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# Mechanical and Hygrothermal Evaluation of Eco-Friendly Cement Mortar Incorporating Upcycled Low-Density Polyethylene

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## Abstract

This study examined the mechanical and hygrothermal response of cement mortars incorporating recycled low-density polyethylene (LDPE) as a partial replacement of fine aggregate at levels of 2.5%, 5.0%, and 7.5% by weight of sand. A reference mixture without polymer was also prepared. The experimental program included determining density, workability, and compressive strength at 7 and 28 days. Based on the mechanical results, the formulation containing 2.5% LDPE was selected for further hygrothermal assessment in 1:5 scale chambers coated with conventional and modified mortars. The incorporation of LDPE progressively decreased both density and compressive strength. At 28 days, the reference mortar reached 5.243 MPa, whereas the mixture with 2.5% LDPE attained 1.461 MPa. Hygrothermal monitoring showed no substantial improvement in indoor temperature regulation; however, the LDPE-modified coating maintained higher indoor relative humidity than the conventional system during the test period. These results indicate that recycled LDPE can be incorporated into cement-based mortars at low replacement levels for exploratory non-structural applications. However, the resulting decrease in mechanical strength restricts its wider applicability and highlights the necessity for further verification to satisfy performance standards tailored to specific applications.

**Keywords:** cement mortar; low-density polyethylene; recycled plastic waste; fine aggregate replacement; compressive strength; hygrothermal behavior

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## 1. Introduction

The construction industry is recognized as one of the major contributors to environmental degradation worldwide, mainly due to intensive natural resource consumption, high energy demand, and large waste generation [1]. Consequently, this issue has encouraged the development of strategies aimed at improving sustainability in the construction sector, resulting in a growing body of research focused on reducing the environmental impact of construction materials and methods [2,3].

Among the various strategies, utilizing alternative raw materials sourced from waste streams has emerged as a viable method to maintain the functional performance of conventional materials while decreasing reliance on non-renewable resources [4,5]. In this regard, substituting a portion of traditional components with those derived from waste has become significant as a practical means to promote the principles of a circular economy in construction [6–8].

Recent studies have shown that plastic waste can be incorporated into cement-based materials as a partial replacement for natural aggregates, thereby reducing the demand for virgin mineral resources and diverting large amounts of plastic from landfills and the environment [9–11].

Different types of recycled polymers, including polyethylene terephthalate (PET), polypropylene (PP), and high-density polyethylene (HDPE), have been investigated in mortars and concretes, with results indicating that density, water absorption, thermal conductivity, and mechanical performance are strongly influenced by polymer type, particle size, replacement ratio, and mixture design [12–15]. In general, low replacement ratios may yield acceptable performance in non-structural applications, whereas higher replacement levels tend to reduce strength and stiffness due to the lower rigidity of plastic particles and their limited adhesion to the cementitious matrix [11,16].

Previous research has reported that cementitious composites containing recycled plastic aggregates may retain certain functional properties while exhibiting reduced compressive strength. For instance, mortar blends that utilized plastic bag waste as a substitute for sand demonstrated a reduction in compressive strength ranging from approximately 18% to 23% when the replacement ratios were between 10% and 20%.

These mixtures also showed enhanced resistance to chloride infiltration and acid damage [17]. Likewise, mortars incorporating recycled polypropylene as a partial fine aggregate replacement maintained satisfactory compressive strength at lower substitution levels; however, higher proportions led to a significant decrease in mechanical performance [18].

Studies on geopolymer mortars incorporating plastic waste have also shown that increasing polymer content may reduce compressive strength due to increased internal porosity, although optimized formulations can still provide useful engineering performance [19]. In addition, mortars incorporating recycled plastic aggregates derived from ABS and waste electrical and electronic equipment have shown reductions in compressive and flexural strength as replacement ratios increase, although their performance may remain suitable for selected applications, depending on mixture composition and intended use [20].

The growing interest in plastic reuse is closely linked to the scale of the global plastic production and waste management problem. In 2022, global plastic production amounted to around 400.3 million metric tons, indicating ongoing expansion in the production of materials utilized for packaging, construction, transportation, electronics, and consumer goods [21,22].

Despite the versatility and economic value of plastics, post-consumer recovery rates remain low, and less than 10% of plastic waste is effectively recycled at the global level, while the remainder is landfilled, incinerated, or released into terrestrial and aquatic environments, contributing to long-term ecological damage and microplastic pollution [21,23,24].

As a result, plastic pollution has become a major environmental, economic, and public health challenge, reinforcing the need for practical reuse pathways that reintroduce waste materials into productive value chains [21,25,26].

Within this framework, material reuse has become a key strategy of the circular economy because it reduces the extraction of virgin resources, limits waste generation, and extends the service life of products and materials [27]. In the case of plastics, the development of reuse and recycling routes, together with improved product design and thermomechanical processing, has enabled their incorporation into new engineering applications, including building materials [3,23,28–32].

In cement-based systems, this approach is particularly attractive because mortars and concretes are widely used materials with high aggregate demand, making them suitable candidates for the valorization of selected waste streams [9,33,34].

The incorporation of recycled plastics into mortar can modify key physical and functional properties, including density, workability, moisture-related behavior, and thermal response, while often reducing mechanical strength relative to conventional formulations [11,33,35].

From an application standpoint, these changes may be disadvantageous for structural uses but potentially beneficial for lightweight, non-load-bearing, or coating systems, where reduced density and altered hygrothermal performance may be of practical interest. The impact of low-density polyethylene (LDPE) waste, particularly from post-consumer bags, has been less extensively documented than that of PET or PP. This is especially true when examining both mechanical and hygrothermal properties together in mortars designed for coating or rendering purposes.

Therefore, this study evaluates the use of recycled low-density polyethylene (LDPE) as a partial replacement of fine aggregate in cement mortar. The research examines the effects of LDPE incorporation on density, workability, compressive strength, and hygrothermal behavior using mortar mixtures prepared with different replacement ratios. Attention is given to the response of the modified mortar under non-structural conditions relevant to coating applications, including its influence on moisture retention and indoor thermal response in scaled masonry chambers. The working hypothesis is that low LDPE replacement ratios may reduce density and alter moisture-related behavior while still preserving a minimum level of performance suitable for exploratory non-structural applications.

## 2. Materials and Methods

### *2.1. Raw Materials*

The experimental program was conducted using blended Portland cement CPC 30R RS, hydrated lime, quartz sand with rounded particles, potable water, and recycled low-density polyethylene (LDPE) obtained from post-consumer commercial plastic bags. Quartz sand was selected as the reference fine aggregate because of its mineral stability, availability, and suitability for mortar production.

The recycled LDPE was selected owing to its wide availability, low density, chemical stability, and potential for reuse in non-structural cement-based applications.

Prior to use, the quartz sand was dried on an electric heating plate for 1.5 h until it was dry and loose. Its particle-size distribution was determined by sieve analysis using standard sieves from No. 4 to No. 200, following NMX-C-077-1997-ONNCCE. The quartz sand had a maximum particle size smaller than 4.75 mm and a fineness modulus of 3.087. The particle-size distribution of the quartz sand is presented in Table 1, and its grading curve is shown in Figure 1.

**Table 1.** Particle size distribution of quartz sand.

| Sieve | Opening (mm) | Mass retained (g) | Retained (%) | Cum. Retained (%) | Passing (%) | NMX lower limit | NMX upper limit |
|---|---|---|---|---|---|---|---|
| #4 | 4.75 | 72.2 | 4.81 | 4.81 | 95.19 | 95 | 100 |
| #8 | 2.36 | 257.4 | 17.16 | 21.97 | 78.03 | 80 | 100 |
| #16 | 1.18 | 299.3 | 19.95 | 41.93 | 58.07 | 50 | 85 |
| #30 | 0.60 | 382.1 | 25.48 | 67.40 | 32.60 | 25 | 60 |
| #50 | 0.30 | 193.9 | 12.93 | 80.33 | 19.67 | 10 | 30 |
| #100 | 0.15 | 178.6 | 11.91 | 92.24 | 7.76 | 2 | 10 |
| #200 | 0.075 | 116.4 | 7.76 | 100.00 | 0.00 | 0 | 0 |

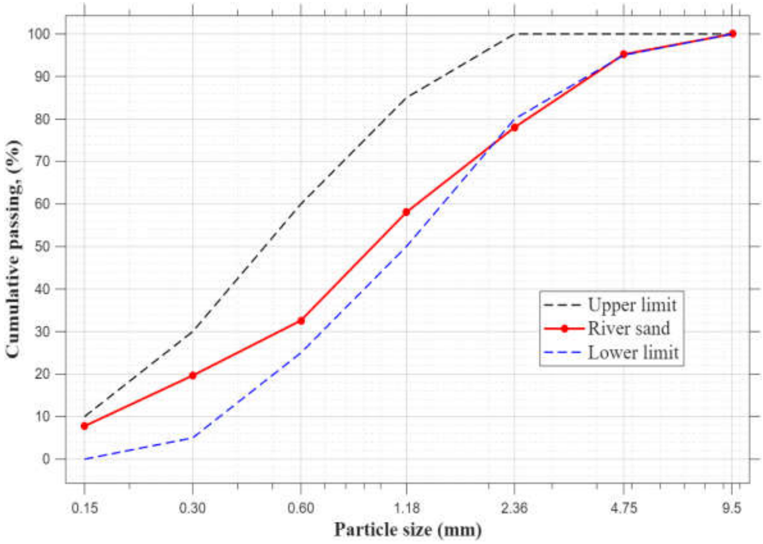

**Figure 1.** Particle size distribution of quartz sand compared with the limits specified in NMX-C-077-ONNCCE.

### 2.2. Processing and Characterization of Recycled LDPE

The recycled plastic fraction consisted of LDPE recovered from discarded commercial bags. The material was manually sorted, washed, and cut using 2½″ steel scissors to produce irregular particles with an area smaller than 0.907 cm². This procedure was selected as a simple mechanical recycling route that could be reproduced under ordinary laboratory conditions. The processing of the LDPE particles is illustrated in Figure 2.

**Figure 2.** Crushed recycled low-density polyethylene (LDPE) used as partial fine aggregate replacement in mortar. **(a)** General view of the material with particle size < 0.90 cm. **(b)** Particle detail showing irregular geometry, smooth surfaces, and characteristic size distribution.

After cutting, the material was manually sieved to determine its particle-size distribution and to compare it with that of the quartz sand used in the reference mortar. According to the manufacturer, the LDPE had a density of 0.94 g/cm³, a tensile strength of 25 MPa, an elongation at break of 500%, a Young’s modulus of 0.30 GPa, and a melting temperature of 115 °C. These properties are summarized in Table 2.

Because the physical and granulometric characteristics of recycled plastic particles strongly influence packing, internal voids, and interfacial interaction within cement-based composites, the preparation and characterization of the polymeric fraction were treated as critical stages of the experimental program [36,37].

**Table 2.** Physical properties of recycled LDPE waste plastic.

| Thickness (μm) | Density (g/cm³) | Tensile strength (MPa) | Elongation at break (%) | Young's modulus (GPa) | Melting temperature (°C) |
|---|---|---|---|---|---|
| 20 | 0.94 | 25 | 500 | 0.30 | 115 |

### *2.3. Mixture Design and Preparation of Mortar Specimens*

The reference mortar was proportioned considering a target compressive strength of 40 kg/cm², which was considered appropriate for the exploratory non-structural application assessed in this study.

The control mixture was prepared with a cement:sand:water ratio of 1:3:0.5 by weight. Recycled LDPE particles were incorporated as a partial replacement of fine aggregate by weight of sand at replacement ratios of 2.5%, 5.0%, and 7.5%, while a control mixture without LDPE was also produced. The mixture proportioning was established considering NMX-C-486-ONNCCE-2014 as a reference framework for mortar design.

For specimen preparation, cement and quartz sand were first dry-mixed for 3 min until a uniform appearance was obtained. The required quantity of recycled LDPE was then gradually incorporated according to the selected replacement ratio, followed by the addition of water. Mixing continued for an additional 3 min to ensure adequate homogenization. Fresh mortar was cast into metallic molds with three 50 mm cubic cavities, and each cavity was filled in two layers compacted with 32 uniformly distributed blows using a steel tamper. The general experimental procedure adopted for mortar preparation, specimen fabrication, and subsequent testing is summarized in Figure 3, whereas the molds and cubic specimens are shown in Figure 4.

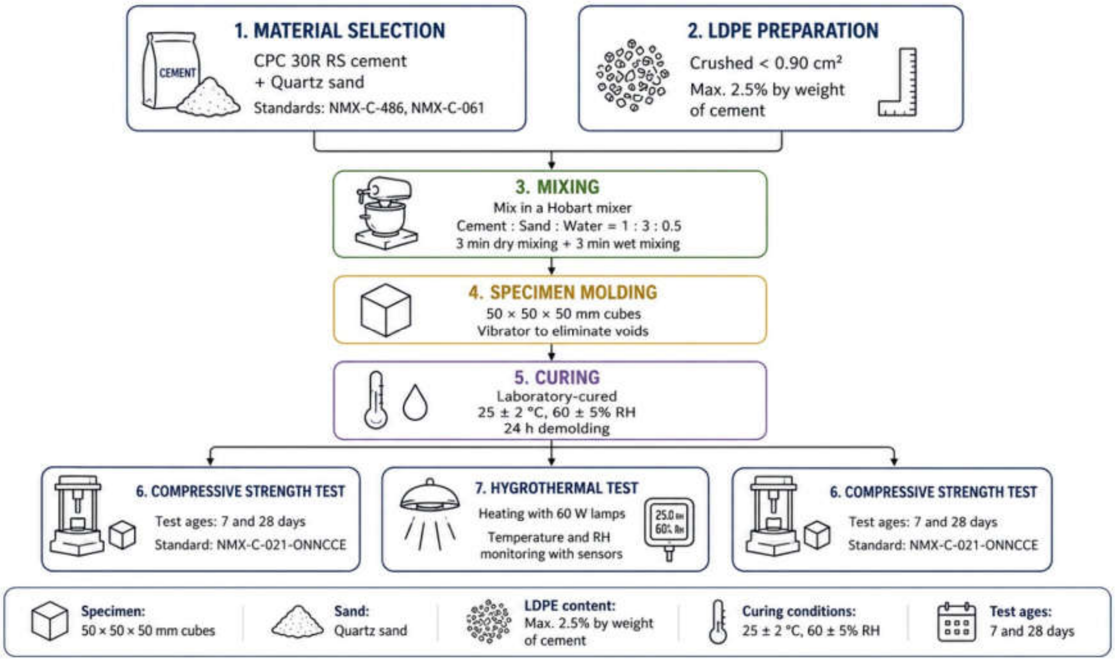

**Figure 3.** Experimental procedure for evaluating LDPE-modified mortars.

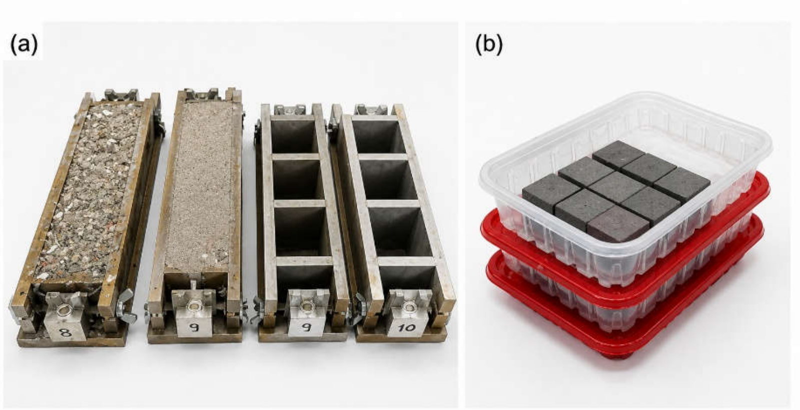

**Figure 4.** Molds and cubic mortar specimens.

### 2.4. Curing and Compressive Strength Testing

After casting, the specimens remained in the molds for 24 h under laboratory conditions. They were then demolded and cured by immersion in water until the 7- and 28-day testing ages. This curing regime was adopted because it provides adequate moisture availability for hydration and reduces variability in strength development among mixtures. For each LDPE replacement ratio and curing age, three cubic specimens were prepared and tested. Specimen preparation and compressive strength testing were performed in accordance with NMX-C-061-ONNCCE and NMX-C-021-ONNCCE for 50 mm cubic specimens.

Compressive tests were performed using a Controls hydraulic compression machine (model C43C04) with a capacity of 2000 kN and a loading surface of 31,415.9 mm². Each specimen was centered between the loading platens, and a compressive load was applied continuously at 1.8 MPa/s until failure. The compression testing setup is shown in Figure 5.

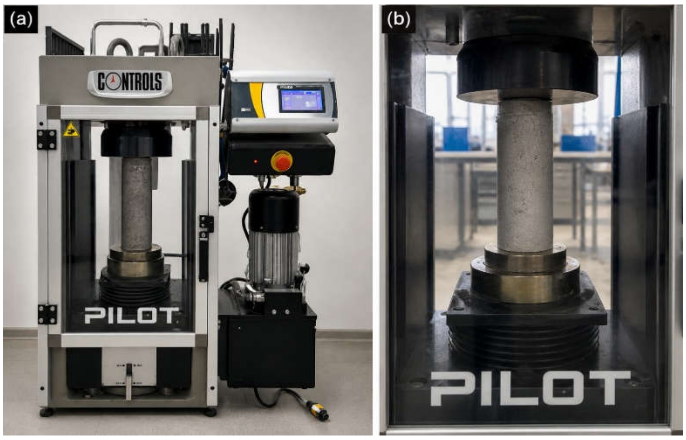

**Figure 5.** Hydraulic compression machine used for mortar testing.

### 2.5. Construction of 1:5 Scale Chambers and Hygrothermal Monitoring

To evaluate the functional response of the selected mortar under controlled hygrothermal conditions, two 1:5 scale chambers were constructed using fired clay bricks cut to scaled dimensions with an electric grinder fitted with a concrete-cutting disc.

Before cutting, the bricks were moistened to reduce dust generation. The masonry units were assembled on reinforced-concrete tables using a 1:5 masonry mortar, with an average joint thickness of 1.43 cm. Seven brick courses were placed to reach a total height of 45 cm, representing a scaled version of a typical low-rise room. The construction and coating stages of the scaled chambers are presented in Figure 6.

**Figure 6.** Construction and coating of the scaled chambers.

To simulate the roof system, prefabricated reinforced concrete slabs measuring 60 × 80 × 5 cm were produced using concrete with a nominal compressive strength of 250 kg/cm$^2$ and No. 2 wire reinforcement.

After completion of the masonry walls, the interior surfaces of one chamber were coated with conventional mortar, whereas the second chamber was coated with the mortar containing 2.5% LDPE as a partial replacement of fine aggregate by weight of sand. In both chambers, the coating mortar was applied to both sides of the wall, with an average thickness of 7 mm. Glass windows and plywood doors were then installed to complete the experimental chambers for hygrothermal monitoring.

The hygrothermal behavior of the coated chambers was evaluated under controlled heating conditions using two 60 W incandescent lamps as internal heat sources. Indoor and outdoor temperature and relative humidity were monitored using three Extech 445580 sensors and one Mannix SAN99DDW sensor. Measurements were recorded every 2 min for 90 min while the lamps remained on, followed by an additional 20 min after the heat source was switched off. The sensors used for temperature and relative humidity monitoring are shown in Figure 7.

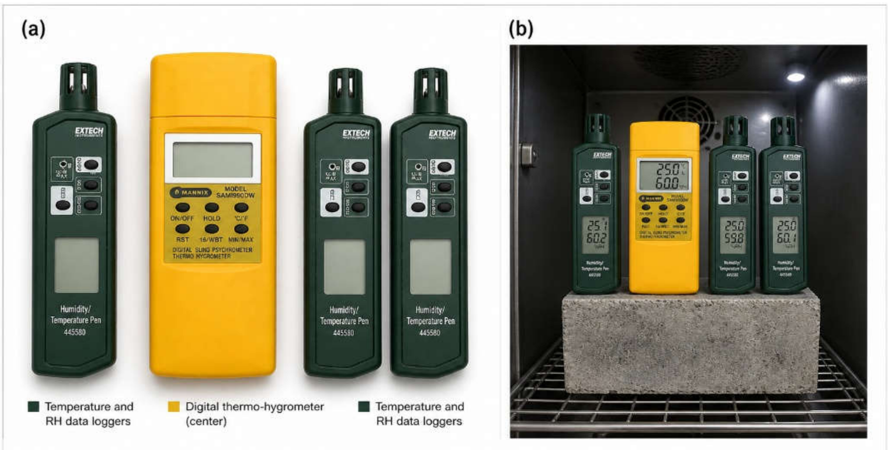

**Figure 7.** Temperature and relative humidity monitoring instruments used during the hygrothermal test.

(a) Instrumentation overview showing the digital thermo-hygrometer (center) and portable temperature and humidity data loggers.

(b) In-situ installation of the devices within the scaled chamber during exposure.

*Note: T = temperature; RH = relative humidity*

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This procedure enabled a direct comparison of the hygrothermal response of chambers coated with conventional and LDPE-modified mortar under controlled heating and cooling conditions.

### 2.6. Workability Assessment

Fresh-state consistency was evaluated immediately after mixing using a slump test. The test was performed on the control mortar and on the mixture containing 2.5% LDPE, which was later selected for chamber-scale application. Slump values were recorded in centimeters as an indicator of workability and flow behavior.

This comparison was intended to determine whether LDPE incorporation altered the fresh rheological response of the mortar and to verify that the selected mixture remained sufficiently workable for coating application.

### 2.7. Data Treatment

Experimental results were expressed as mean values, and standard deviations were calculated for compressive strength results. Density reduction and normalized compressive strength were determined relative to the control mixture to facilitate comparison among replacement levels.

The hygrothermal assessment was based on the time evolution of indoor temperature, ambient temperature, indoor relative humidity, and the corresponding chamber-to-ambient differences. Because of the exploratory character of the study and the limited number of specimens per condition, the results were interpreted primarily through descriptive comparison of trends and average values.

## 3. Results

The results obtained from the granulometric characterization of the materials, mass variation, compressive strength, mortar consistency, and hygrothermal behavior of the scaled chambers are presented in this section. The analysis focuses on identifying the mechanical and hygrothermal effects of partially replacing sand with LDPE.

### 3.1. Granulometric Characterization of the Materials

The particle-size distribution of the recycled LDPE particles was determined to compare their grading characteristics with those of the previously described natural fine aggregate. The results show a markedly different granulometric profile from that of the quartz sand used in the reference mortar (see Table 3).

**Table 3.** Particle size distribution of recycled LDPE particles.

| Sieve | Opening (mm) | Mass retained (g) | Retained (%) | Cum. Retained (%) | Passing (%) |
|---|---|---|---|---|---|
| #4 | 4.75 | 6.5 | 2.17 | 2.17 | 97.83 |
| #8 | 2.36 | 219.4 | 73.28 | 75.45 | 24.55 |
| #16 | 1.18 | 62.0 | 20.71 | 96.16 | 3.84 |
| #30 | 0.60 | 9.6 | 3.21 | 99.37 | 0.63 |
| #50 | 0.30 | 1.6 | 0.53 | 99.90 | 0.10 |
| #100 | 0.15 | 0.2 | 0.07 | 99.97 | 0.03 |
| #200 | 0.075 | 0.1 | 0.03 | 100.00 | 0.00 |

The LDPE particles were concentrated mainly within the intermediate size ranges, particularly in sieve No. 8 (2.36 mm), where approximately 73% of the material was retained.

This result indicates that the plastic fraction exhibits a coarser and less continuous grading than the natural aggregate. Likewise, the proportion of fine particles smaller than 0.60 mm was extremely low, accounting for less than 1% of the total mass analyzed.

A graphical comparison of the two materials (see Figure 8) clearly shows that LDPE occupies a narrower particle-size range and lacks the finer fractions that promote efficient particle packing in conventional mortars.

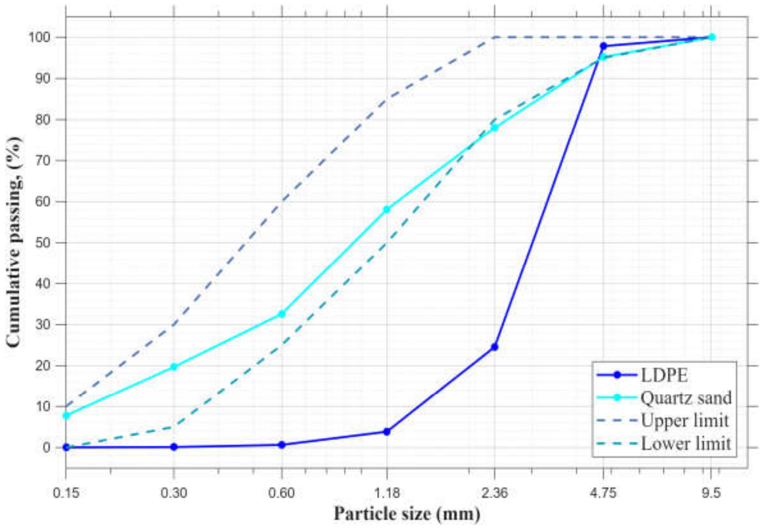

**Figure 8.** Particle size distribution of quartz sand and recycled LDPE.

From a microstructural standpoint, this incompatibility in particle-size distribution may lead to a less efficient granular skeleton when LDPE partially replaces the natural aggregate. The scarcity of fine particles may increase the internal void content and weaken the interfacial transition zone between the polymeric particles and the cementitious matrix. This behavior provides a plausible explanation for the subsequent reduction in compressive strength observed in the modified mortars.

### *3.2. Variation in Specimen Mass*

The average density of the mortar specimens decreased progressively with increasing LDPE sand replacement ratio, confirming the lightweighting effect of the recycled polymer (Table 4 and Figure 9).

The control mortar exhibited the highest density, with an average value of 1.661 g/cm³, whereas the mixtures containing 2.5%, 5.0%, and 7.5% LDPE reached average densities of 1.483, 1.389, and 1.205 g/cm³, respectively. These values represent density reductions of 10.71%, 16.37%, and 27.43% relative to the mortar without replacement.

This trend is directly associated with the lower specific mass of LDPE compared with quartz sand, leading to a systematic reduction in the apparent density of the hardened mortar as the polymer content increases. The decrease was evident even at the lowest replacement level, indicating that small amounts of LDPE are sufficient to modify the internal structure of the material.

**Table 4.** Average mass, density, and density reduction of mortar specimens with LDPE replacement.

| LDPE (%) | Average Weight (g) | Average density (g/cm³) | Density reduction (%) |
|---|---|---|---|
| 0.0 | 207.62 | 1.661 | 0.00 |
| 2.5 | 185.38 | 1.483 | 10.71 |
| 5.0 | 173.63 | 1.389 | 16.37 |
| 7.5 | 150.68 | 1.205 | 27.43 |

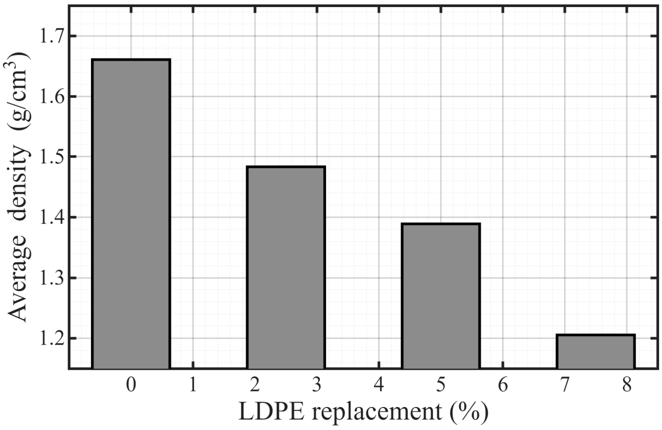

**Figure 9.** Average density of mortar specimens as a function of the LDPE replacement ratio.

The nearly monotonic reduction in density also suggests that LDPE's effect on the mortar's physical behavior remained stable within the studied range. From an application standpoint, this reduction may be advantageous in non-structural systems where lower self-weight is desirable, such as coatings or rendering mortars. The reduction in density indicates a less dense internal composition, which could lead to the observed decline in compressive strength in the LDPE-modified mixtures.

### *3.3. Compressive Strength and Selection of the Optimum LDPE Replacement Ratio*

The incorporation of LDPE as a partial replacement for quartz sand produced a substantial reduction in compressive strength at both curing ages (Table 5 and Figure 10).

The control mortar exhibited the highest compressive strength, reaching 1.706 MPa at 7 days and 5.243 MPa after 28 days. In comparison, all mixtures modified with LDPE displayed significantly reduced strength values, suggesting that the inclusion of polymer adversely impacted the mortar's mechanical performance.

At 7 days, compressive strength decreased progressively from 0.765 MPa for the mixture containing 2.5% LDPE to 0.598 MPa for 5% LDPE and 0.395 MPa for 7.5% LDPE, indicating a clear reduction in early-age strength as the replacement ratio increased.

**Table 5.** Average compressive strength of mortar specimens at 7 and 28 days.

| LDPE (%) | Strength 7 days (MPa) | SD | Strength 28 days (MPa) | SD |
|---|---|---|---|---|
| 0 | 1.706 | 0.405 | 5.243 | 0.673 |
| 2.5 | 0.765 | 0.090 | 1.461 | 0.265 |
| 5 | 0.598 | 0.036 | 1.994 | 0.247 |
| 7.5 | 0.395 | 0.080 | 0.896 | 0.274 |

At 28 days, a comparable overall pattern was noted; however, the mixture that included 5% LDPE achieved a marginally greater strength of 1.994 MPa compared to the mixture with 2.5% LDPE, which recorded 1.461 MPa. Despite this local deviation, the general findings were consistent, with the mixture containing 7.5% LDPE registering the weakest strength at 0.896 MPa.

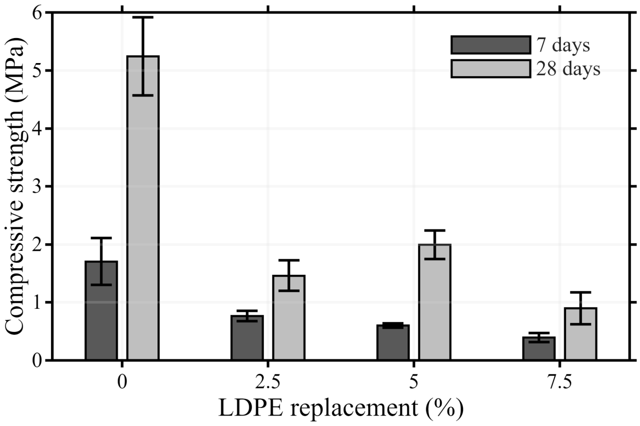

**Figure 10.** Compressive strength of mortars with different LDPE replacement ratios at 7 and 28 days (mean ± standard deviation, n = 3).

The normalized strength results further confirmed the magnitude of the mechanical loss (Table 6 and Figure 11). At 7 days, the modified mortars retained only 45%, 35%, and 23% of the control strength for replacement ratios of 2.5%, 5.0%, and 7.5% LDPE, respectively. At 28 days, the respective values were 28%, 38%, and 17%, suggesting that the loss in mechanical performance remained evident after 28 days of curing.

Overall, the findings indicate that the inclusion of LDPE consistently led to a decrease in compressive strength. This reduction can be linked to the polymer's low stiffness, insufficient bonding with the cement matrix, and alterations in the granular structure of the mortar. While a slight improvement was noted in the mixture containing 5% LDPE at 28 days, the general trend supports the conclusion that higher LDPE levels result in a decline in mechanical performance.

**Table 6.** Normalized compressive strength of LDPE-modified mortars relative to the control mixture.

| LDPE (%) | Normalized strength (7 days) | Normalized strength (28 days) |
|---|---|---|
| 0.0 | 1.00 | 1.00 |
| 2.5 | 0.45 | 0.28 |
| 5.0 | 0.35 | 0.38 |
| 7.5 | 0.23 | 0.17 |

Based on the compressive strength results, LDPE incorporation progressively reduced the mortar's mechanical performance as the replacement ratio increased. Although all modified mixtures exhibited lower strength than the control mortar, the mixture containing 2.5% LDPE presented the most favorable compromise between density reduction and residual compressive strength among the formulations evaluated.

Considering both density reduction and residual mechanical performance, the 2.5% LDPE mixture was selected as the most conservative formulation for subsequent exploratory non-structural hygrothermal assessment within the experimental range studied.

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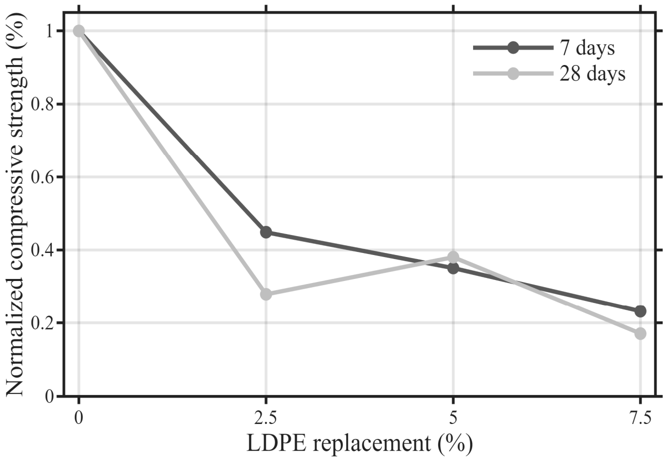

**Figure 11.** Normalized compressive strength of mortars as a function of the LDPE replacement ratio.

### *3.4. Slump of Control and LDPE-Modified Mortars*

The workability of the fresh mortar was evaluated using a slump test. The control mortar exhibited a slump of 17 cm, while the formulation incorporating a 2.5% replacement of sand with LDPE achieved a slump of 19 cm, indicating a slight increase in the workability of the modified mortar (Table 7).

This increase in slump may be associated with the hydrophobic nature of LDPE particles, which absorb less moisture compared to mineral aggregates, promoting greater movement of particles within the fresh mix. Consequently, LDPE incorporation likely reduced internal friction among the solid constituents, enhancing mortar flowability.

**Table 7.** Slump values of the control mortar and the mortar containing 2.5% LDPE.

| Material | Slump (cm) |
|---|---|
| Control mortar | 17 |
| LDPE-modified mortar | 19 |

Although both values slightly exceed the ranges commonly recommended for masonry mortars, the mixtures evaluated in this study were intended for non-structural coating applications, in which greater workability may be beneficial for material placement and surface finishing. Therefore, the observed consistency levels were considered appropriate for this type of application.

However, the findings indicate that optimizing the particle-size distribution of LDPE could strengthen the internal cohesion of the mortar and align its rheological properties more closely with those of conventional materials.

### *3.5. Hygrothermal Performance of Mortar with 2.5% LDPE*

Based on the previously obtained compressive strength results, the 2.5% LDPE mixture was selected as the most conservative formulation for subsequent exploratory non-structural hygrothermal assessment.

The hygrothermal behavior of the scaled chambers coated with conventional and modified mortar was evaluated by continuously monitoring indoor temperature and relative humidity during the thermal test.

The combined evolution of both variables is shown in Figure 12, which presents a direct comparison between the control mortar and the mortar modified with 2.5% LDPE.

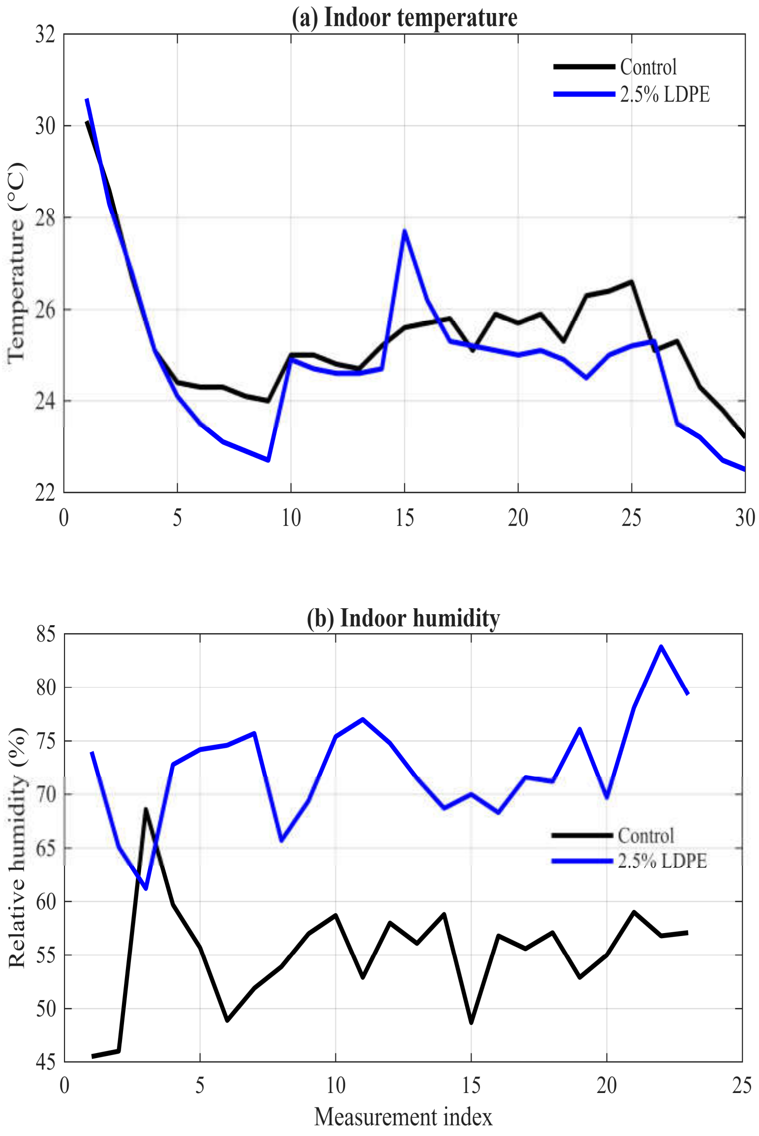

**Figure 12.** Combined evolution of indoor temperature and relative humidity in the control and LDPE-modified chambers during the thermal test.

### 3.5.1. Temperature Evolution Inside the Chambers

The temporal evolution of temperature inside the scaled chambers coated with control mortar and mortar modified with 2.5% LDPE was monitored during the thermal test. The temperature data suggest that both systems exhibited comparable trends during the observation period, characterized by an initial drop in indoor temperature followed by a phase of stabilization (Figure 13).

In the chamber treated with control mortar, the indoor temperature exhibited a rapid decrease during the early measurements, subsequently stabilizing within a range of approximately 24-26 °C for much of the test duration. In contrast, the ambient temperature displayed more fluctuation, peaking at nearly 36 °C around the midpoint of the experiment before declining as the monitoring period concluded.

Comparable temporal behavior was observed in the chamber coated with LDPE-modified mortar. However, the indoor temperature of the LDPE system showed slightly smaller fluctuations and remained relatively stable at 24–26 °C for much of the test. Even though the variations between the two systems were not significant in absolute terms, the LDPE-modified mortar generally exhibited a marginally more consistent indoor thermal response.

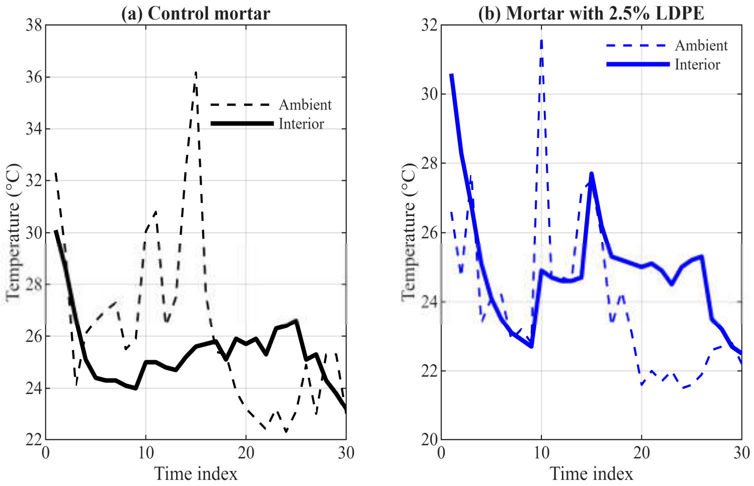

**Figure 13.** Ambient and indoor temperature evolution of the control and LDPE-modified scaled chambers during the thermal test.

The average temperature values recorded during the experiment support this observation (Table 8). The control chamber showed an average ambient temperature of 26.27 °C and an average indoor temperature of 25.41 °C, resulting in a mean indoor-to-ambient temperature difference (ΔT) of −0.86 °C. In contrast, the chamber coated with mortar containing 2.5% LDPE recorded an average ambient temperature of 23.97 °C and an average indoor temperature of 24.90 °C, producing a mean difference of +0.93 °C.

**Table 8.** Summary of average ambient and indoor temperature and relative humidity during the thermal test.

| Variable | Control | 2.5% LDPE |
|---|---|---|
| Average ambient temperature (°C) | 26.27 | 23.97 |
| Average indoor temperature (°C) | 25.41 | 24.90 |
| Average ΔT (°C) | -0.86 | +0.93 |
| Average ambient relative humidity (%) | 30.83 | 23.88 |
| Average indoor relative humidity (%) | 55.25 | 72.53 |
| Average ΔRH (%) | 24.42 | 48.65 |

This result indicates that the LDPE-modified mortar tended to maintain the indoor temperature slightly above the ambient temperature over a greater number of measurement intervals. The temporal evolution of the indoor-to-ambient temperature difference confirms this tendency (Figure 14), with the curve for the mortar with LDPE remaining above the reference line ΔT = 0 more frequently than that of the control mortar.

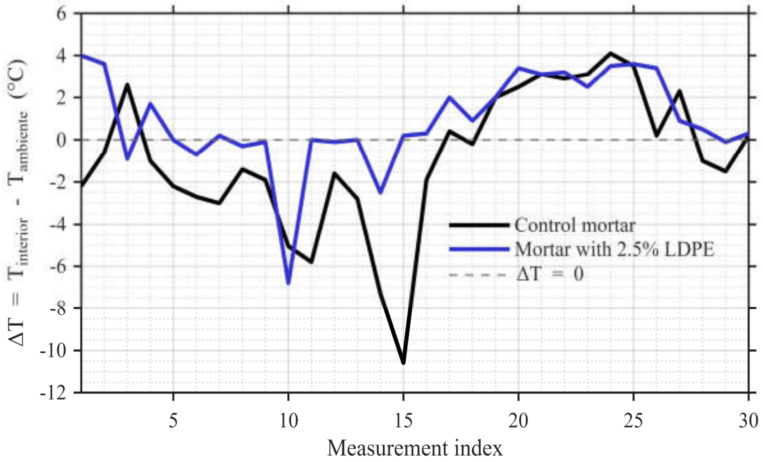

**Figure 14.** Indoor-to-ambient temperature difference (ΔT) of control and LDPE-modified chambers during the thermal test.

Nonetheless, the overall magnitude of the thermal differences observed between the two systems was quite modest. As a result, while the inclusion of LDPE might offer a slight enhancement in the thermal stability of the system, the findings do not indicate a substantial thermal insulation effect given the experimental conditions examined in this study.

### 3.5.2. Relative Humidity Evolution

Unlike thermal behavior, the relative humidity results showed more pronounced differences between the conventional mortar and the mortar modified with 2.5% LDPE.

The temporal evolution of relative humidity inside the chambers is presented in Figure 15. The chamber coated with control mortar showed indoor relative humidity values generally ranging from 49% to 59%, with occasional increases to near 68%. In contrast, the chamber coated with LDPE-modified mortar maintained considerably higher humidity levels throughout the test period, fluctuating approximately between 61% and 84%.

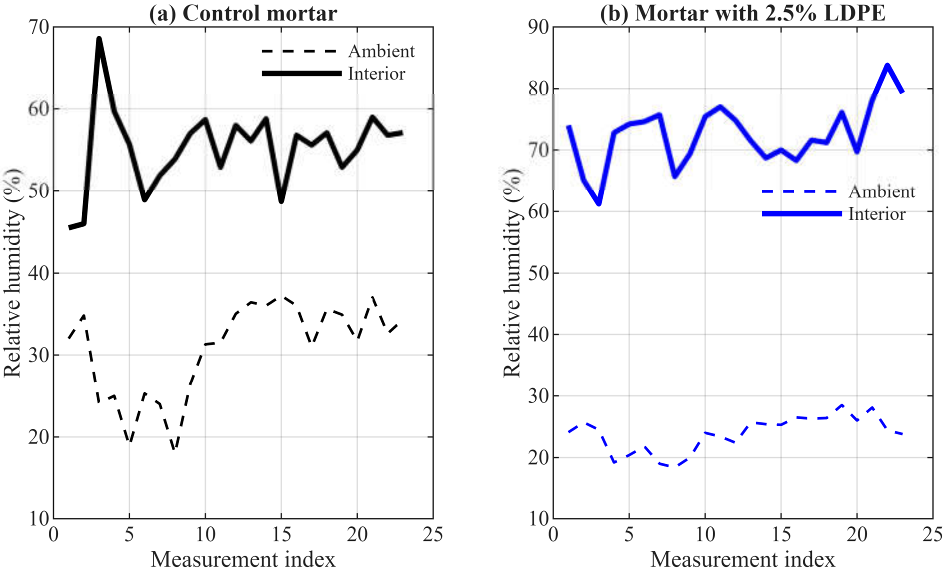

**Figure 15.** Ambient and indoor relative humidity evolution of the control and LDPE-modified scaled chambers during the thermal test.

The average values summarized in Table 8 further highlight this difference. The control chamber exhibited an average indoor relative humidity of 55.25%, whereas the chamber coated with LDPE-modified mortar reached 72.53%. This represents an increase of approximately 17 percentage points in the modified system's indoor relative humidity.

Likewise, the difference between indoor and ambient relative humidity increased significantly. The control system exhibited an average indoor-to-ambient difference of 24.42 percentage points, whereas the LDPE-modified system showed an average difference of 48.65 percentage points, indicating a considerably greater hygrometric gradient in the modified system.

The persistence of higher indoor humidity levels in the LDPE chamber suggests that incorporating this polymer modifies the moisture transport and retention behavior of the mortar. This effect may be related to changes in the material's porous structure and in vapor diffusion mechanisms induced by the presence of polymeric particles within the cementitious matrix.

### 3.5.3. Overall Hygrothermal Response

The combined analysis of temperature and relative humidity results enables the identification of the predominant effect of incorporating 2.5% LDPE on the system's hygrothermal behavior.

Although the temperature differences between the control and modified mortar were relatively small, the LDPE-containing mortar consistently maintained higher indoor relative humidity. This indicates that the addition of LDPE mainly affects processes related to moisture retention and regulation, rather than substantially modifying heat flow through the system.

From a practical perspective, the findings indicate that adding small quantities of recycled LDPE to coating mortars could influence the hygrothermal conditions of interior environments. While the thermal effect noted was modest, the increased moisture-retention ability of the modified mortar may be relevant for the environmental performance of coating and rendering systems. In summary, the data suggest that including 2.5% LDPE results in a noticeable alteration in the hygrothermal properties of the mortar, especially regarding its impact on indoor relative humidity.

## 4. Discussion

The experimental results obtained in this study show that incorporating recycled low-density polyethylene (LDPE) as a partial replacement for fine aggregate significantly modifies the physical, mechanical, and functional behavior of cement mortar. In particular, the presence of polymeric particles led to a progressive reduction in material density, a marked decrease in compressive strength, and measurable changes in the system's hygrothermal response.

These effects are consistent with the general behavior reported for cement-based composites containing recycled plastic aggregates, in which the lower density, lower stiffness, and different surface characteristics of the polymeric phase alter both the granular structure and the matrix–aggregate interaction [12,16,33,38].

The reduction in density observed in the specimens is directly related to the much lower density of LDPE (0.94 g/cm$^3$) compared with conventional mineral aggregates. As the LDPE replacement ratio increased, the average mass and density of the mortar cubes decreased progressively, reaching a maximum density reduction of 27.43% at 7.5% replacement.

This result confirms the lightweighting effect of the recycled polymer within the cementitious matrix and agrees with previous studies on mortars and concretes modified with recycled plastics, where increasing polymer content generally leads to lower density and modified packing behavior [12,16,33,38].

More recent evidence also supports this trend; for example, Nas et al. [39] reported a general decrease in unit weight and compressive strength as plastic aggregate content increased in composite mortars, whereas Houti et al. [40] found that recycled PVC in plaster mortar reduced density and improved thermal-related performance, although with mechanical trade-offs.

However, the reduction in density was accompanied by a substantial decrease in compressive strength. At 28 days, strength losses relative to the reference mortar were approximately 72.13% for 2.5% LDPE, 61.97% for 5% LDPE, and 82.92% for 7.5% LDPE.

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This behavior is consistent with the literature on cementitious materials containing recycled plastic aggregates, where the inclusion of polymeric particles tends to reduce the mechanical capacity of the material because of the low modulus of elasticity of plastics and their limited bond with the cement paste [14,41,42].

The present results also align with recent findings on plastic-containing mortars, in which increasing plastic aggregate content led to a general reduction in compressive strength, even when other variables such as fibers or recycled mineral fractions were present [39].

Several microstructural mechanisms help explain this reduction in strength. First, the elastic modulus of LDPE (≈0.3 GPa) is substantially lower than that of natural mineral aggregates, reducing the efficiency of stress transfer within the hardened mortar. Second, the polymer's hydrophobicity limits interfacial adhesion between plastic particles and the cementitious matrix, favoring weaker interfacial transition zones and increasing internal porosity. Third, the granulometric analysis showed that the LDPE particles differed markedly from the quartz sand in particle-size distribution, likely disrupting particle packing and reducing compactness.

These mechanisms have been widely recognized in previous reviews on recycled plastic aggregates in cementitious composites [11,14]. Recent review work has further emphasized that the intrinsic hydrophobicity of recycled plastic aggregates is a major contributor to weak cement–polymer compatibility, and that surface treatment is often necessary when higher mechanical performance is required [37].

An atypical result was identified in the mixture containing 5% LDPE, which showed slightly higher compressive strength than the 2.5% LDPE mixture at 28 days. While this variation does not alter the general downward trend, it indicates that differences in specimen preparation, compaction, or curing processes might have impacted the outcome.

Similar scatter has been observed in studies involving heterogeneous recycled plastic fractions, where small differences in particle distribution, entrapped air, or interfacial quality can lead to non-monotonic responses at specific dosages [19,39]. Therefore, the 5% mixture should be viewed as an isolated anomaly within a generally consistent mechanical pattern, rather than as proof of a lasting enhancement compared to the 2.5% LDPE.

In terms of fresh-state performance, the mortar with 2.5% LDPE demonstrated a slightly greater slump (19 cm) than the control mortar (17 cm), suggesting enhanced workability. This phenomenon may be linked to the hydrophobic characteristics of the LDPE particles and their reduced water absorption when compared to mineral aggregates, which can lead to decreased internal friction and improved particle movement in the fresh mixture.

Comparable trends have been reported in other cement-based systems modified with recycled polymers, in which certain plastic fractions exert a lubricating effect and alter rheological behavior depending on particle shape, size, and dosage [3,13].

It should be noted, however, that not all recycled polymer systems behave identically; for example, Smarzewski et al. [43] reported that the addition of polymer shot to concrete reduced workability while improving other physical and thermal properties, underscoring that the fresh-state response depends strongly on the geometry and mode of incorporation of the polymeric phase.

The hygrothermal results showed that LDPE had a limited effect on indoor temperature evolution during the thermal test, as both chambers followed broadly similar thermal profiles. In contrast, the chamber coated with LDPE-modified mortar consistently maintained a higher indoor relative humidity, with an average increase of approximately 17 percentage points compared with the control system.

This suggests that the main effect of LDPE incorporation in this study was related to moisture retention and regulation rather than to a strong thermal insulation effect. A plausible explanation is that the polymeric fraction altered the mortar's pore structure and vapor transport pathways, thereby modifying the balance between heat and moisture transfer.

Previous studies have reported that recycled plastic aggregates can reduce thermal conductivity and alter moisture-related behavior in mortars and concretes, although these advantages are often accompanied by mechanical tradeoffs [10,15,16].

Recent plaster-mortar research with recycled PVC has similarly shown that lightweight polymer-modified mortars may improve thermal and hydric performance while maintaining serviceability for non-load-bearing applications, although adhesion and strength still require careful control [40].

From technical and environmental perspectives, the results indicate that the controlled incorporation of LDPE into cement mortars may be a feasible strategy within circular-economy approaches to construction materials.

The marked strength reduction clearly limits the use of these mortars in structural or load-bearing elements. Nevertheless, low replacement levels may still be relevant for non-structural applications such as coatings, renders, or lightweight finishing layers, where reduced density and modified hygrothermal behavior may be advantageous.

In this sense, the present findings do not support broad claims of improved mechanical performance, but they do support the selective use of LDPE-modified mortar in applications where low self-weight and moisture-related functional behavior are more important than load-bearing capacity.

This interpretation is consistent with recent literature indicating that incorporating recycled polymers can be environmentally valuable and functionally useful, provided that application limits are clearly respected and that mixture design remains aligned with the target use [37,40,43].

## 5. Conclusions

This study evaluated the mechanical and hygrothermal behavior of cement mortars modified with recycled low-density polyethylene (LDPE) used as a partial replacement of fine aggregate. Based on the experimental results obtained, the following conclusions can be drawn:

1. LDPE incorporation produced a clear and persistent reduction in compressive strength, and this reduction generally intensified as the replacement ratio increased. The loss of strength is attributed to the low stiffness of the polymer, weak interfacial adhesion with the cementitious matrix, and disruption of efficient granular packing due to the different particle-size distribution of the plastic fraction.
2. The incorporation of LDPE also caused a progressive reduction in mortar density, confirming its lightweighting effect. Even at the lowest replacement level, the material exhibited a measurable decrease in apparent density, indicating that small dosages of LDPE are sufficient to modify the mortar’s physical structure.
3. Among the replacement levels evaluated, the mixture containing 2.5% LDPE showed the most balanced overall response when density reduction and mechanical performance were considered together. Although its compressive strength remained markedly lower than that of the control mortar, it represented the most conservative formulation for subsequent non-structural assessment within the range studied.
4. The hygrothermal assessment indicated that the addition of LDPE had a minimal effect on the indoor thermal behavior within the experimental parameters examined, as both chambers displayed comparable temperature patterns throughout the heating and cooling phases.
5. In contrast, the modified mortar produced a noticeable increase in indoor relative humidity, indicating that LDPE had a measurable effect on the moisture retention and moisture-regulation behavior of the system. Within the experimental setup used in this work, this effect was more pronounced than any thermal benefit.
6. In summary, the findings indicate that recycled LDPE can be integrated into cement mortars as a component of a circular economy approach, provided that specific application conditions are well defined. Its use is not justified for structural purposes based on the present data; however, low replacement levels may be considered for exploratory non-load-bearing applications in

which reduced density and modified hygrothermal response are desirable and mechanical demand is limited.

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