focused exclusively on environmental impacts associated with raw material acquisition, material processing, transportation of raw materials, and mortar production. For recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA), the environmental impact was estimated assuming that the recycled materials were produced directly at the construction site from construction and demolition waste. Consequently, transportation processes were excluded from the analysis. Furthermore, recycled materials were treated as secondary raw materials; therefore, environmental burdens related to raw material extraction and primary production processes were not included in the assessment. The GWP values for recycled aggregates were estimated based solely on emissions gen-

erated during the crushing process, considering only the material processing stage (A3). The calculations were performed using crushing equipment operating parameters and fuel consumption associated with the processing of construction and demolition waste. The following assumptions were adopted:

- Crushing equipment productivity: 10,000 kg/h.
- Fuel consumption: 15 L/h.
- Diesel fuel emission factor (GWP): 3.35 kg CO_2 eq/L.

The GWP values used in the calculations are presented in Table 1 and were obtained from environmental product declarations (EPDs) and environmental documentation available for materials used in mortar production. The total carbon footprint of each mortar composition was subsequently estimated based on the mass proportions of individual mixture components and their corresponding GWP values.

Table 1. Global warming potential (GWP) values of materials used for carbon footprint assessment.

Lp.	Material	GWP (A1–A3) [kg CO_2 eq/kg]	Source
1	CEM I 42.5 R	0.6640	[51]
2	CEM II/A-M (S-LL) 52.5 N	0.4920	[52]
3	CEM II/A-LL 42.5 R	0.5970	[53]
4	CEM V/A (S-V) 42.5 N-LH/HSR/NA	0.3230	[54]
5	Sand 0–2 mm	0.0023	[51]
6	Water	0.0003	[51]
7	Recycled Ceramic Fine Aggregate	0.0050	[51,55]
8	Recycled Concrete Fine Aggregate	0.0050	[51,55]

3. Results

3.1. Particle-Size Distribution of Aggregates

Figure 1 presents the particle-size distribution of the natural sand and the recycled fine aggregates used in the study. The grading curves indicate noticeable differences between the reference sand and the recycled aggregates, particularly within the intermediate-particle-size range.

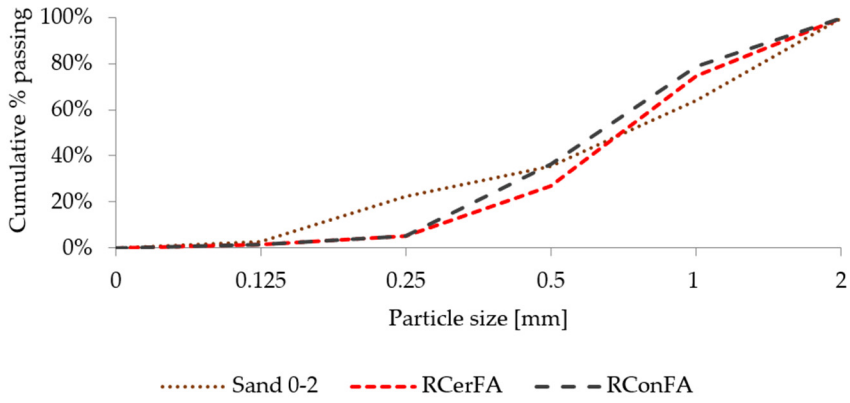


Figure 1. Particle-size distribution curves of natural sand, recycled ceramic fine aggregate (RCerFA), and recycled concrete fine aggregate (RConFA).

The natural sand exhibited a relatively uniform and continuous grading curve, characteristic of standard fine aggregate used in cement mortars. Both recycled aggregates displayed a steeper rise in the intermediate-size range (0.5–1.0 mm) than natural sand,

indicating a comparatively narrower particle-size distribution concentrated in this fraction. Within this range, RCerFA passed less material than natural sand at the 0.5 mm sieve (27.0% vs. 35.3%) but more at the 1.0 mm sieve (74.8% vs. 63.9%), whereas RConFA passed a similar or slightly higher proportion than natural sand at both sieves (36.2% and 78.7%, respectively). Consequently, RConFA exhibited a marginally finer overall grading than RCerFA across the intermediate fraction, which may reflect a greater proportion of residual mortar fines adhered to the concrete-derived particles compared to the more uniformly fired ceramic fragments. Such differences in particle-size distribution, together with the surface texture of both materials, may influence water demand, workability, and packing behavior in the mortar matrix. The particle-size distributions of both recycled aggregates fell within a comparable range to natural sand across the tested sieve fractions. A formal comparison against standard grading limits was not performed and is recommended for future characterization work.

3.2. Bulk Density of Aggregates

Figure 2 presents the loose and tapped bulk density values of the investigated aggregates. The results indicate that natural sand exhibited the highest bulk density among all tested materials, both in the loose and tapped state. The recycled aggregates showed lower bulk density values compared to natural sand. A noticeable increase in density was observed after tapping for all aggregates, indicating improved particle packing. The difference between loose and tapped bulk density was more pronounced for the recycled aggregates, suggesting a greater susceptibility to particle rearrangement under compaction. In the loose state, RCerFA exhibited a slightly lower bulk density than RConFA (1256.7 and 1280.0 kg/m^3, respectively). After tapping, however, RCerFA reached a slightly higher bulk density than RConFA (1560.0 and 1546.7 kg/m^3, respectively). Therefore, the results do not indicate a consistently lower bulk density of RCerFA, but rather suggest differences in the particle rearrangement and packing behavior of the two recycled aggregates during compaction.

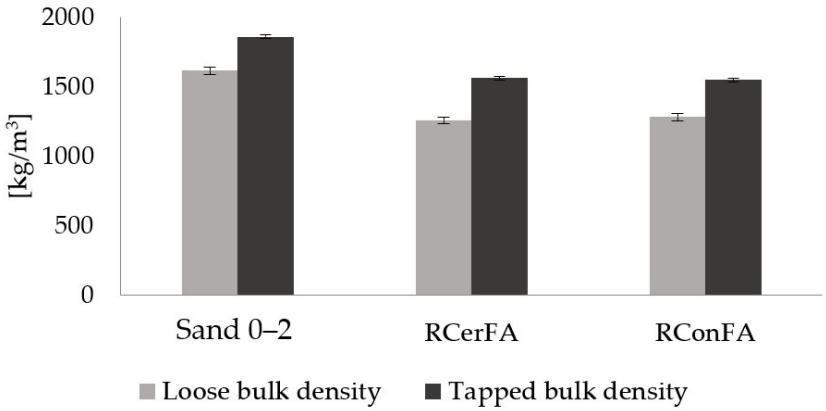


Figure 2. Loose and tapped bulk density of natural sand, recycled ceramic fine aggregate (RCerFA), and recycled concrete fine aggregate (RConFA). Values are presented as means ± standard deviation (n = 3).

3.3. Flexural and Compressive Strength of Mortars

Figure 3 presents the flexural and compressive strength results for mortars prepared with different cement types and varying replacement levels of recycled aggregates. The results demonstrate that the mechanical performance of the mortars was strongly influenced by both the type of recycled aggregate and its replacement ratio.

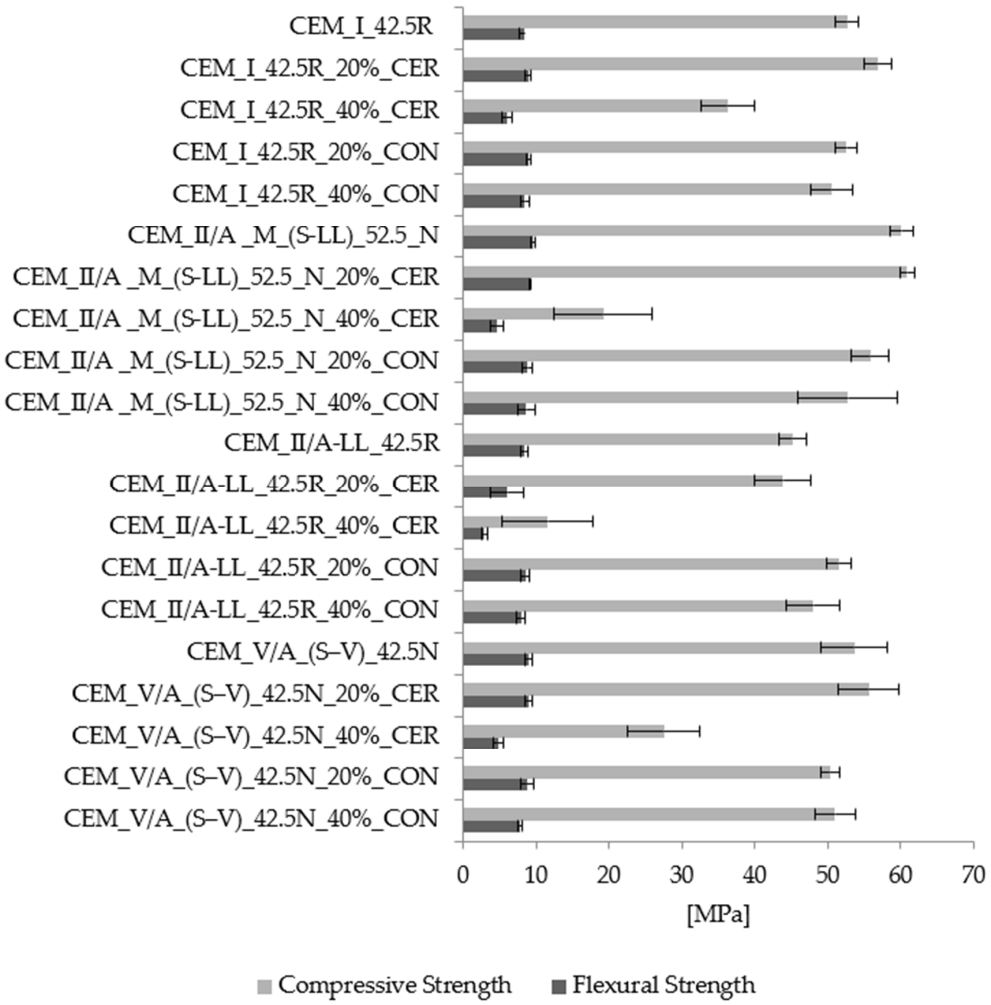


Figure 3. Flexural and compressive strength of mortars containing recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA). Error bars represent standard deviation values.

In general, mixtures containing recycled concrete fine aggregate (RConFA) maintained mechanical properties comparable to the reference mortars. For most cement types, the incorporation of 20% RConFA resulted in compressive strength values very close to or slightly higher than the control mixtures. Even at 40% replacement, the decrease in compressive strength remained relatively moderate. This effect was particularly visible for mortars based on CEM V/A (S–V) 42.5 N and CEM I 42.5 R cements, where compressive strength values above 50 N/mm^2 were still achieved.

In contrast, the use of recycled ceramic fine aggregate (RCerFA) caused a more pronounced reduction in strength, especially at the 40% replacement level. Although mixtures containing 20% RCerFA occasionally exhibited slight improvements or only minor reductions in strength, increasing the replacement ratio to 40% significantly deteriorated both compressive and flexural performance. The greatest decrease was observed for mortars prepared with CEM II/A-LL 42.5 R cement, where compressive strength dropped to approximately 12 N/mm^2 and flexural strength to below 3 N/mm^2. Additionally, ceramic aggregates may exhibit lower mechanical resistance compared to natural sand and recycled concrete particles.

The flexural strength results followed trends similar to compressive strength. Mortars containing RConFA retained relatively stable flexural performance, whereas mixtures with 40% RCerFA showed a substantial decrease in bending strength. Nevertheless, mixtures

containing 20% recycled aggregates generally maintained satisfactory mechanical performance, indicating that partial replacement of natural sand with recycled fine aggregates is feasible for cement mortar production. One-way ANOVA confirmed that differences among mixtures were statistically significant within each cement type ($p < 0.001$ for both flexural and compressive strength). However, pairwise Welch's t-tests indicated that several individual mixtures did not differ significantly from their reference or from one another—for example, CEM_V/A(S–V)42.5N and its 20% RCerFA counterpart ($p = 0.951$ flexural, $p = 0.444$ compressive), and the 20% and 40% RConFA mixtures within both the CEM_V/A(S–V)42.5N and CEM_II/A-LL_42.5R series (all $p > 0.05$)—indicating that no statistically significant differences were detected in these selected pairwise comparisons. In the cross-series comparison between the CEM II/A-LL 42.5 R mortars containing 20% or 40% RConFA and the reference CEM V/A (S–V) 42.5 N mortar, no statistically significant differences were found ($p > 0.05$), except for compressive strength between the 40% RConFA mixture and the CEM V/A (S–V) 42.5 N reference ($p = 0.042$).

3.4. Freeze–Thaw Resistance of Mortars

Figure 4 and Table 2 present the results of freeze–thaw resistance tests performed on mortars containing recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA). If the samples were destroyed after a given number of cycles, "-" was entered in place of the values in Table 2, as it was not possible to assess their residual strength. This applied to all mixtures containing 40% RCerFA, which remained testable after 50 freeze–thaw cycles but disintegrated before the 100-cycle evaluation. In addition, with the exception of the 40% RCerFA mixture, all CEM V/A (S–V) 42.5 N-based mixtures could still be tested after 100 cycles, when their strength-retention coefficients ranged from 45% to 54%, but disintegrated before reaching 150 cycles. The analysis included compressive strength after 50, 100, and 150 freeze–thaw cycles and residual compressive strength expressed as a percentage of the reference strength. The obtained results indicate that the frost resistance of the investigated mortars strongly depended on the cement type, recycled aggregate type, and replacement level. In general, mortars containing recycled concrete fine aggregate exhibited better freeze–thaw durability than mixtures incorporating recycled ceramic fine aggregate at the 40% replacement level.

For mortars based on CEM I 42.5 R cement, the incorporation of 20% RCerFA resulted in improved durability performance compared to the reference mixture. The compressive strength of this mixture increased from 53.0 N/mm^2 after 50 cycles to 55.5 N/mm^2 after 100 cycles and 56.3 N/mm^2 after 150 cycles, while the residual compressive strength remained close to 90%. However, increasing the RCerFA content to 40% led to a substantial decrease in freeze–thaw resistance in absolute terms. The compressive strength dropped to approximately 36 N/mm^2 after 50 cycles, compared with 53.0 N/mm^2 for the 20% RCerFA mixture, and further measurements after extended cycling were not possible. It should be noted that this mixture shows a high strength-retention coefficient (C_{50} = 94.5%) only because its unfrozen reference specimens were themselves weak (38.4 N/mm^2). The coefficient therefore does not indicate favorable frost resistance in this case. A similar tendency was observed for mortars prepared with CEM II/A-M (S-LL) 52.5 N cement. The mixture containing 20% RCerFA achieved the highest absolute residual strength among all tested compositions, maintaining compressive strength values of approximately 60 N/mm^2 after 100 cycles and over 56 N/mm^2 after 150 cycles. The residual compressive strength remained above 84%, confirming very good durability performance. In contrast, the mortar containing 40% RCerFA experienced significant degradation already after 50 cycles, with compressive strength decreasing to approximately 12 N/mm^2.

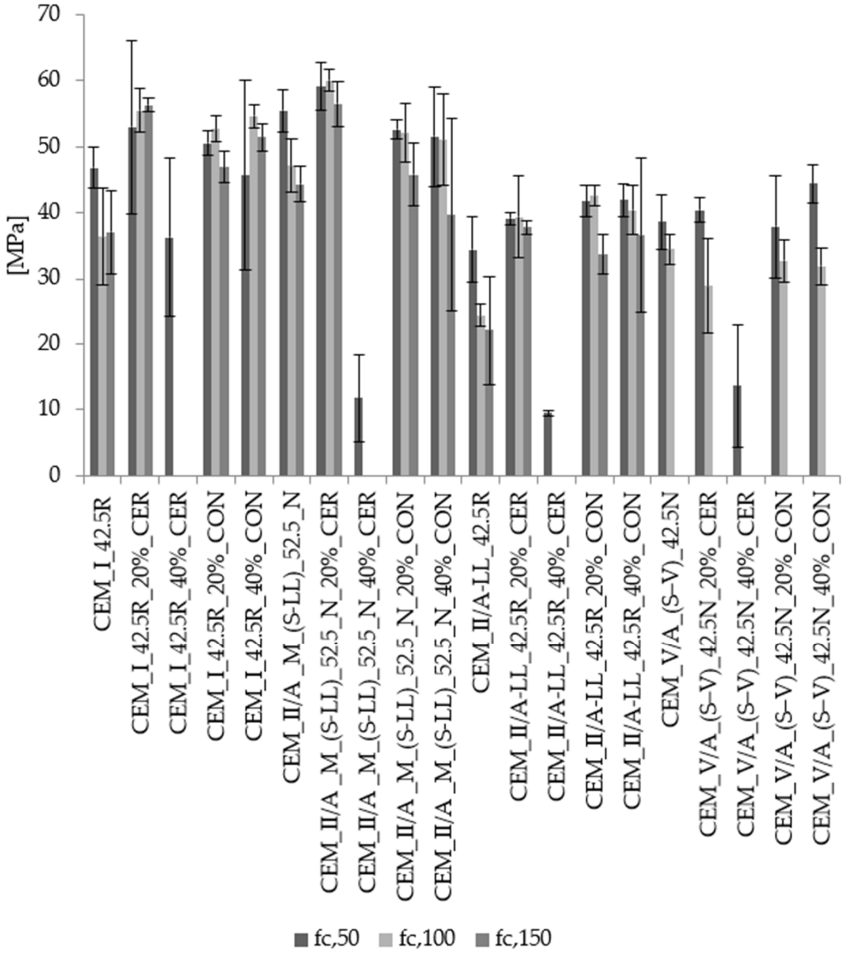


Figure 4. Compressive strength of mortars after 50, 100, and 150 freeze–thaw cycles. Error bars represent standard deviation values.

Table 2. Compressive strength retention (C) of mortars after 50, 100, and 150 freeze–thaw cycles.

Lp.	Sample	C_{50}	C_{100}	C_{150}
1	CEM_I_42.5R	83.27%	59.72%	58.14%
2	CEM_I_42.5R_20%_CER	86.76%	93.11%	89.61%
3	CEM_I_42.5R_40%_CER	94.45%	-	-
4	CEM_I_42.5R_20%_CON	88.34%	92.12%	79.33%
5	CEM_I_42.5R_40%_CON	88.30%	99.80%	84.85%
6	CEM_II/A _M_(S-LL)_52.5_N	87.40%	74.48%	67.92%
7	CEM_II/A _M_(S-LL)_52.5_N_20%_CER	92.17%	89.93%	84.70%
8	CEM_II/A _M_(S-LL)_52.5_N_40%_CER	56.59%	-	-
9	CEM_II/A _M_(S-LL)_52.5_N_20%_CON	85.76%	82.07%	74.42%
10	CEM_II/A _M_(S-LL)_52.5_N_40%_CON	88.33%	80.97%	64.30%
11	CEM_II/A-LL_42.5R	69.02%	49.43%	41.60%
12	CEM_II/A-LL_42.5R_20%_CER	75.41%	78.03%	72.46%
13	CEM_II/A-LL_42.5R_40%_CER	75.59%	-	-
14	CEM_II/A-LL_42.5R_20%_CON	77.66%	75.00%	60.37%
15	CEM_II/A-LL_42.5R_40%_CON	85.29%	76.01%	70.07%
16	CEM_V/A_(S–V)_42.5N	61.32%	52.28%	-
17	CEM_V/A_(S–V)_42.5N_20%_CER	68.82%	45.37%	-
18	CEM_V/A_(S–V)_42.5N_40%_CER	45.50%	-	-
19	CEM_V/A_(S–V)_42.5N_20%_CON	63.24%	52.80%	-
20	CEM_V/A_(S–V)_42.5N_40%_CON	74.05%	53.80%	-

The lowest absolute residual strength was observed for mixtures prepared with CEM II/A-LL 42.5 R cement containing 40% RCerFA, which retained only 9.5 N/mm^2 after 50 cycles, and for the corresponding CEM II/A-M (S-LL) 52.5 N and CEM V/A (S–V) 42.5 N mixtures (11.8 and 13.6 N/mm^2, respectively). These mortars exhibited severe structural deterioration during cyclic freezing and thawing and could not be tested after 100 cycles. The relatively high values of C (e.g., 75.6% for the CEM II/A-LL 42.5 R mixture) result from the equally low strength of their unfrozen reference specimens (12.6 N/mm^2). In comparison, mortars incorporating recycled concrete fine aggregate demonstrated significantly better freeze–thaw performance. For most cement types and replacement levels, the compressive strength remained within the range of approximately 40–55 N/mm^2 after freeze–thaw exposure, while residual compressive strength values frequently exceeded 70–80%.

The results also demonstrated that moderate replacement of natural sand with recycled aggregates, particularly recycled concrete fine aggregate, did not significantly reduce freeze–thaw resistance. In some cases, the incorporation of 20% recycled aggregate even improved durability performance compared to the reference mortars. However, excessive replacement with recycled ceramic aggregate adversely affected the compressive strength after cycling and the ability of the mortars to survive extended freeze–thaw exposure. One-way ANOVA performed within each cement type confirmed these observations statistically. For CEM_I_42.5R, differences in compressive strength after 50 freeze–thaw cycles among all tested mixtures were not statistically significant ($p = 0.170$), indicating that neither RCerFA nor RConFA replacement significantly altered early-stage frost resistance for this cement. In contrast, significant differences were confirmed for the remaining three cement types ($p < 0.001$), consistent with the pronounced deterioration observed for high RCerFA content. Pairwise comparisons further showed that the 20% and 40% RConFA mixtures generally did not differ significantly from one another within a given cement type ($p = 0.10$–0.91), with the single exception of the CEM_I_42.5R series after 150 cycles (46.9 vs. 51.4 N/mm^2, $p = 0.007$). Apart from this case, no statistically significant difference was detected between the two RConFA replacement levels within the tested range.

3.5. Pozzolanic Potential of Recycled Materials Used as Partial Cement Replacements

Table 3 and Figures 5 and 6 present the results of the pozzolanic potential assessment for mortars in which 25% of the cement binder was replaced with recycled ceramic fine aggregate (RCerFA) or recycled concrete fine aggregate (RConFA). In Figure 5, the red line denotes the author-defined 75% comparative benchmark for the flexural strength index. This benchmark is not a normative criterion specified in EN 450-1. In Figure 6, the red line represents the 75% compressive strength activity benchmark adopted following the principle defined in EN 450-1. It should be emphasized that the recycled ceramic and recycled concrete materials used in the pozzolanic potential assessment were not subjected to additional grinding prior to testing. Therefore, the obtained activity indices reflect the overall strength contribution of the recycled materials in their post-crushing condition. The pozzolanic potential indices were determined based on flexural and compressive strength values in accordance with EN 450-1 [49]. The sample designation system used in this part of the study was based on the type of recycled material followed by the cement type. For example, the designation 25%_CER_CEM_I_42.5R refers to a mortar in which 25% of the cement binder was replaced with recycled ceramic material in a mixture prepared with CEM I 42.5 R cement, whereas 25%_CON_CEM_V/A(S–V)_42.5N denotes a mortar containing 25% recycled concrete material used with CEM V/A (S–V) 42.5 N cement.

Table 3. Flexural and compressive strength of mortars used for pozzolanic potential index (PPI) determination.

Lp.	Sample	Flexural Strength [N/mm^2]	Compressive Strength [N/mm^2]
1	CEM_I_42.5R	8.4 ± 0.7	52.6 ± 1.7
2	25%_CER_CEM_I_42.5R	6.8 ± 0.3	35.1 ± 0.2
3	25%_CON_CEM_I_42.5R	6.5 ± 0.1	34.7 ± 1.7
4	CEM_II/A_M_(S-LL)_52.5_N	9.5 ± 0.3	60.1 ± 1.6
5	25%_CER_CEM_II/A_M_(S-LL)_52.5_N	7.4 ± 0.4	38.7 ± 1.6
6	25%_CON_CEM_II/A_M_(S-LL)_52.5_N	6.9 ± 0.1	34.8 ± 1.8
7	CEM_II/A-LL_42.5R	8.4 ± 0.4	45.1 ± 1.9
8	25%_CER_CEM_II/A-LL_42.5R	6.9 ± 0.2	32.7 ± 0.8
9	25%_CON_CEM_II/A-LL_42.5R	6.6 ± 0.3	35.3 ± 1.7
10	CEM_V/A_(S–V)_42.5N	8.9 ± 0.5	53.6 ± 4.5
11	25%_CER_CEM_V/A_(S–V)_42.5N	7.0 ± 0.8	39.7 ± 0.7
12	25%_CON_CEM_V/A_(S–V)_42.5N	6.9 ± 1.3	34.3 ± 2.1

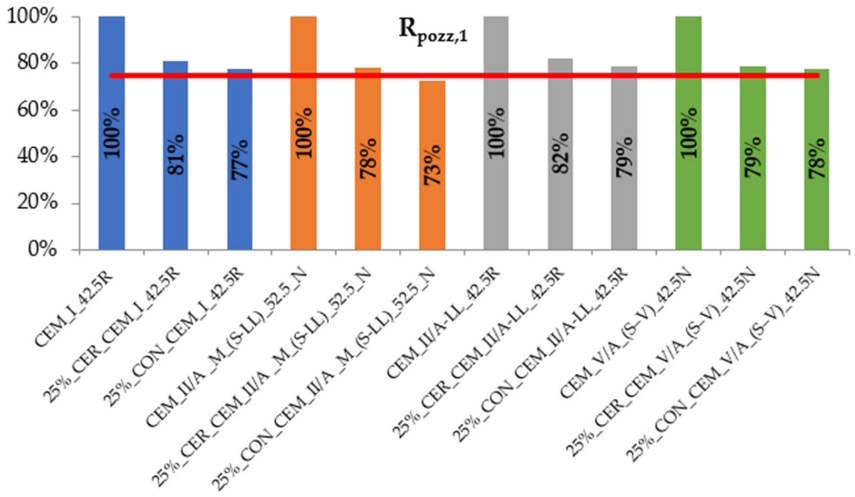


Figure 5. Flexural pozzolanic potential index ($R_{pozz,1}$) of mortars containing recycled ceramic material (RCerFA) and recycled concrete material (RConFA).

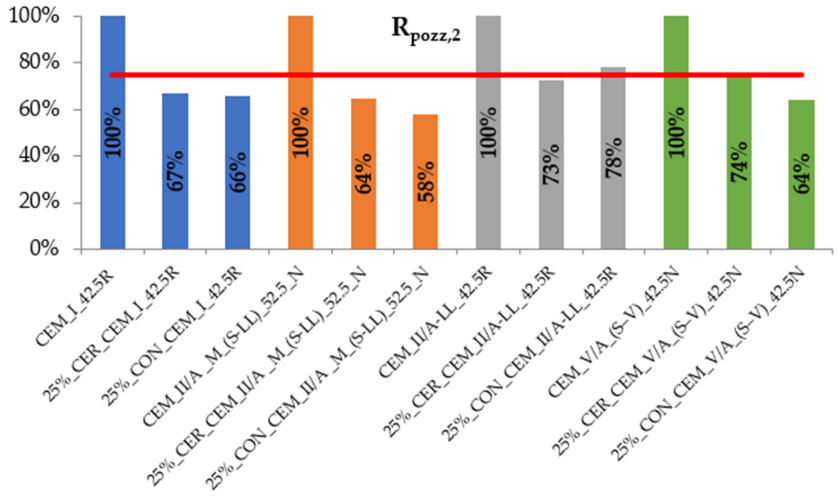


Figure 6. Compressive pozzolanic potential index ($R_{pozz,2}$) of mortars containing recycled ceramic material (RCerFA) and recycled concrete material (RConFA).

The reference mortars prepared only with cement binder were assumed as 100% activity for each cement type. The obtained results indicate that the incorporation of

recycled materials generally reduced both flexural and compressive strength compared to the reference mixtures. However, the extent of this reduction depended on the type of recycled material and cement composition. The flexural pozzolanic potential index values ($R_{pozz,1}$) showed that most mixtures containing RCerFA achieved results close to or above the threshold value of 75%, which is commonly considered the minimum requirement for pozzolanic potential. The highest flexural activity index among modified mortars was obtained for the mixture based on CEM II/A-LL 42.5 R cement, reaching approximately 82%. Similar values, ranging from approximately 78% to 81%, were recorded for mixtures prepared with CEM I 42.5 R, CEM II/A-M (S-LL) 52.5 N, and CEM V/A (S–V) 42.5 N cements. In contrast, mixtures containing RConFA generally exhibited slightly lower flexural activity index values, remaining in the range of approximately 72–79%. Nevertheless, several mortars still achieved values close to the required 75% limit.

The compressive strength-based activity indices ranged from 58% to 78%. Only the 25%_CON_CEM_II/A-LL_42.5R mixture achieved a value above the 75% criterion, reaching 78%, whereas all RCerFA mixtures and the remaining RConFA mixtures remained below this threshold. Nevertheless, exceeding the strength-based criterion alone cannot be considered confirmation of chemical pozzolanic reaction. The recycled materials were used in their coarse, unground condition, and the experimental program did not include an inert-filler control or an independent reaction measurement capable of distinguishing chemical reactivity from dilution, particle-packing, and filler effects. Therefore, the obtained indices should be interpreted as indicators of the overall contribution of the recycled materials to mortar strength rather than as direct evidence of pozzolanic potential. Grinding the recycled materials to a particle size comparable to that of the cement binder may increase their reactivity; however, this requires verification using complementary methods in future research.

3.6. Scanning Electron Microscopy Analysis

Scanning electron microscopy (SEM) observations were performed on 28-day mortar specimens prepared for the pozzolanic potential assessment, in which 25% of cement was replaced with recycled ceramic material (RCerFA) or recycled concrete material (RConFA) without additional grinding treatment. These observations therefore characterize the cement-replacement specimens used for pozzolanic potential assessment and are not intended to represent the microstructure of the 20%/40% aggregate-replacement mixtures evaluated in Sections 3.3 and 3.4. The analysis was conducted prior to freeze–thaw exposure and aimed to evaluate the initial matrix morphology, pore distribution, and the interaction between recycled particles and hydration products. Representative SEM micrographs of the investigated mortars are presented in Figure 7.

The SEM observations revealed visible differences in microstructure depending on both the recycled material type and cement composition. Mortars containing recycled ceramic material generally exhibited a relatively homogeneous matrix with hydration products distributed around angular ceramic particles. In mixtures prepared with CEM I 42.5 R and CEM II/A-M (S-LL) 52.5 N cements, the matrix appeared relatively continuous, while the occurrence of larger pores and discontinuities remained limited. Fine pores were still visible within the matrix; however, they were relatively uniformly distributed throughout the observed area. The specimen containing 25% RCerFA and CEM II/A-LL 42.5 R cement exhibited slightly higher local porosity and less uniform distribution of hydration products compared to the remaining ceramic-based mixtures. In contrast, the mixture prepared with CEM V/A (S–V) 42.5 N cement showed a relatively compact matrix with finely distributed hydration products surrounding recycled ceramic particles. Mortars containing recycled concrete material exhibited a more heterogeneous morphology

compared to mixtures incorporating recycled ceramic fines. In samples prepared with CEM I 42.5 R and CEM II/A-LL 42.5 R cements, irregular particles surrounded by remnants of old hydrated cement paste and locally increased pore content were observed. Several microvoids and discontinuities were visible near recycled concrete particles, which may be associated with the porous nature of adhered mortar originating from demolished concrete. More uniform matrix morphology was observed for mortars containing 25% RConFA and blended cements, particularly CEM II/A-M (S-LL) 52.5 N and CEM V/A (S–V) 42.5 N. In these mixtures, hydration products appeared more evenly distributed and the occurrence of larger discontinuities remained limited. No extensive microcracking was observed in the analyzed specimens after 28 days of curing. However, because the SEM observations were qualitative and no unmodified reference specimen or independent reaction measurement was included, the relatively compact morphology observed in selected RCerFA mixtures cannot be considered evidence of chemical pozzolanic reaction.

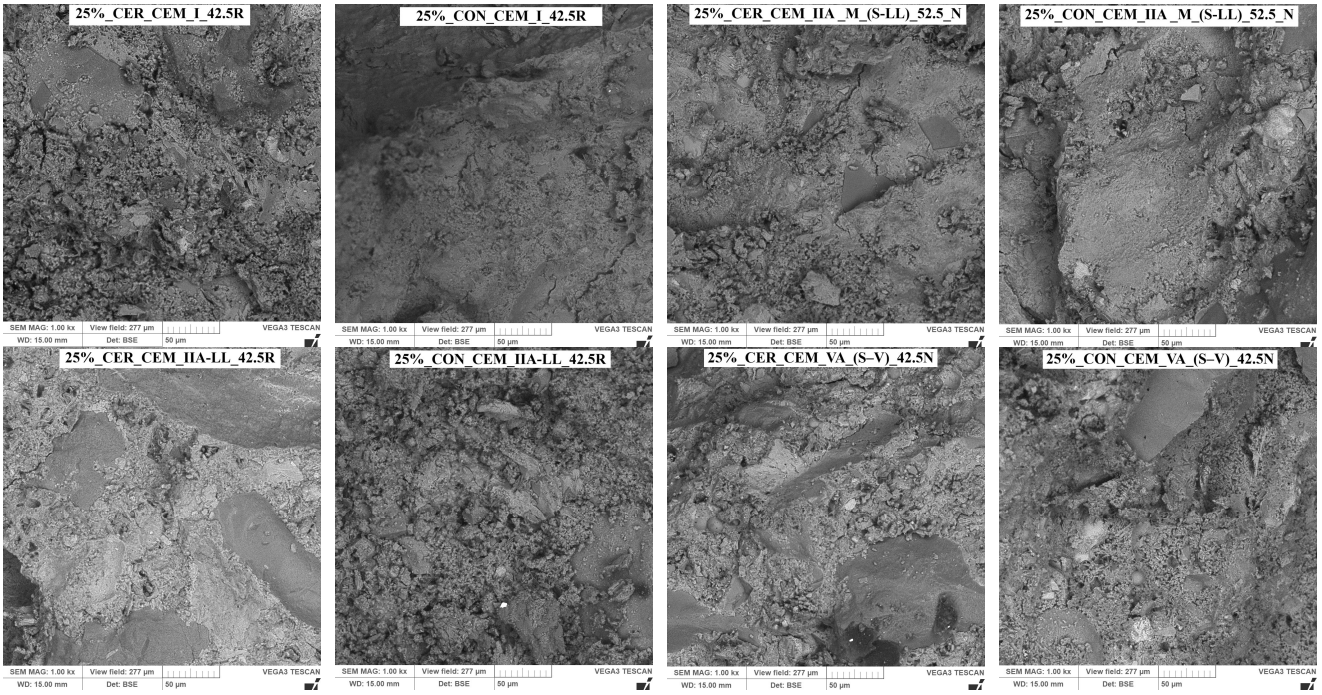


Figure 7. Representative SEM micrographs of 28-day mortars containing recycled ceramic and recycled concrete fines as partial cement replacements.

3.7. Carbon Footprint Assessment

Figures 8 and 9 present the global warming potential (GWP) values of the investigated mortar mixtures, expressed per kilogram of fresh mortar (kg CO_2 eq/kg of mortar) rather than per unit volume to avoid the need for volumetric normalization using constituent densities. The GWP of each mixture was calculated directly from the laboratory batch proportions (450 g cement, 225 g water, 1350 g aggregate, per EN 196-1) and the corresponding GWP factors listed in Table 1, normalized to the constant total batch mass (2025 g). Because aggregate and cement replacement were performed on a mass basis, the total batch mass remained identical across all replacement levels within each cement series, allowing a direct mass-normalized comparison without density-based assumptions. Consequently, the cement and water content—and GWP contributions—remained constant across all mixtures within each cement series, while differences in the calculated GWP resulted solely from replacing part of the natural sand with RCerFA or RConFA. The same calculation approach was applied to the mortars used for the pozzolanic potential assessment: 25% of the cement-binder mass in the reference composition was replaced with the correspond-

ing mass of RCerFA or RConFA. In these mixtures, the natural-sand and water content remained constant, while the cement contribution to GWP decreased in proportion to the replaced cement mass and was supplemented by the GWP contribution of the recycled material. The results indicate that cement was the dominant contributor to the total carbon footprint for all analyzed compositions, whereas the contribution of natural sand, water, and recycled aggregates remained relatively low. Among the investigated binders, mortars prepared with CEM I 42.5 R cement exhibited the highest environmental impact, with total GWP values ranging from approximately 0.149 to 0.150 kg CO_2 eq/kg of mortar. This behavior is directly associated with the high clinker content characteristic of Portland cement, which is responsible for significant CO_2 emissions during production.

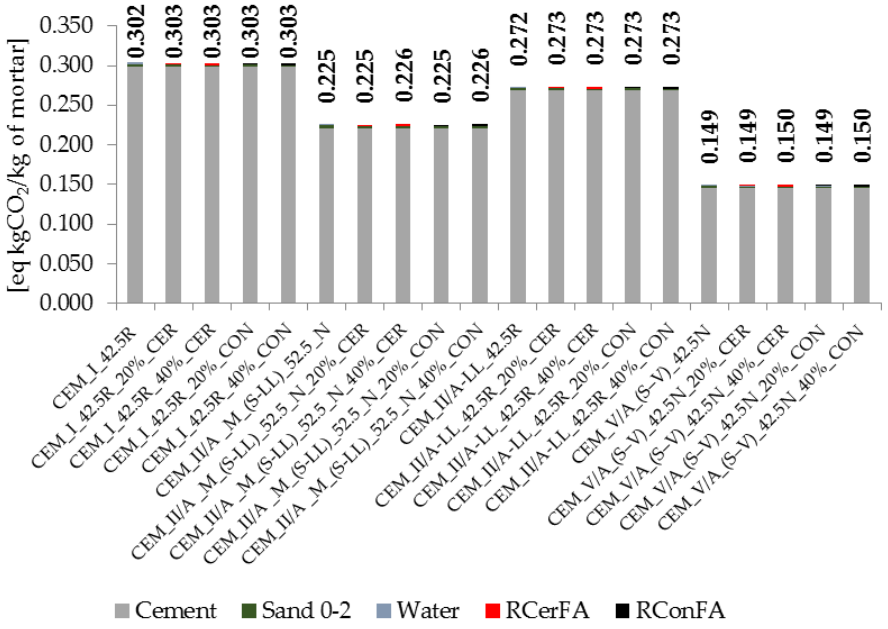


Figure 8. Contribution of individual mortar components to the total global warming potential (GWP) of the investigated mixtures.

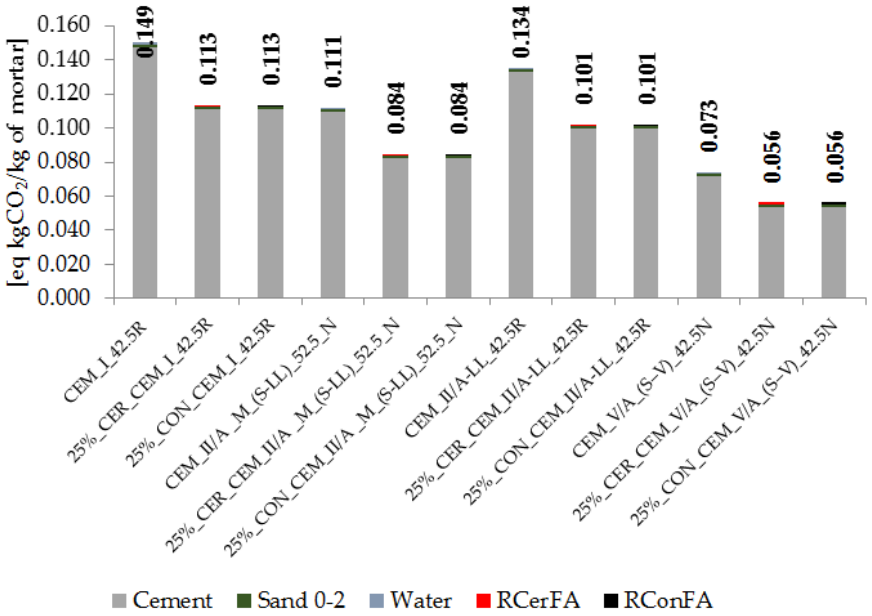


Figure 9. Contribution of individual mortar components to the total global warming potential (GWP) of the investigated mixtures where cement was replaced by recycled materials.

Mortars based on CEM II/A-M (S-LL) 52.5 N and CEM II/A-LL 42.5 R cements showed noticeably lower carbon footprint values, reaching approximately 0.111–0.112 kg CO_2 eq/kg of mortar and 0.134–0.135 kg CO_2 eq/kg of mortar, respectively. The reduced environmental impact of these mixtures results from the lower clinker content and the incorporation of supplementary cementitious materials and limestone additions in blended cements. The lowest GWP values were obtained for mortars prepared with CEM V/A (S–V) 42.5 N cement. The total carbon footprint of these mixtures ranged from approximately 0.073 to 0.074 kg CO_2 eq/kg of mortar, representing a significant reduction compared to mortars based on CEM I 42.5 R cement. This reduction can be attributed to the high proportion of mineral additions used in CEM V cement production, which substantially lowers CO_2 emissions associated with clinker manufacturing. The incorporation of recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA) resulted in only minor increases in the calculated GWP. Because the cement and water content remained constant, these changes resulted solely from replacing natural sand with recycled aggregates having a higher unit GWP. Relative to the reference mortars, total GWP increased by approximately 0.2–0.5% at the 20% replacement level and by approximately 0.5–1.0% at the 40% replacement level. Because RCerFA and RConFA share an identical GWP factor per kilogram (Table 1), their contribution to total GWP is essentially the same at a given replacement level, and the two materials are therefore not distinguishable on the basis of carbon footprint alone. Thus, aggregate replacement did not directly reduce the calculated production-stage GWP, although it reduced natural-sand consumption and supported waste valorization.

The obtained results indicate that the cement type had a considerably greater influence on the environmental performance of mortars than the partial replacement of natural aggregate with recycled materials. Nevertheless, the use of recycled aggregates contributes to improved resource efficiency and waste management while maintaining low additional environmental burdens.

For mixtures in which 25% of the cement binder was replaced with recycled ceramic or concrete material (Figure 9), the total carbon footprint decreased proportionally across all investigated cement types: from 0.149 to 0.113 kg CO_2 eq/kg of mortar for CEM I 42.5 R (24.6% reduction), from 0.111 to 0.084 kg CO_2 eq/kg of mortar for CEM II/A-M (S-LL) 52.5N (24.4%), from 0.134 to 0.101 kg CO_2 eq/kg of mortar for CEM II/A-LL 42.5 R (24.5%), and from 0.073 to 0.056 kg CO_2 eq/kg of mortar for CEM V/A (S–V) 42.5 N (24.1%). This consistent reduction, closely matching the 25% substitution level, reflects the negligible GWP contribution of the recycled materials themselves (Table 1) such that the carbon footprint scales almost linearly with the remaining cement content. This indicates that partial cement replacement produced a substantially larger calculated reduction in A1–A3 GWP than aggregate replacement (Figure 8), which caused only slight GWP increases. However, this comparison does not demonstrate equivalent mechanical performance, durability, or service life of the cement-replacement mortars.

4. Discussion

The obtained results confirmed that the performance of mortars containing recycled fine aggregates strongly depended on the replacement level, aggregate type, and cement composition. Moderate incorporation of recycled materials generally preserved satisfactory mechanical performance and freeze–thaw resistance while reducing natural resource consumption and supporting circular use of construction and demolition waste. Similar observations regarding the beneficial effect of moderate recycled aggregate replacement levels have been reported in previous studies investigating freeze–thaw durability of recycled mortars and concretes [56,57].

The physical characterization of the investigated aggregates demonstrated that both recycled materials exhibited lower bulk density values than natural sand, suggesting differences in particle morphology and packing behavior. In addition, the differences in loose and tapped bulk density between RCerFA and RConFA (Section 3.2) may reflect differences in particle packing and rearrangement; however, the relatively favorable behavior observed for mixtures containing 20% RCerFA cannot be directly attributed to higher porosity or internal curing because these properties were not measured. Previous studies demonstrated that ceramic fines may improve particle packing and reduce pore connectivity due to filler effects and matrix densification [23,58]. At the same time, recycled fine aggregates are generally characterized by increased porosity and water absorption, which may negatively affect pore structure development and freeze–thaw resistance [42,59,60].

The mechanical strength results demonstrated that mortars containing recycled concrete fine aggregate generally maintained relatively stable compressive and flexural strength values, particularly at the 20% replacement level. In contrast, increasing the RCerFA replacement level to 40% caused a substantial reduction in mechanical performance, especially for mixtures prepared with CEM II/A-LL 42.5 R cement. This deterioration may adversely affect the interfacial transition zone and mortar compactness. This suggests that within the tested range, 20% RCerFA provided a more favorable balance than 40%. In contrast, the more stable performance of RConFA up to 40% may reflect the characteristics of concrete-derived fines, including their residual cement paste content and predominantly inert filler effect. Similar trends were reported in studies indicating that excessive amounts of recycled ceramic material may negatively affect matrix compactness and mechanical stability [41,61].

The freeze–thaw resistance results further confirmed the significant influence of recycled aggregate type and replacement level on mortar durability. Mixtures containing 20% recycled aggregate frequently maintained high residual compressive strength values even after prolonged freeze–thaw exposure. Similar observations have been reported for mortars and concretes incorporating moderate amounts of recycled ceramic and concrete fines [43]. In selected cases, the compressive strength after freeze–thaw exposure remained comparable to the reference values. This behavior may be associated with continued hydration of unhydrated clinker phases. In addition, the porous structure of recycled ceramic particles may contribute to internal curing effects by gradually releasing absorbed water and supporting further hydration and local pore refinement, as also suggested for clay-burnt brick fines in cementitious mortars [62].

The strength retention results remained relatively high for most mixtures, indicating acceptable structural stability during freeze–thaw exposure. However, clear deterioration was observed for mixtures containing 40% recycled ceramic aggregate. Previous studies demonstrated that increased porosity and water absorption of recycled aggregates intensify freeze–thaw degradation by promoting internal ice pressure development and progressive microstructural damage [63]. Similar degradation mechanisms were observed in the present study, where several mixtures containing high ceramic aggregate content experienced severe damage after relatively limited freeze–thaw exposure.

The strength-based activity indices did not demonstrate consistently superior behavior of either recycled material. Only the 25%_CON_CEM_II/A-LL_42.5R mixture exceeded the 75% compressive strength index criterion, reaching 78%. However, in the absence of an inert-filler control and independent reaction measurements, this result cannot be interpreted as confirmation of chemical pozzolanic reaction. The obtained indices should therefore be interpreted as indicators of the overall strength contribution of the recycled materials, reflecting dilution, particle-packing, filler effects, and any possible chemical reactivity. In contrast, when the recycled materials were used as aggregate replacements, their coarse particle size contributed to matrix packing without requiring chemical reactivity. This

indicates that the appropriate replacement pathway-aggregate or binder-depends on the intended mechanism of action of the recycled material [23,64].

The SEM observations revealed that mortars containing recycled ceramic material exhibited homogeneous matrix morphology and continuous particle distribution. In contrast, mortars containing recycled concrete material showed a more heterogeneous structure with visible remnants of old hydrated cement paste and locally increased pore content. Similar microstructural characteristics of recycled concrete fines and ceramic waste particles were previously reported in studies concerning recycled cementitious materials and recycled aggregate mortars [27,29,65]. The relatively compact matrix observed in selected RCerFA mixtures should be interpreted only as a qualitative morphological observation, and in the absence of an unmodified reference specimen, EDS, thermal analysis, or another independent reaction measurement cannot be attributed to chemical pozzolanic reaction.

The environmental assessment demonstrated that cement type had a substantially greater influence on the total carbon footprint than the incorporation of recycled aggregates. The lowest GWP values were obtained for mixtures prepared with CEM V/A (S–V) 42.5 N cement due to the reduced clinker content and increased proportion of mineral additions. Nevertheless, although recycled aggregate incorporation slightly increased the calculated production-stage GWP, it contributed to improved resource efficiency and waste valorization with only limited additional environmental burden. Similar conclusions were reported in previous LCA studies focused on recycled cementitious composites and recycled aggregate mortars [66,67].

Overall, the obtained results indicate that low-carbon cements provide the primary mechanism for reducing production-stage GWP, while recycled fine aggregates support natural-resource conservation and waste valorization. However, the replacement level should be carefully controlled to avoid excessive deterioration of mechanical performance and freeze–thaw resistance, particularly in mixtures containing high amounts of recycled ceramic aggregate. Considering the combined mechanical and environmental performance up to 100 freeze–thaw cycles, mortars containing 20% recycled aggregate and CEM V/A showed a potentially favorable short-term balance. The low GWP of these mixtures resulted primarily from the use of CEM V/A rather than from recycled aggregate incorporation. However, their relatively low strength-retention coefficients after 100 cycles and complete disintegration before 150 cycles indicate that their freeze–thaw resistance requires further verification.

It should also be noted that the mixing water content was kept constant across all compositions, without pre-saturation or absorption-based correction of the recycled aggregates. Given their higher water absorption relative to natural sand, this may have introduced variation in the effective water-to-cement ratio between mixtures, which should be considered when interpreting the reported strength and durability comparisons. Furthermore, this preliminary study did not include detailed chemical, mineralogical, or physical characterization of the recycled materials (e.g., XRD, XRF, specific gravity, water absorption, or fines content). Such analyses, together with a volumetric rather than mass-based mixture design, are recommended as a follow-up investigation to further elucidate the mechanisms underlying the observed performance differences. Additionally, the microstructural analysis was limited to qualitative SEM observations. Complementary techniques such as energy-dispersive X-ray spectroscopy (EDS) or thermal analysis (TGA/DSC) were not performed in this preliminary study and are recommended for future work to quantitatively confirm the phase composition of the reaction products. In addition, the pozzolanic potential assessment did not include an inert-filler control or an independent reaction measurement (e.g., calorimetry, bound-water content) to isolate dilution and physical packing effects from genuine pozzolanic reactivity. The reported strength ratios should therefore be

interpreted as an overall strength-contribution indicator rather than a confirmed measurement of chemical pozzolanic reaction, consistent with the revised interpretation presented in Section 3.5. Similarly, the SEM observations remained qualitative. Although the embedded scale bars allow approximate estimation of feature sizes, no systematic quantitative image analysis (e.g., automated pore-area quantification) was performed. Finally, SEM observations did not include an unmodified reference specimen (0% replacement) for direct microstructural comparison. This is recommended for future work. The present study focused primarily on freeze–thaw durability, mechanical performance, pozzolanic potential, and environmental assessment. Additional investigations concerning chloride penetration, carbonation resistance, shrinkage behavior, long-term durability, and detailed microstructural characterization would provide a more comprehensive understanding of the applicability of recycled fine aggregates in durable low-carbon cementitious composites.

5. Conclusions

This study evaluated the influence of recycled ceramic fine aggregate (RCerFA) and recycled concrete fine aggregate (RConFA) on the mechanical performance, freeze–thaw durability, pozzolanic potential, and environmental impact of low-carbon cement mortars prepared with different cement types. The obtained results demonstrated the following.

- Moderate replacement of natural sand with recycled fine aggregates (20%) generally preserved satisfactory mechanical performance and freeze–thaw resistance.
- Mortars containing recycled concrete fine aggregate exhibited more stable freeze–thaw performance than mixtures with recycled ceramic aggregate at the 40% replacement level.
- High ceramic aggregate content (40%) substantially reduced mechanical performance and accelerated freeze–thaw deterioration.
- Neither recycled material demonstrated confirmed pozzolanic reactivity in its unground condition. Only the 25%_CON_CEM_II/A-LL_42.5R mixture exceeded the 75% compressive strength index criterion, although this result alone does not confirm chemical pozzolanic reaction. Further testing using ground materials, an inert-filler control, and independent reaction measurements is required.
- Cement type had a greater influence on the total carbon footprint than recycled aggregate incorporation, with the lowest GWP values obtained for low-clinker blended cements. Aggregate replacement caused only a slight increase in the calculated GWP (below approximately 1%), while reducing natural-sand consumption and supporting waste valorization. In contrast, the 25% cement-replacement scenarios reduced the calculated A1–A3 GWP by approximately 24%, although the environmental significance of this reduction requires verification using performance-equivalent functional units.

The findings confirm the potential applicability of recycled fine aggregates in sustainable low-carbon cement mortars and support circular economy strategies based on the reuse of construction and demolition waste. The proposed approach may be of particular significance for projects involving a demolition phase. One such potential project could be the modernization of railway infrastructure (including railway stations). Recycled materials obtained from the demolition or modernization of railway stations may potentially be reused in new cementitious composites as part of a closed-loop material cycle. The proposed materials may also be used in building construction projects that include a demolition phase. Further studies should include detailed microstructural characterization and long-term durability assessment of mortars containing recycled fine aggregates.

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Abbreviations

The following abbreviations are used in this manuscript.

GWP	global warming potential
LCA	life cycle assessment
PPI	pozzolanic potential index
RCerFA	recycled ceramic fine aggregate
RConFA	recycled concrete fine aggregate

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