frontiers in Built Environment

TYPE Original Research
PUBLISHED 05 June 2026
DOI 10.3389/fbuil.2026.1847807

Check for updates

OPEN ACCESS

EDITED BY
Paul Awoyera,
Prince Mohammad bin Fahd University, Saudi Arabia

REVIEWED BY
Fuyuan Gong,
Zhejiang University, China
Iman Salaheldin Osman El Mahallawi,
Cairo University, Egypt

*CORRESPONDENCE
Andrés Emanuel Díaz,
andres@exa.unsa.edu.ar

RECEIVED 05 April 2026
REVISED 07 May 2026
ACCEPTED 11 May 2026
PUBLISHED 05 June 2026

CITATION
Díaz AE, Al-Hakemi H, Di Lalla N and Hernández AL (2026) Valorization of EPS and LDPE plastic waste in concrete tiles: mechanical properties, thermal insulation, and building energy simulation of a social housing case study.
Front. Built Environ. 12:1847807.
doi: 10.3389/fbuil.2026.1847807

COPYRIGHT
© 2026 Díaz, Al-Hakemi, Di Lalla and Hernández. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Valorization of EPS and LDPE plastic waste in concrete tiles: mechanical properties, thermal insulation, and building energy simulation of a social housing case study

Andrés Emanuel Díaz [1,2]*, Haitham Al-Hakemi [2], Nicolas Di Lalla [1] and Alejandro Luis Hernández [1,2]

[1]Instituto de Investigaciones en Energía No Convencional (INENCO), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Salta, Argentina, [2]Departamento de Física, Universidad Nacional de Salta (UNSa), Salta, Argentina

Plastic waste management is a global environmental challenge. This research explores a sustainable solution through the development of concrete tiles incorporating recycled plastic aggregates. An experimental methodology was designed evaluating three mixtures: a control mix (B_1) without waste, and two mixes with partial replacement of traditional aggregates by Expanded Polystyrene (EPS) and Low-Density Polyethylene (LDPE) waste (B_2 and B_3). Properties in the fresh and hardened state (slump, flexural and compressive strength, water absorption, density, thermal conductivity, and impact resistance) were analyzed. Additionally, the energy impact at the building level was assessed through dynamic simulations (SIMEDIF) of a social housing unit, comparing a Base Case with a Strategic Case incorporating the B_2 tile, high-performance bricks, and double glazing. Experimental results indicate that B_2 and B_3 comply with IRAM standards, reducing density by up to 14% and thermal conductivity by up to 47% compared to the control. The thermal simulation revealed that during the critical winter period, the Improved Case raised minimum indoor temperatures by up to +2.4 °C and reduced heating demand by up to 35%. In summer, it lowered maximum indoor temperatures by up to 3.5 °C and reduced cooling demand by up to 38%. Mix B_2 exhibited the best overall balance. The study concludes that it is feasible to produce tiles with plastic aggregates that not only improve thermal insulation at the material level but also generate significant energy savings at the housing scale, offering a viable alternative for waste valorization in sustainable construction.

KEYWORDS
building energy simulation, concrete tiles, EPS, LDPE, recycled plastic aggregates, thermal comfort

1 Introduction

Plastic waste management represents one of the greatest environmental challenges on a global scale, due to its persistence in the environment and the high volume generated. In parallel, the construction industry, in its constant search for more sustainable materials, presents itself as a potential channel for the valorization of these wastes, thus contributing to

the principles of the circular economy. Recent studies have explored various waste-derived construction materials. For example, Javed et al. (2025) discussed strategies for improving circularity in ceramic tile production, while Bwambale et al. (2025) reviewed the utilization of agricultural residues in ceramic tiles. Duguma et al. (2024) demonstrated the viability of using LDPE waste as a binder for outdoor paver tiles. Rathinam et al. (2025) investigated the strength and bonding characteristics of mortar with recycled sand from construction and demolition wastes. Nukah et al. (2024) developed low carbon concrete and geopolymer concrete using lightweight coarse aggregate and cement replacement materials. Bhaskarrao Gayake et al. (2025) conducted a multi-criteria analysis of impact strength in concrete with PET bottle waste additives. Yunusu et al. (2025) reviewed the utilization of agricultural residues in ceramic tiles. Wang et al. (2023) performed a multi-scale and multi-chemo-physics lifecycle evaluation of structural concrete under environmental and mechanical impacts. Additionally, research on alternative bricks and insulating materials has shown the potential of incorporating plastic waste into lightweight composites (Díaz and Hernandez, 2025b; Diaz and Hernandez, 2025a; Díaz et al., 2025). However, most investigations have focused on either structural concrete elements or on relatively thick masonry units, where compressive strength and thermal mass are the governing properties.

The ceramic and construction materials sector has shown growing interest in the incorporation of wastes of various natures. There is a significant drive to evolve traditional production techniques towards zero-waste manufacturing models, integrating waste from other industries to minimize environmental impact. This transition is not only desirable from an ecological perspective but is also being driven by regulatory incentives and market policies that promote circularity (Javed et al., 2025). Along the same lines, recent research has explored the use of agricultural residues (Bwambale et al., 2025) and by-products from porcelain tile manufacturing (Zanatta et al., 2020) as alternative raw materials, technically validating this practice.

Within this framework, polyolefin-type plastics, such as low-density polyethylene (LDPE) and expanded polystyrene (EPS), are ideal candidates for reuse in cementitious matrices. Their incorporation as aggregates in mortars and concretes not only addresses the problem of their final disposal but can also confer beneficial properties to the composite material, such as reduced density and improved thermal insulation. Furthermore, as demonstrated with paving tiles (Duguma et al., 2024), the use of low-density polyethylene (LDPE) waste as a binder can result in products with mechanical properties that meet required standards, showing very low water absorption and adequate resistance for outdoor applications.

However, most research has focused on their use as aggregates in massive concrete elements or as the main binder in plastic composites. There is a specific knowledge gap regarding the manufacture of thin pre-cast concrete tiles (typically 1.5–2.5 cm thick) that use a combination of plastic aggregates (LDPE) and EPS particles, aimed at applications requiring a balance between mechanical properties, reduced weight, and thermal insulation. Thin pre-cast concrete tiles (thickness 1.5–2.5 cm) present fundamentally different requirements from massive elements. Because of their slenderness, flexural strength, impact resistance, and dimensional stability are the critical mechanical properties, while thermal performance is dominated by thermal conductivity rather than heat capacity. Furthermore, the manufacturing process for thin tiles demands precise control of workability and surface finish. The interaction between the tile and the subfloor also influences the overall thermal performance of the building envelope. Despite the growing interest in recycled-aggregate concretes, a specific knowledge gap remains regarding the production of thin concrete tiles that combine EPS and LDPE particles as a partial replacement for natural aggregates, aiming to balance adequate mechanical strength with enhanced thermal insulation and reduced weight.

This work presents an experimental investigation on the development and characterization of concrete tiles with LDPE and EPS plastic waste aggregates. The main objective was to evaluate the effect of partial replacement of traditional aggregates by these plastic wastes on the fresh and hardened properties of concrete, with special emphasis on flexural strength, water absorption, thermal conductivity, and impact resistance. The results demonstrate that it is possible to produce tiles that comply with current regulatory requirements, while also offering a significant improvement in thermal insulation, thus contributing to a more sustainable construction practice and offering a viable solution for plastic waste valorization. Beyond material-level properties, it is essential to understand how these plastic-aggregate tiles perform when integrated into an actual dwelling. Dynamic building thermal simulation allows quantifying the impact of new materials on indoor comfort and energy demand, a critical aspect for the transition towards nearly Zero-Energy Buildings (nZEB). However, most studies on recycled materials stop at physicochemical and mechanical characterization, without evaluating their energy performance at the building scale. There is, therefore, a gap between the development of sustainable materials and the demonstration of their real benefit in terms of energy savings and thermal comfort in housing.

2 Methodology

The present study was carried out using a systematic experimental approach aimed at developing and characterizing concrete tiles with plastic waste aggregates. For this purpose, three different mix designs were prepared: a control mix without waste (B_1) and two mixes with partial replacement of traditional aggregates by EPS and LDPE waste (B_2 and B_3). Properties in the fresh state (slump) and hardened state (flexural and compressive strength, water absorption, density, thermal conductivity, and impact resistance) were evaluated following current international standards. The following sections detail the materials used, the mix design procedures, manufacturing processes, and the testing methods employed for specimen characterization.

2.1 Mix designs

The mix designs were developed using the American Concrete Institute (ACI) method, which allows reaching the final mix proportion in a practical manner by making successive corrections for slump and strength. The basis for the calculation

10.3389/fbuil.2026.1847807

TABLE 1 Mix designs for the tile series per cubic meter (m^3) of mixture.

Component	B_1	B_2	B_3
Water [kg]	176	140	122
Cement [kg]	270	250	167
Fine aggregate (fineness modulus 3.75) [kg]	569	515	500
EPS aggregate [kg]	0	9	9
Plastic aggregate (LDPE) [kg]	0	45	54
Superplasticizer additive (density 1.09 kg/m^3)	1.2	1.2	1.2
Pigment [kg]	2.22	2.40	3.6
Density [kg/m^3]	1137	1081	975

is the expression of one cubic meter (m^3) of concrete as the sum of the solid volume of each component of the mixture (ACI 211.1, 2009). Mix design is a process consisting of three interrelated steps:

- Selection of constituents.
- Determination of their relative quantities to produce, as economically as possible, a mixture with appropriate characteristics in both fresh and hardened states.
- Adjustment of the estimated quantities by testing trial batches.

The standard governing concrete mix designs is ACI 211.1, which in turn is based on ASTM C33, referencing granulometric specifications. For this testing stage, an iron oxide aggregate (red pigment) was used in the mixture, which produces a red color in the concrete (Table 1). Three mix design groups were prepared, with the following designations:

- B_1: Without waste aggregates. Water/cement ratio (w/c) = 0.65. 2.22 kg of red pigment (complies with ASTM C 979). Percentage of fine aggregate and cement (Portland CPC 30): 55% fine and 45% coarse.
- B_2: 9 kg of EPS waste (crushed to 1–3 mm) and 45 kg of LDPE plastic waste (5 mm pellets). 2.4 kg of red pigment (9% more than specimen B_1). w/c = 0.56. Percentage of fine aggregate and cement: 55% fine and 45% coarse (9.5% less fine and coarse aggregates than specimen B_1).
- B_3: 9 kg of EPS waste (same as specimen B_2). 54 kg of LDPE plastic waste (16% more than specimen B_2). 3.6 kg of red pigment (63% more than specimen B_1 and 50% more than specimen B_2). w/c = 0.73. Percentage of fine and coarse aggregate: 55% fine and 45% coarse (12% less fine and coarse aggregates than specimen B_1).

B_3 density equals 14.2% reduction from B_1. The target slump for all mixes was set at 4 ± 1 cm to ensure consistent workability during casting of thin tiles. Because plastic aggregates exhibit negligible water absorption and a smooth, rounded shape, the water demand and paste volume had to be adjusted to avoid segregation. Preliminary trials showed that a w/c of 0.65 for the control mix provided good cohesion; for B_2, a lower w/c (0.56) was sufficient due to the lubricating effect of LDPE, while B_3 required a higher w/c (0.73) because the increased plastic content reduced paste coverage.



FIGURE 1
The LDPE pellets (three to five mm) and crushed EPS (one to three mm) with a scale bar.

Cement content was also adjusted to maintain paste volume in a range that ensured coating of all aggregates. While this procedure follows the ACI trial-batch methodology, we acknowledge that the simultaneous variation of w/c and cement content precludes a purely single-variable analysis. The observed trends are therefore the combined result of aggregate substitution and matrix variation. This constraint is discussed further in Section 4. The reference tile (B_1) used a natural siliceous river sand with fineness modulus 3.75 and maximum particle size 4.75 mm (no coarse aggregate was employed, as the tile thickness precludes large particles). The sand meets ASTM C33 specifications.

2.2 Preparation of trial batches

Figure 1 shows the size of the LDPE and EPS aggregates used in this article.

The procedure for preparing the mixtures was as follows:

1. Water was added to the recycled aggregates, mixed, and left to dry for approximately 15 min. Figure 2 shows the aggregates used to form the paste for the tiles.
2. The recycled aggregate(s) (according to the corresponding mix design) were placed into the concrete mixer.
3. 20% of the water was mixed with the pigment.
4. The additive and cement were added together with 20% of the mixing water.
5. After a few minutes of mixing, the fine aggregate was added with 10% of the mixing water (Figure 3A).
6. After 3 minutes of mixing, the remaining water (50%) was added (Figure 3B).
7. The temperature of the mixture was measured, and then the square molds for thermal conductivity testing and the

10.3389/fbuil.2026.1847807



FIGURE 2
Aggregates used for the preparation of the tile series.

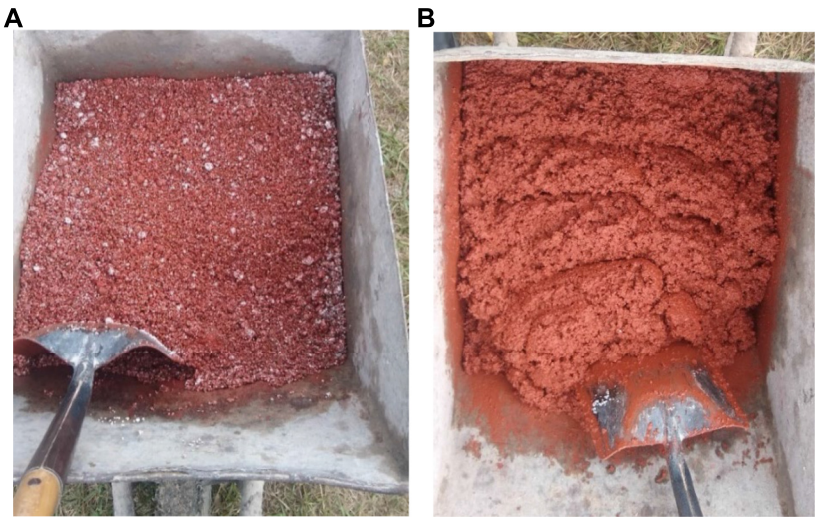


FIGURE 3
(A) Inclusion of aggregates for tile manufacturing, **(B)** Final stage of the paste.

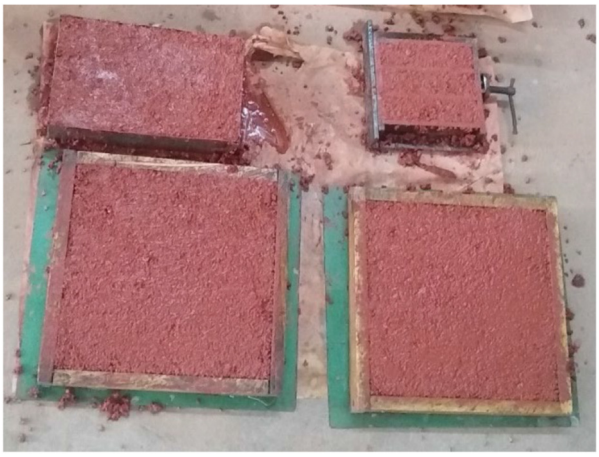


FIGURE 4
Filling of the molds for subsequent thermal conductivity tests.

cylindrical steel molds for the trial batches were filled (Figure 4).

2.3 Fresh state tests

To verify the influence of recycled aggregates on the workability of the mixtures, fresh state tests were carried out by determining the slump using the Abrams cone (IRAM 1536, 2023). The cone was filled with the mixture; the test was repeated twice for each trial batch, obtaining an average slump value.

2.4 Hardened state tests

Compressive strength tests were carried out after 7 and 28 days of curing on cylindrical specimens of 100 mm × 200 mm, according to IRAM 1546 (2017). Flexural and impact tests were performed after 7 and 28 days of specimen preparation following

10.3389/fbuil.2026.1847807

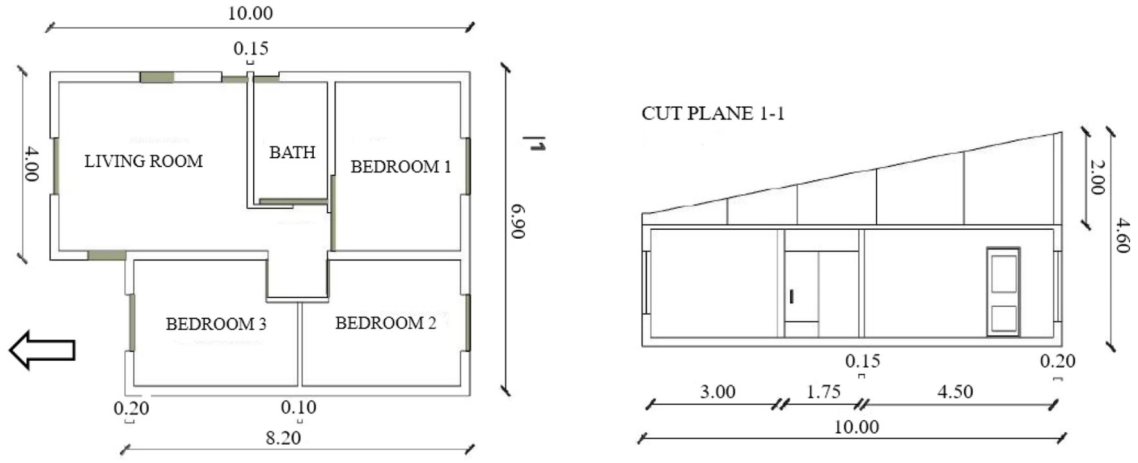


FIGURE 5
The floor plan and elevation of the social housing (all dimensions in meters).

TABLE 2 Thermal properties of building components.

Component	Thickness (m)	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat (J/kg·K)
B_2 tile	0.02	1081	0.48 (experimental)	840 (estimated)
Hollow ceramic brick	0.18	800	0.35	1000
Puma Punku brick (improved)	0.18	1050	0.25	1050
Gypsum ceiling	0.012	800	0.25	1000
Single glazing	0.006	–	U = 5.8 W/m^2·K	–
Double hermetic glazing (DVH)	0.024	–	U = 2.8 W/m^2·K	–

IRAM 1522 (2020) standard. The specimens had a prismatic shape of 40 mm × 40 mm × 160 mm. To analyze the thermal behavior, the thermal conductivity coefficient was determined using a hot plate apparatus, according to IRAM 11559 (1995) (Diaz and Hernandez, 2025b). For the measurements, two twin specimens of each mixture were required, since this equipment model needs two samples with similar characteristics to measure thermal conductivity. The specimen dimensions were 300 mm high × 300 mm wide × 40 mm thick.

2.5 Integrated thermal performance evaluation: building simulation

A typical social housing unit in Salta (Figure 5), Argentina, was modelled using SIMEDIF v2.0 (Flores and Lesino, 2001), a well-validated building energy simulation tool that solves the 1-D transient heat conduction equation using a finite-difference scheme with hourly time steps. The model includes convective/radiative heat exchange, solar radiation distribution through windows, and internal heat gains. The weather file used is the Typical Meteorological Year (TMYPlus) for Salta (Díaz and Hernández, 2025a).

Table 2 lists the thermal properties of all envelope components. The properties of the B_2 concrete tile (density, thermal conductivity, specific heat) were taken from the experimental measurements of this study. For the base case components (hollow ceramic brick, galvanized sheet roof, single glazing), properties were taken from the Argentine standard IRAM 11601 (2004).

The model was validated against monitored indoor temperatures of a similar unoccupied prototype and against monthly electricity bills of an occupied dwelling; the simulated heating demand deviated by less than 8% from actual consumption (Flores Larsen et al., 2008). Sensitivity analyses were conducted by varying the infiltration rate, internal gains, and convective coefficients, confirming that results are robust (±5% in energy demand).

The base case envelope consisted of 0.18 m hollow ceramic brick walls, uninsulated galvanised sheet roof, single glazing, and a traditional concrete floor tile (assumed identical to B_1 in thermal properties). An "Improved Case" was defined with: (i) B_2 tile as floor finish; (ii) Puma Punku brick for all walls; (iii) double hermetic glazing. Additionally, to isolate the effect of the tile alone, a third case was simulated in which only the floor tile was changed from the base material to B_2 ("Tile-only Case").

Indoor temperature setpoints were: heating 22.1 °C (daytime)/18 °C (night); cooling 24.4 °C (daytime)/18 °C (night). Air change rates were 2 ACH during occupied hours (08:00–22:00) and 1 ACH at night. Internal gains from four occupants and electric equipment were modelled as 3.1 W/m^2 average.

10.3389/fbuil.2026.1847807

TABLE 3 Slump test results and water/cement ratio used.

Specimen	Recycled material	W/c ratio	Slump [cm]	Compressive strength [MPa] At 28 days
B_2	EPS and LDPE	0.56	3.5	18.2
B_3	EPS and LDPE	0.73	4.5	12.5
B_1	———	0.65	4.0	24.8

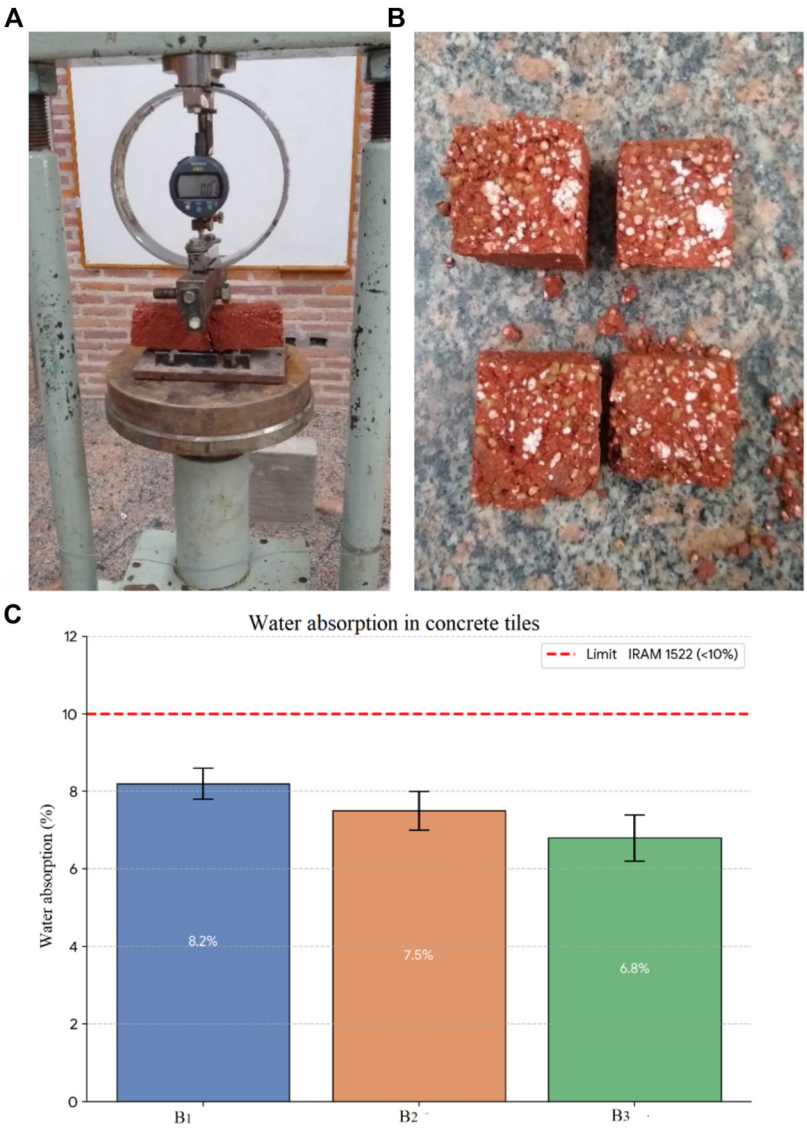


FIGURE 6
(A) Flexural strength test, **(B)** Specimens B_3 (upper) and B_2 (lower) after the flexural strength test. **(C)** Water absorption and error bars (standard deviation of three specimens), all mixes met the IRAM 1522 (2020) requirement (<10% absorption).

3 Results

The results of the slump test are presented in Table 3. As observed, the water/cement ratio (w/c) was increased to make the mixture more fluid. The mixture with the highest slump was B_3, which has a higher weight content of plastic aggregates, while the lowest slump corresponded to specimen B_2, which contains less plastic aggregate and more fine and coarse aggregates.

The compressive strength of the specimens at 28 days showed a clear downward trend as the concentration of plastic waste increased. While the control mix (B_1) reached 24.8 MPa, the B_2 and B_3 mixtures retained 73% and 50% of this strength, respectively.

10.3389/fbuil.2026.1847807

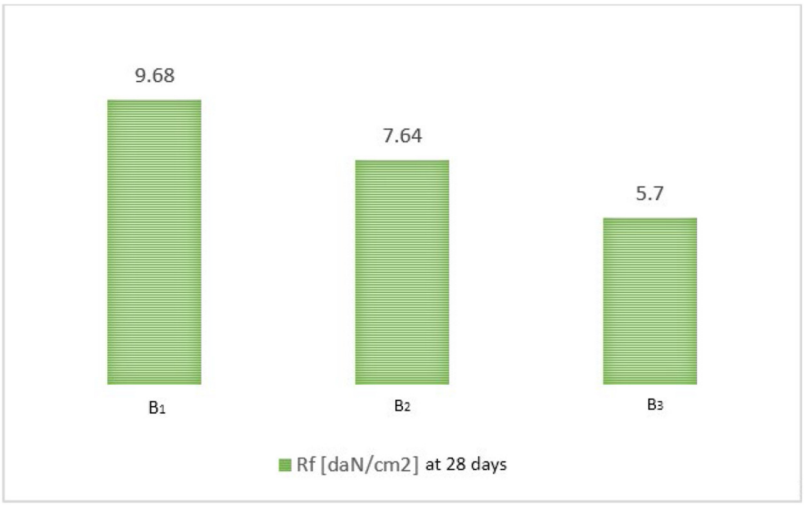


FIGURE 7
Flexural strength (Rf) results.

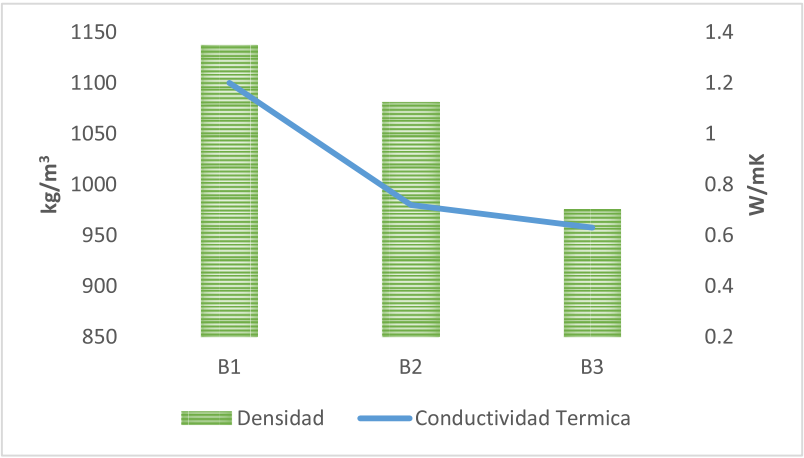


FIGURE 8
Density and thermal conductivity results.

This decline in mechanical performance mirrors the reduction in the total cementitious matrix volume as traditional aggregates are replaced by lightweight plastics. Furthermore, the loss of strength is attributed to the poor adhesion between the hydrophobic surfaces of the LDPE and EPS aggregates and the cement paste, which creates a weaker interfacial transition zone compared to natural aggregates. Despite this reduction, the values obtained for B_2 remain robust for applications in pre-cast concrete tiles where high structural loads are not the primary requirement, but thermal efficiency is prioritized.

Figure 6A shows the flexural strength test being performed on the specimens. This test corresponds to specimen B_2, which yielded a value of 7.64 daN/cm^2, exceeding the minimum requirement of five daN/cm^2 established by IRAM 1522 (2020) standard. Specimen B_3 yielded 5.7 daN/cm^2, also passing the minimum required by the standard, while the control specimen B_1 gave the highest value at 9.68 daN/cm^2. Figure 6B shows specimens B_2 and B_3 after the flexural strength test; the upper part of the image shows specimen B_3, where the distribution of EPS and LDPE aggregates can be observed.

Figure 6C illustrates the water absorption percentages for the evaluated concrete tiles, with error bars representing the standard deviation across three tested specimens for each mix design. As depicted in the graph, the control mix (B_1) and the formulations incorporating EPS and LDPE plastic waste aggregates (B_2 and B_3) all exhibited water absorption levels well below the 10% maximum limit. Consequently, all the developed mixtures successfully comply with the requirements established by the IRAM 1522 (2020) standard, confirming that the partial substitution of traditional aggregates with these recycled plastics maintains adequate permeability properties suitable for outdoor applications.

10.3389/fbuil.2026.1847807

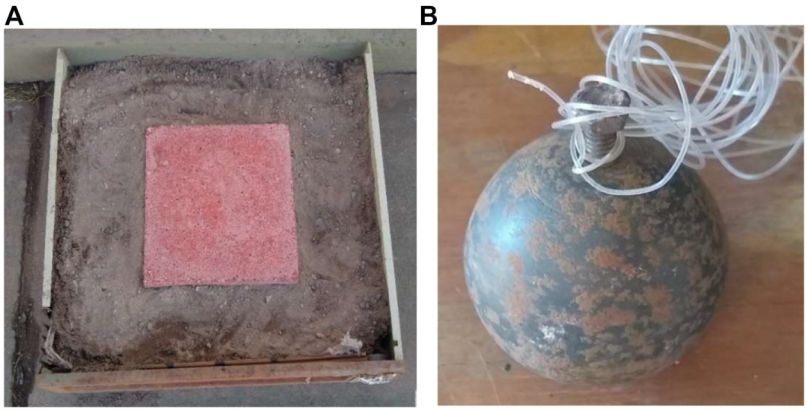


FIGURE 9
(A) Sand box, **(B)** Iron sphere for impact testing.

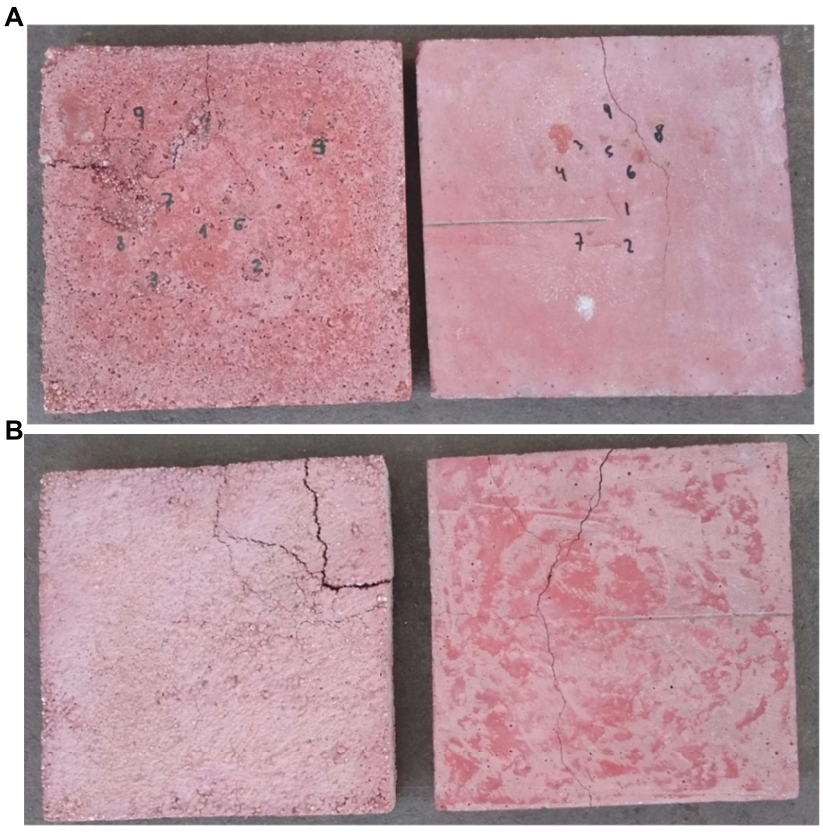


FIGURE 10
(A) Impact marks from the sphere drops, with specimen B_2 on the left and specimen B_1 on the right, **(B)** Difference in crack patterns between specimens upon fracture.

The graph in Figure 7 shows the flexural strength results, ordered from highest to lowest flexural strength, with B_1 being the control specimen. B_2 has 9.5% less fine and coarse aggregate than the control specimen, while B_3 has 12% less.

The density and thermal conductivity tests were satisfactory, as shown in Figure 8. Density and consequently thermal conductivity were reduced with respect to the control specimen B_1. Specimen B_2 achieved 40% lower thermal conductivity and 9% lower density, while specimen B_3 exhibited 47% lower thermal conductivity and 14% lower density.

For the impact test, a box measuring 60 cm × 60 cm × 20 cm high was used, with a 10 cm high layer of medium sand (Figure 9A). A

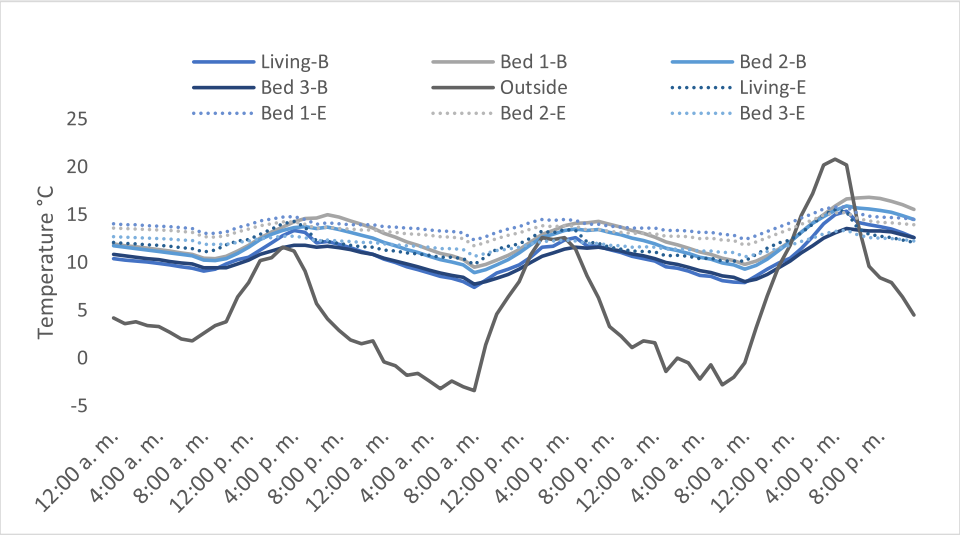


FIGURE 11
Temperature evolution for both cases during the days June 27–29.

650-g iron sphere (Figure 9B) was dropped from different heights until tile fracture was achieved. The dimensions of the tested tiles were 30 cm × 30 cm × 2 cm thick.

The iron sphere was dropped from nine different heights, starting from 30 cm up to 250 cm, the height at which tiles B_1 and B_2 fractured (Figure 10A). By analyzing Figures 10A,B, the difference in crack patterns between the tiles can be observed. Tile B_2 did not exhibit a continuous crack upon the final impact, whereas tile B_1 showed a continuous crack that extended across the entire length of the tile (Figure 10B). This behavior is attributed to the plastic and EPS waste aggregates, which absorbed and dampened the impact of the iron sphere.

The iron sphere (mass 0.65 kg) was dropped from increasing heights. The critical drop height (i.e., the first height causing fracture after three repeated drops) and impact energy are:

B_1: 250 cm → 15.9 J.

B_2: 250 cm → 15.9 J (no continuous crack; see fracture pattern).

B_3: 200 cm → 12.7 J.

After the impact sequence, the residual flexural strength was measured: B_1 retained 60% of its original strength; B_2 retained 85%; B_3 retained 72%. The superior performance of B_2 is attributed to energy dissipation by the plastic particles, which also prevented the propagation of continuous cracks.

3.1 Integrated thermal simulation

The incorporation of tiles with plastic aggregates (B_2) together with wall and window improvements (Strategic Case) resulted in a significant improvement in the thermal behavior of the dwelling compared to the Base Case, both in winter and summer.

Cold Period (Autumn-Winter): Figure 11 shows the evolution of indoor temperature for the most critical days (June 27–29). While the Base Case presented minimum temperatures as low as 7.4 °C in the dining room, the Strategic Case raised this minimum to 9.8 °C (an improvement of +2.4 °C). Similarly, the average temperatures of the bedrooms (Bed 1, Bed 2, and Bed 3) increased between 1 °C and 2 °C, and the thermal amplitudes were drastically reduced (for example, in Bedroom 3 (Bed 3), the amplitude decreased from ±7.1 °C to ±2.8 °C). In energy terms, the total heating demand of the dwelling for the analyzed days was reduced by up to 35% (Figure 12), decreasing from 62.1 kW/day to 40.1 kW/day for the Strategic Case "E".

Warm Period (Spring-Summer): During the warm days of November (26–28), the Strategic Case managed to reduce maximum indoor temperatures by up to 3.5 °C (for example, in Bedroom 3 (Bed 3) it decreased from 31.5 °C to 28.0 °C), as observed in Figure 13. This resulted in a notable decrease in the cooling load required to maintain comfort. The energy demand for cooling was reduced by an average of 38% across the four orientations. For the most critical case, the total daily load decreased from −63.9 kW to −41.0 kW (Figure 14), representing a reduction of 36%.

To quantify the isolated effect of the B_2 tile, the "Tile-only Case" was compared with the Base Case. For the south orientation during the cold period (June 27–29), the minimum dining-room temperature increased from 7.4 °C to 7.9 °C (+0.5 °C), and the heating demand decreased by 12% (from 62.1 to 54.7 kW/day). During the warm period (November 26–28), the maximum bedroom temperature dropped from 31.5 °C to 30.8 °C (−0.7 °C), and the cooling demand decreased by 9% (from 63.9 to 58.1 kW/day). These improvements, though smaller than the full retrofitted case, confirm that the tile alone provides measurable thermal benefits, predominantly through its lower thermal conductivity reducing heat transfer through the floor.

These results demonstrate that the use of tile B_2, with its lower thermal conductivity (40% reduction vs. control), effectively helps decouple indoor temperature from outdoor temperature, dampening cold and heat peaks. The synergy with the Puma Punku brick and double glazing maximizes energy savings, validating these recycled materials as an integral sustainable construction strategy.

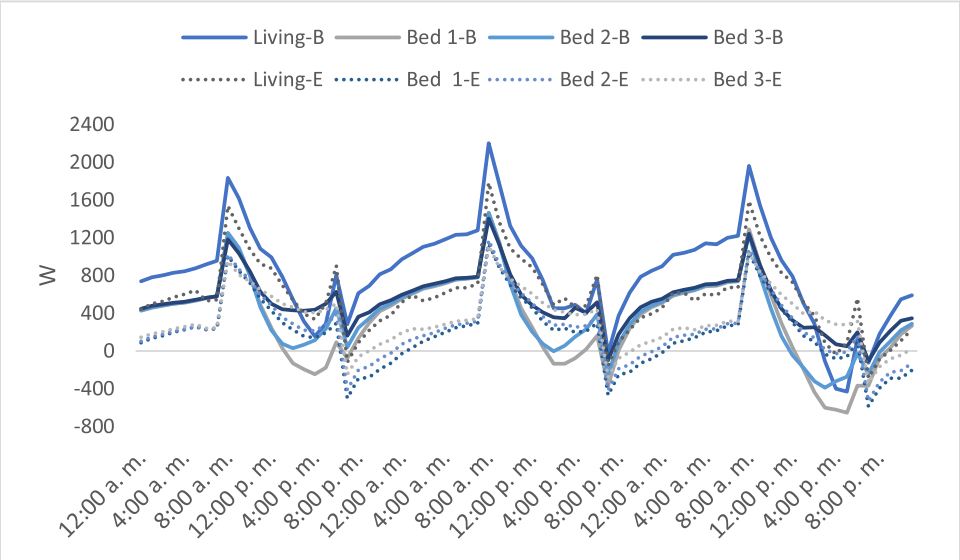


FIGURE 12
Auxiliary energy demand for the Base Case and Strategic Case during the days June 27–29.

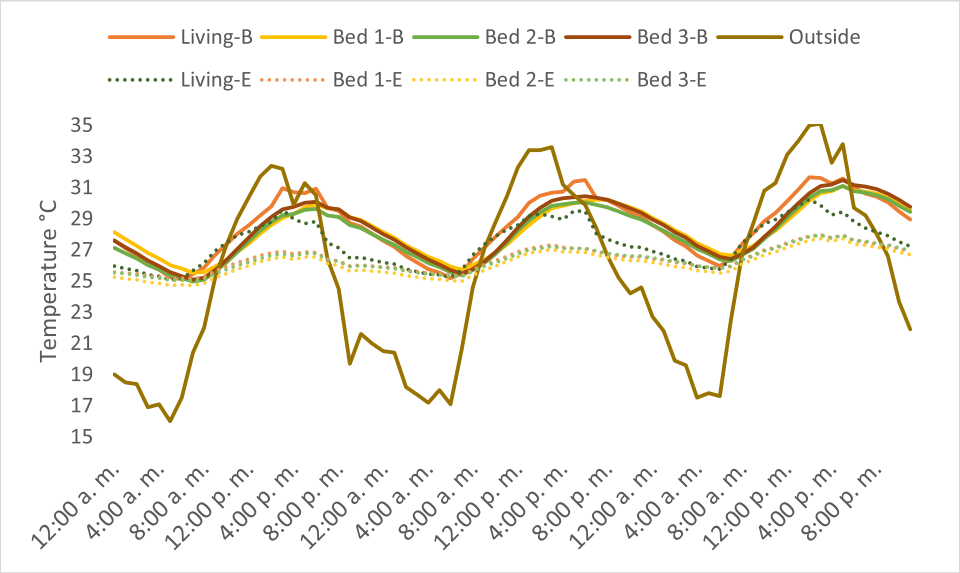


FIGURE 13
Temperature evolution for the Base Case and Strategic Case during the days November 26–28.

4 Discussion

The results obtained in this study demonstrate that the incorporation of plastic waste (EPS and LDPE) as aggregates in the manufacturing of concrete tiles is technically viable and environmentally promising. The significant reduction in density (up to 14%) and thermal conductivity (up to 47%) in mixtures B_2 and B_3 is consistent with reports in the literature for cementitious composites with plastic aggregates (Duguma et al., 2024). This improvement in thermal properties is particularly relevant for outdoor applications, where thermal insulation can contribute to building energy efficiency, a key aspect of sustainable construction (Javed et al., 2025). The decrease in flexural strength observed in the plastic-containing mixtures (B_2 and B_3) compared to the control (B_1) was expected, given the poor adhesion between the cementitious matrix and hydrophobic plastic aggregates, a widely documented phenomenon (Bwambale et al., 2025). However, it is crucial to highlight that both values (5.7 and 7.64 daN/cm^2) exceeded the minimum required by IRAM 1522 (2020) standard (5 daN/cm^2), confirming that the loss of strength does not



FIGURE 14
Auxiliary energy demand for the Base Case and Strategic Case during the days November 26–28.

compromise the product's functionality for its intended use. This finding is consistent with that of Duguma et al. (2024), who also reported adequate mechanical strengths in tiles with LDPE. The observed decrease in mechanical strength is consistent with the formation of a weak interfacial transition zone (ITZ) between the hydrophobic plastic aggregates and the cementitious matrix. As widely reported (Bwambale et al., 2025; Duguma et al., 2024), such poor adhesion increases micro-porosity and allows micro-crack initiation under loading. The higher water absorption of B_3 (though still below 10%) corroborates this effect. Although microstructural imaging was beyond the scope of the present study, future work will incorporate SEM and mercury intrusion porosimetry to quantify the ITZ and pore structure.

The superior performance of mixture B_2 over B_3 suggests that there is an optimal substitution percentage beyond which mechanical properties may degrade more significantly without proportional gains in thermal properties. This result is consistent with the lower w/c ratio. This underscores the importance of optimizing the mix design to achieve a balance between mechanical and thermal performance, a common challenge in the development of materials with waste (Zanatta et al., 2020).

The greater ductility and non-continuous crack pattern observed in the impact test for tiles B_2 and B_3 is a novel and highly favorable result. This behavior, attributable to the ability of plastics to absorb and distribute impact energy, is not typically reported in traditional ceramic or concrete tiles. This advantage could open new applications in areas requiring some degree of impact resilience.

The scale jump from material characterization (tile) to its performance in a complete building constitutes one of the most novel contributions of this work. The simulation results (Figures 10, 11, 13, 14) demonstrate that the 40% reduction in thermal conductivity of tile B_2, in synergy with an improved envelope (Puma Punku brick and double glazing), translates into quantifiable and substantial energy benefits. The mitigation of extreme indoor temperature peaks (+2.4 °C in winter minimums and −3.5 °C in summer maximums) shows that the set of recycled materials acts as an effective thermal buffer, improving passive comfort. This observation is consistent with studies reporting that thermal inertia and insulation provided by lightweight materials with waste can attenuate daily temperature oscillations (Díaz and Hernández, 2025b).

The energy demand savings (35% in heating and 38% in cooling for the most critical orientation) are particularly relevant in a context of climate change and energy transition, where reducing the load on HVAC systems is a priority. Although other authors have reported improvements in thermal properties of plastic composites (Duguma et al., 2024; Javed et al., 2025), very few have quantified the real impact of such materials on the energy efficiency of a complete dwelling through dynamic simulation. This integrated analysis allows us to affirm that the substitution of traditional materials with plastic waste alternatives (such as tile B_2) is not only technically viable at the product level but is also strategically beneficial for achieving nearly Zero-Energy Building (nZEB) standards in temperate-extreme climates such as Salta. Future lines of research should explore a life cycle assessment (LCA) that accounts for the balance between the reduction of environmental impact through waste use and the operational savings from lower energy demand. The sensitivity analysis reveals that the B_2 tile alone contributes about one-third of the heating energy savings of the full Improved Case. This confirms that the floor, being a large surface in contact with the ground, is a significant path for heat loss, and its improvement matters even without other envelope upgrades. The synergy with the Puma Punku brick and double glazing amplifies the benefits, but the tile's individual contribution is non-negligible.

Although this study demonstrated success at the laboratory scale, a recognized limitation is the need to evaluate the long-term performance of these tiles, including their weather

resistance, freeze-thaw cycles, and potential UV degradation of exposed plastics. Future research should scale up production to an industrial level to validate the economic and technical feasibility of the process. Likewise, surface treatments on plastic aggregates are recommended to further improve adhesion to the cementitious matrix and potentially increase mechanical strength without sacrificing the beneficial thermal and density properties.

The results of this work align with and strengthen the body of literature advocating for the circular economy in the construction industry. It is confirmed that plastic waste, far from being a problematic waste, can be transformed into a valuable resource for developing innovative construction materials with improved properties, directly contributing to the sustainability of the sector.

5 Conclusion

This study demonstrated the technical feasibility and building-scale energy benefit of using plastic waste (EPS and LDPE) as aggregates in the manufacturing of concrete tiles. The partial substitution of traditional aggregates by these wastes resulted in composites with mechanical properties that comply with regulatory standards (IRAM 1522, 2020), while also conferring key beneficial characteristics.

The plastic-containing mix designs (B_2 and B_3) exhibited a significant reduction in density (up to 14% less) and a notable improvement in thermal insulation, with a decrease in thermal conductivity of up to 47% compared to the control mix (B_1). Although a decrease in flexural strength was observed compared to the control, the values obtained (5.7 and 7.64 daN/cm^2 for B_3 and B_2, respectively) exceeded the minimum required by the standard. Mix B_2 showed the best overall balance of mechanical, thermal, and workability properties. Furthermore, the impact test revealed a more ductile behavior in the plastic-containing tiles, which developed less continuous cracks than the traditional tile.

The compressive strength analysis at 28 days confirms that while the incorporation of EPS and LDPE waste reduces mechanical performance, the B_2 mixture maintains a functional strength of 18.1 MPa, retaining 73% of the control's capacity. This decline is directly linked to the reduced volume of the cementitious matrix and the characteristically poor adhesion of hydrophobic plastic aggregates. These results validate the use of these recycled composites for concrete tiles, provided that the substitution level is optimized to balance mechanical stability with the achieved thermal benefits.

The main contribution of this work lies in the quantification of the energy impact of these tiles at the housing level. Through dynamic simulations (Base Case vs. Strategic Case with B_2 tile), it was demonstrated that the use of this recycled material, together with an optimized envelope, allows: (i) raising winter minimum temperatures by up to 2.4 °C and reducing heating demand by up to 35%; (ii) lowering summer maximum temperatures by up to 3.5 °C and reducing cooling demand by up to 38%. The B_2 tile alone was responsible for 12% heating demand reduction and 9% cooling demand reduction, highlighting its standalone value for energy retrofits.

This research validates the use of EPS and LDPE waste to produce lightweight tiles with high thermal insulation, suitable for outdoor applications, and demonstrates that their adoption in social housing projects can significantly contribute to energy savings and user comfort. The results position these tiles as a promising and sustainable solution for plastic waste valorization in the construction industry, aligned with the principles of circular economy and sustainable building.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AD: Methodology, Formal Analysis, Conceptualization, Investigation, Writing – review and editing, Resources, Writing – original draft, Software. HA-H: Investigation, Conceptualization, Writing – original draft, Data curation. ND: Writing – original draft, Methodology, Formal Analysis. AH: Resources, Validation, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the Research Council of the National University of Salta (Consejo de Investigación de la Universidad Nacional de Salta) through Project CIUNSa No. 3037. I also wish to thank the Research Council of the National University of Salta for their support.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

ACI 211.1 (2009). *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*. American Concrete Institute.

Bhaskarrao Gayake, S., Jadhav, S. V., Gaikwad, S. G., Kasar, R. S., Parhe, P. R., and Desai, A. K. (2025). Multi-criteria analysis of impact strength in concrete with PET bottle waste additives. *Int. J. Struct. Eng.* 15, 69–87. doi:10.1504/IJSTRUCTE.2025.144371

Bwambale, Y., Yiga, V. A., and Lubwama, M. (2025). Utilization of agricultural residues in ceramic tiles review. *Open Ceram.* 100783, 100783. doi:10.1016/j.oceram.2025.10783

Díaz, A. E., and Hernández, A. L. (2025a). Experimental study to measure conductive heat transfer properties in new materials with environmental waste aggregates. *Am. J. Phys. Appl.* 13 (2), 17–27. doi:10.11648/j.ajpa.20251302.11

Díaz, A. E., and Hernández, A. L. (2025b). Typical weather year for the design of thermal applications in social housing. *J. Appl. Mat. Sci. Eng. Res.* 9 (1), 01–13. doi:10.33140/JAMSER.09.01.01

Díaz, A. E., Di Lalla, N., and Hernández, A. L. (2025). Analysis of a new brick design using plastic waste. *Clean. Waste Syst.* 12, 12–100339. doi:10.1016/j.clwas.2025.100339

Duguma, D. A., Demeke, S., Bekele, T., and Malimo, M. (2024). Recycling and reusing potential of disposable low-density polyethylene plastic waste for flexible paver tile construction for outdoor application. *Heliyon* 10 (3), e29381. doi:10.1016/j.heliyon.2024.e29381

Flores, L. S., and Lesino, G. (2001). Modelo térmico del programa SIMEDIF de simulación de edificios (Versión 2.0). *Energía Renov. Y Medio Ambiente* 9, 15–24. Available online at: https://www.researchgate.net/publication/265997504_MODELO_TERMICO_DEL_PROGRAMA_SIMEDIF_DE_SIMULACION_DE_EDIFICIOS. ISSN0328-932X (Accessed April 2, 2026).

Flores Larsen, S., Filippín, C., Beascochea, A., and Lesino, G. (2008). An experience on integrating monitoring and simulation tools in the design of energy-saving buildings. *Energy Build.* 40 (6), 987–997. doi:10.1016/j.enbuild.2007.08.004

IRAM 11559 (1995). "Acondicionamiento térmico: Determinación de la resistencia térmica y propiedades conexas en régimen estacionario," in *Método De La Placa Caliente Con Guarda*. Buenos Aires, Argentina: Instituto Argentino de Normalización y Certificación (IRAM).

IRAM 11601 (2004). "Aislamiento térmico de edifícios: Métodos de cálculo," in *Propiedades Térmicas De Los Componentes Y Elementos De Construcción En Régimen Estacionario*. Buenos Aires, Argentina: Instituto Argentino de Normalización y Certificación (IRAM).

IRAM 1522 (2020). *Baldosas De Cemento. Métodos De Ensayo*. Buenos Aires, Argentina: Instituto Argentino de Normalización y Certificación (IRAM).

IRAM 1536 (2023). *Hormigón Fresco De Cemento: Método De Ensayo De La Consistencia Utilizando El Tronco De Cono*. Buenos Aires, Argentina: Instituto Argentino de Normalización y Certificación (IRAM).

IRAM 1546 (2017). *Hormigón De Cemento: Método De Ensayo De Compresión*. Buenos Aires, Argentina: Instituto Argentino de Normalización y Certificación (IRAM).

Javed, S., Conte, S., Molinari, C., Rosa, R., Ferrari, A. M., Dondi, M., et al. (2025). Strategies and pathways to improve circularity in ceramic tile production. *J. Clean. Prod.* 145788, 145788. doi:10.1016/j.jclepro.2025.145788

Nukah, P., Abbey, S., Booth, C., and Oti, J. (2024). Development of low carbon concrete and prospective of geopolymer concrete using lightweight coarse aggregate and cement replacement materials. *Constr. Build. Mater.* 428, 136295. doi:10.1016/j.conbuildmat.2024.136295

Rathinam, K., Shanmugavel, P., and Varadharaj, M. (2025). Strength and bonding characteristics of mortar with recycled sand from construction and demolition wastes. *Int. J. Struct. Eng.* 15, 219–231. doi:10.1504/IJSTRUCTE.2025.148379

Wang, Z., Gong, F., and Maekawa, K. (2023). Multi-scale and multi-chemo–physics lifecycle evaluation of structural concrete under environmental and mechanical impacts. *J. Intelligent Constr.* 1, 9180003–9180018. doi:10.26599/JIC.2023.9180003

Yunusu, B., Yiga, V. A., and Lubwama, M. (2025). Utilization of agricultural residues in ceramic tiles: a review. *Open Ceram.* 100783, 1–10. doi:10.1016/j.oceram.2025.100783

Zanatta, T., Rozineide, A., Boca Santa, A., Padoin, N., Soares, C., and Gracher, R. H. (2020). Eco-friendly ceramic tiles: development based on technical and market demands. *J. Mater. Res. Technol.* 12, 2153–2165. doi:10.1016/j.jmrt.2020.12.081