



# Application of recycled high-density polyethylene for construction of non-structural wattle and daub walls

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## Abstract

The evolution of construction techniques has spanned millennia, integrating locally sourced materials with innovative technological advancements. The use of earth in construction demonstrates remarkable versatility, exhibiting plasticity when wet and robust solidity upon drying. The environmental sustainability and abundant availability of earth further reinforce its role in architectural practices. This research explores the integration of recycled thermoplastic technology with traditional earthen construction methods, focusing on non-structural walls combining thermoplastic frameworks and mixed earth techniques. The study places particular emphasis on recycled High-Density Polyethylene (r-HDPE), a material that has garnered acclaim for its role in sustainable development through the reuse of secondary raw materials and its high moldability. The primary function of r-HDPE in this context is as a supplemental framework supporting earthen materials. Utilizing recycling and production methods from *Precious Plastic*, the research emphasizes the prototyping of r-HDPE structures with diverse configurations, digitally designed to create components ranging from beams to intricate truss networks. The earthen mortar comprises fine and coarse sand, wheat straw, and lime, adhering to traditional mixed earth construction practices. While the materials share structural limitations with conventional mixed earth methods, the potential addition of composites to thermoplastics could improve strength but hinder mechanical recyclability, favoring chemical recycling as an alternative. This study prioritizes recyclability with minimal environmental impact, limiting its scope to mechanical recycling without composite additives. The objective of this study is to achieve a balance between innovative applications of recycled thermoplastics and long-term environmental stewardship, thereby enhancing the synergy between sustainability and construction practices.

**Keywords** Earth architecture · Wattle-and-daub · Recyclability · r-HDPE

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## 1 Introduction

The use of earth in construction dates back to 8000 BC, establishing it as one of the earliest materials employed in architectural practices. Its application enables a wide range of construction techniques in housing architecture, integrating a practical understanding of building systems with the cumulative knowledge acquired through historical and evolutionary processes [1]. Earth is a universally available material, present on every continent, and its adaptability allows for diverse applications in distinct cultural contexts. This universality has driven the evolution and diversification of techniques that employ raw earth in housing construction, such as rammed earth, adobe and wattle and daub techniques.

The adoption of earthen construction methods, especially within the fields of vernacular and sustainable architecture, is marked by a series of advantageous characteristics. These benefits include reduced environmental impact, improved thermal and acoustic performance, and significant reductions in energy consumption [2]. The use of earth in civil construction is facilitated by its plasticity when moist and its rigidity when dry, in addition to its inherent material benefits and global abundance. Furthermore, the combination of earth with other materials enhances its structural utility and broadens its range of applications in architectural practices [3].

CRATerre has developed a classification system that identifies 18 earth-based construction processes, which are grouped into three principal categories: monolithic load-bearing systems, load-bearing masonry systems, and systems where earth serves as infill within a supporting structure [4]. This research focuses on mixed-earth techniques, a subset of the latter category, which involves the use of earth as a coating for structural supports. The evolution of earth-based construction techniques has unfolded across various geographical regions, and the intrinsic properties of the material allow for the transposition of similar construction techniques between different countries due to the material's global availability.

The continuous introduction of new materials driven by technological advancements has led to their increasing integration into daily life. Among these materials, thermoplastics constitute a major category, with their production emerging as a key industrial process since the onset of the 21st century. The demand across multiple sectors has necessitated the production of thermoplastics on a global scale. In 2002, global thermoplastic production was estimated at 120 million tonnes, a figure that had risen to 400 million tonnes annually by 2022 [5]. Projections from the European Commission indicate a substantial increase in thermoplastic production in the coming years.

The life cycle of certain thermoplastics allows for both production and recycling, thereby enabling their reuse as secondary raw materials in future production cycles. However, the inadequate disposal of these materials has led to extensive contamination of both terrestrial and marine ecosystems, making these potentially valuable secondary raw materials inaccessible. Research on thermoplastics has demonstrated continuous progress in production and recycling processes. The physical and chemical properties of thermoplastics have garnered interest due to the potential contributions these materials could offer in the field of architecture.

The use of recycled thermoplastics in the fabrication of support structures, subsequently coated with earth, offers the possibility of developing an innovative mixed-earth technique. This approach promotes the reuse of secondary raw materials in the construction of internal wall structures. The goal is to establish a construction process that incorporates recycled

and recyclable materials. The use of recycled thermoplastic structures in construction would support the recovery of substantial volumes of plastic waste, which could be processed and densified into rigid structural components with extended life cycles, enabling applications that endure for decades. This study proposes an analysis of the application of earthen mortars to prototypes built with recycled thermoplastics.

## 2 Earth as a construction material

The term “earthen architecture” refers to any construction that utilizes earth as a primary material, without altering its inherent mineralogical composition [6]. Mixed-earth techniques constitute a category of construction systems in which earth is employed as a covering or infill material within a supporting framework. This construction system has been disseminated across multiple continents, displaying regional adaptations and methodological variations over the centuries. The terminology for mixed-earth techniques differs according to regional and cultural contexts. Examples include *Wattle and Daub* (United States of America), *Tabique* (Portugal), *Torchis* (France), *Taipa de Mão* (Brazil) (Fig. 1), *Quincha* (Chile), and *Bahareque* (Spain). These techniques share a fundamental characteristic: the use of internal frameworks that are subsequently coated with earth. The frameworks generally consist of primary structural elements that serve as the load-bearing core of the wall. These elements are responsible for receiving and transferring the loads imposed by secondary structures, which in turn support the earthen infill or coating. Protecting these structures from the harmful effects of rising moisture is crucial to ensuring their durability and structural integrity (Fig. 2).

The supporting frameworks, often referred to as secondary structures or lattices, typically consist of wooden slats arranged in vertical, horizontal, or transverse configurations.



**Fig. 1** Residential project with *taipa de mão* walls. In the images it is possible to see the brick elevation structure, the primary horizontal and vertical wooden structure, and the secondary structure made of bamboo in the transversal direction. The variation between the internal and external layers of the wall. Project by Karin Schwambach, Bonito, Brazil



**Fig. 2** The internal frameworks are covered with earth. The construction with earth characterized by the possibility of using earth from the site

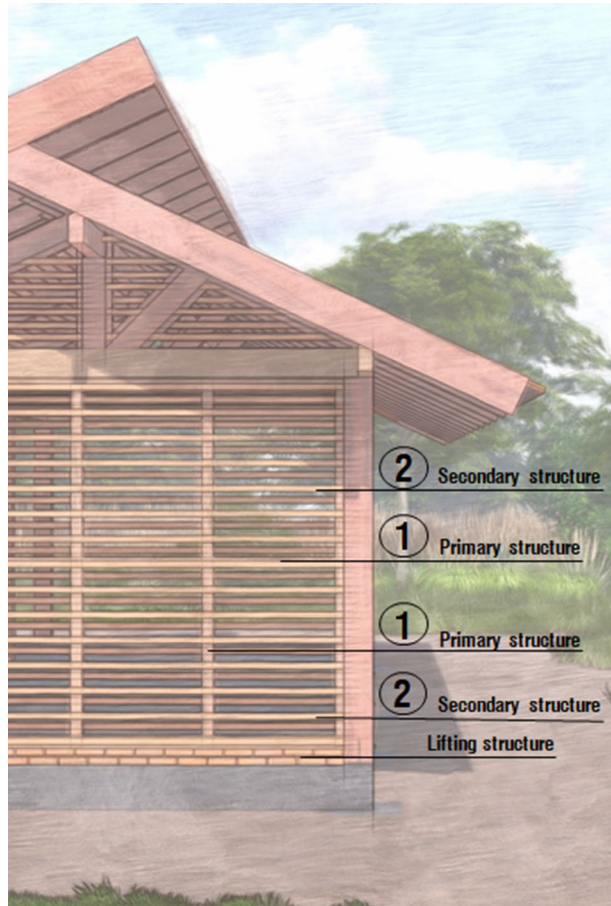
These frameworks serve as the internal structural core of the wall, providing support for the earthen coating (Fig. 3). Such structures are generally composed of vegetal or industrial materials [7]. Examples include frameworks made from wood, bamboo, or metallic mesh, as well as prefabricated wooden panels. Unlike monolithic earth construction techniques, mixed-earth techniques can be implemented after the building's roof has been erected. This approach offers practical advantages, as it allows for the assembly of the framework and the application of earth to occur under protection from adverse weather conditions. As a result, mixed-earth walls are often autonomous structures, which enables the use of different materials in their construction [8].

The application of earth to these frameworks is carried out through a process known as earth plastering, or *barreamento* in Portuguese. The use of earth as a sealing material enhances the thermal inertia, hygroscopicity, and acoustic performance of the structure, while simultaneously protecting the internal framework from external environmental factors. To facilitate cohesion during the plastering process and to improve key properties such as elasticity—essential in this construction system due to the dilation and vibration of the supporting structures—stabilizers are incorporated into the earth mixture [7].

The typical composition of the earth used in mixed-earth techniques is approximately 50% sand, 30% silt, and 20% clay, with the addition of fibers and natural or synthetic stabilizers to improve mechanical strength, durability, impermeability, and plasticity. The most commonly used stabilizers and fibers include quicklime, hydrated lime, vegetable latex, animal or vegetable fats, manure, straw, and hay. However, the specific choice of materials may vary depending on the resources available at the construction site [7].

The combination of earth and fibers results in a porous material that is inherently susceptible to weathering. Therefore, it is essential to provide adequate protection through the application of earth plastering or other forms of coating to safeguard the structure against environmental degradation.

**Fig. 3** Building structure with (1) primary and (2) secondary wattle and daub structure



### 3 Recyclability of thermoplastic

Thermoplastics are polymers that soften and flow when exposed to specific temperatures and pressures. Once these conditions are removed, the polymer undergoes a solidification process, resulting in the formation of the intended product. The application of heat and pressure can be repeated multiple times, allowing thermoplastics to regain their malleability and fluidity. This reversible process facilitates the reuse and recycling of these materials [9]. The majority of thermoplastics are produced through compression molding, injection molding, or extrusion processes, which enable large-scale manufacturing of objects with precise dimensions and shapes. The properties of polymers make them particularly appealing due to their malleability, lightweight nature, impact resistance, resistance to decomposition, and corrosion resistance, along with their relatively low maintenance costs. However, thermoplastics exhibit distinctive molecular structures that limit their capacity for compositional blending with other materials [10].

Despite the indispensable role of plastics in contemporary society, inadequate waste management has led to significant environmental challenges due to the large volume of materials produced. Fortunately, a substantial proportion of these materials can be recy-

ced, thereby transforming them into secondary raw materials. Advances in recycling processes, combined with progress in thermoplastic forming techniques, have facilitated the production of higher-quality products at reduced costs. These advancements have markedly enhanced the manufacturing and implementation of recycled thermoplastics across various industries in recent years [5].

In 2022, high-density polyethylene (HDPE) accounted for 12.2% of global thermoplastic production, corresponding to approximately 50 million tonnes. In Europe, an estimated 54.1 million tons of plastic were consumed in 2022, with the construction market maintaining second place, accounting for 22.9% of the total consumption, equivalent to approximately 12.5 million tons of plastic. It is noteworthy, however, that the construction market leads in post-consumer recycled plastics conversion by application, demonstrating significant interest in the applicability of recyclable and recycled materials, representing 41.2% of the total volume, equivalent to 2.8 million tons [5]. Despite the pervasive utilization of thermoplastics in the construction market, there are presently no analogous examples comparable to the innovation under development in this investigation. This underscores the innovation of the latter, while also indicating the need for further exploration in the scientific domain.

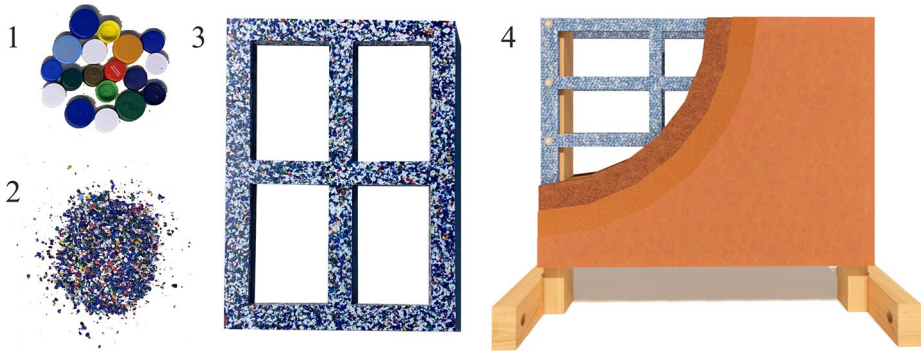
To enable the development of r-HDPE structures for this investigation, the methods of *Precious Plastic* were employed. Since 2012, *Precious Plastic* has established a global open-source network where diverse users create products derived from recycled thermoplastics, such as High Density Polyethylene, Polypropylene, and Polystyrene, for the production of furniture, objects, and utensils.

The advantages of HDPE include its recyclability and its versatility in production processes such as compression, extrusion, and injection molding. These processes enable precise control over the quantity of thermoplastic material used, thereby minimizing material waste during manufacturing. The aim of this research is to employ recycled thermoplastics to produce prefabricated frameworks by recovering substantial volumes of plastic waste. This waste is subsequently processed and densified to create rigid structural components with an extended life cycle (Fig. 4).

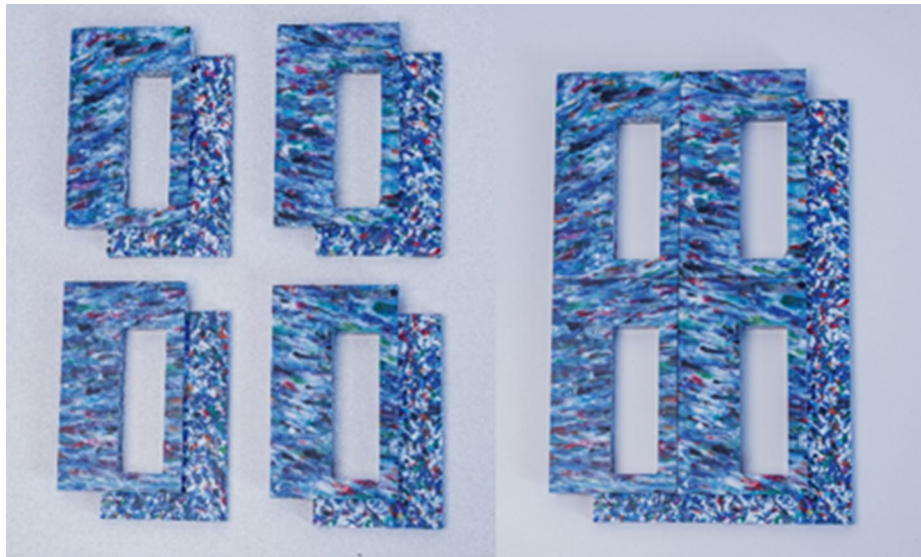
This investigation focuses on two thermoplastic forming processes: compression molding, in which thermoplastic material is compressed within a heated mold, and injection molding, where thermoplastic in a viscous fluid state is injected into a mold cavity. Both processes facilitate the fabrication of panels with continuous lattice structures. Unlike wooden lattice panels, which require joints to connect multiple elements, thermoplastic lattice panels can be produced as continuous, monolithic structures.

The extrusion molding process enables the continuous production of individual components with varying cross-sections and lengths. Among the extrusion-based forming methods, Fusion and Deposition Molding—also known as 3D printing—stands out due to its innovative developments and future potential. These forming processes, when combined with advancements in design and manufacturing software such as Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and Computer-Aided Manufacturing (CAM), establish a seamless digital workflow from conceptualization to quantification and production, thereby enhancing efficiency in construction applications (Fig. 5).

It is essential to recognize that thermoplastics exhibit viscoelastic properties, combining the characteristics of both viscous fluids and elastic solids. One of the most significant limitations on the use of thermoplastic structures is their sensitivity to temperature. This is



**Fig. 4** Process of transforming HDPE caps into panels for r-HDPE prototypes. (1) HDPE caps; (2) ground caps; (3) panel r-HDPE; (4) illustration of prototype with earth



**Fig. 5** Prototypes for analyzing connection points between recycled High Density Polyethylene structures

because viscoelastic materials lose their rigidity when exposed to elevated temperatures, which poses a critical challenge for their application as structural materials [11].

## 4 Methods

The objective of this research is to explore the constructive potential of a mixed-earth technique that incorporates prefabricated lattice frameworks made from recycled high-density polyethylene (HDPE) thermoplastic. This approach enables the use of locally available materials for the construction of non-structural walls in single-family dwellings. The aim is to develop a construction technique that integrates earth—a malleable and recyclable mate-

rial that can potentially be sourced directly from the construction site—with recycled HDPE to create secondary structural elements that support the earthen coating (Fig. 6).

The proposal seeks to establish a circular economy model based on open-loop recycling. This research project aims to investigate the potential of thermoplastic recycling and the sustainable application of earth in construction.

The soils under examination were sourced from two locations: one from a private property in Palmela, Portugal, and the other from the Instituto Superior de Agronomia (ISA) at the University of Lisbon, Portugal. This approach enables a comparative analysis of soils from distinct geographical regions.

The recycled HDPE structures are produced using HDPE caps, with the sorting and processing activities carried out in collaboration with FabLab Lisboa, utilizing recycling and production methods from *Precious Plastic*. The production process involves mechanical recycling and compression molding techniques. The objective of this research is to propose a construction process that supports an open life cycle for the materials. This approach would enable the reuse or return of the earth to its natural state, the repurposing of the wooden primary structures, and the recycling and reuse of the thermoplastic secondary structures in the same or alternative applications.

Given this objective, it is essential to consider the composition of the earthen material. The research, therefore, incorporates only sand (as a physical stabilizer), hydrated lime (as a chemical stabilizer), and natural fibers [12]. In contrast, the thermoplastic prototypes are composed exclusively of high-density polyethylene (HDPE), without the inclusion of other thermoplastics, chemical additives, or fibers. This design choice facilitates future mechanical recycling processes and ensures the integrity of the recycled material [13].

Laboratory and field tests are conducted to perform a quantitative and qualitative analysis of the earthen material, aiming to characterize the soil and determine its optimal composition (Fig. 7). This analysis involves the examination of granulometric distribution, plasticity, and water-related behavior, including absorption, drying, and shrinkage. These physical characterization tests are conducted in accordance with the standards and specifications established by LNEC.

The following standards and specifications are applied:

- **E195-1966:** Soils: Dry preparation of samples for identification testing.
- **E239-1970:** Soils: Wet sieving granulometric analysis.

**Fig. 6** Application of earth plaster on the PA4 Prototype, consisting of two prefabricated lattices in recycled high-density polyethylene with dimensions  $800 \times 450 \times 20$  millimeters each panel



- **E196-1966:** Soils: Granulometric analysis.
- **NP83-1965:** Soils: Determination of particle density.
- **NP84-1965:** Soils: Determination of water content.
- **NP143-1969:** Soils: Determination of consistency limits.

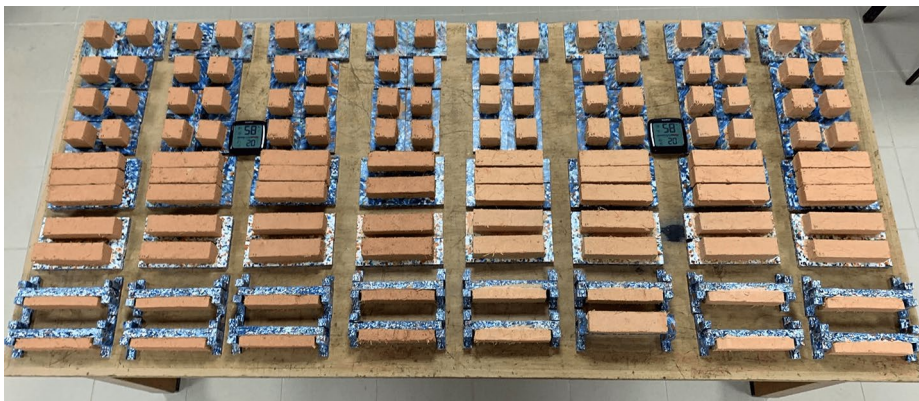
Expedited tests are also conducted to facilitate the analysis of soil granulometry, workability, and shrinkage. These tests include the odor test, drop ball test, glass test, cord test, ribbon test, dry tablet test, and exudation test. The results obtained from these field tests are subsequently compared to those derived from laboratory analyses to ensure consistency and accuracy [3].

The second phase will utilize soil sourced from the Instituto Superior de Agronomia for the testing of Prototypes B. Prototypes PB1, PB2, PB3, and PB4 correspond, respectively, to Prototypes PA1, PA2, PA3, and PA4 (Fig. 8). The third phase will employ soil of an identical composition to that used in the second phase, which will be applied to Prototypes C1 and C2. These prototypes have surface dimensions exceeding one square meter and are composed of eight panels, each with a dimension of  $600 \times 600 \times 20$  millimeters, made from recycled HDPE, allowing for a detailed analysis of the connection points.

The primary objective of this study is to evaluate the compatibility of different soil characteristics with recycled HDPE structures. To achieve this, the prototypes will be subjected to mechanical tests to assess their deformation under applied loads and to analyze their structural and constructive properties.

Earth serves as a protective material, shielding the HDPE structures from potential environmental and functional challenges, such as flammability, temperature sensitivity, UV degradation, and solvent exposure [14].

All laboratory and field activities are part of a direct observational experimental process, which will be meticulously documented and substantiated. The laboratory processes for the production and analysis of samples and prototypes will be carried out at the laboratories of the Faculdade de Arquitetura da Universidade de Lisboa (FAUL) in collaboration with the Engineering Research and Innovation for Sustainability (CERIS) laboratories at the Instituto Superior Técnico (IST) and the Instituto Superior de Engenharia de Lisboa (ISEL).



**Fig. 7** Composition analysis of soil samples: earth, sand and straw & earth, sand, lime and straw. For the analysis of the different behavior in flexion and compression, the samples have variations in their compositions

**Fig. 8** Earth plastering process of the PA4 prototype. Prototype dimension  $800 \times 450 \times 160$  millimeters, composed of two panels measuring  $800 \times 450 \times 20$  millimeters each



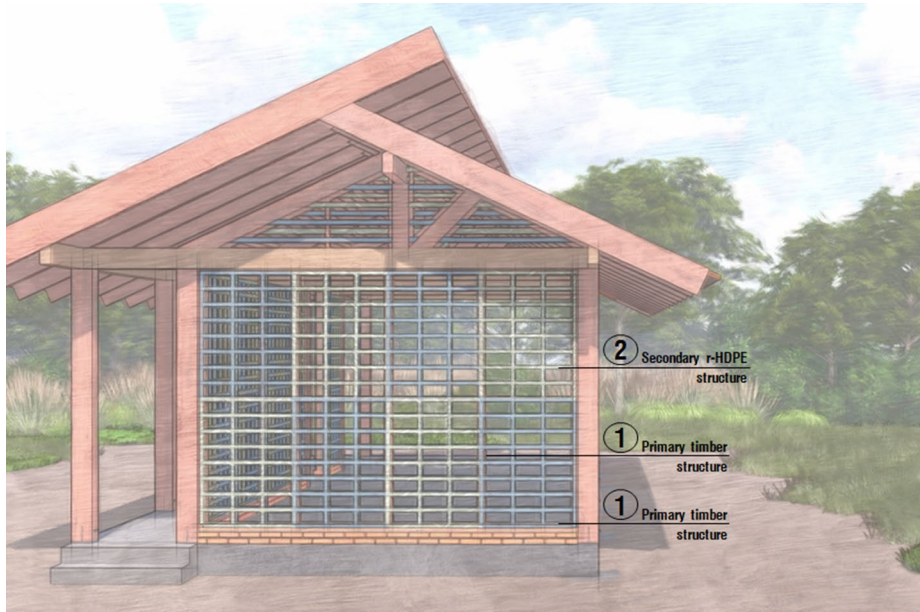
## 5 Results

To use soil in the mixed earth technique, it is preferable that the collected soil has a composition of approximately 50% sand, 30% silt, and 20% clay [7]. This composition is based on literature from Brazil; however, due to the universal nature of soil, it was possible to collect soil with similar characteristics in Palmela, Portugal. This highlights the potential for replicating the mixed earth technique across different continents. Notably, in both mentioned countries, mixed earth techniques are utilized and hold historical significance.

The analysis of the earth samples involved variations in the addition of coarse and fine sand, lime, wheat straw, and water. The composition of the earth mortar used in the first phase of the prototypes consists of 60% soil, 40% sand (75% fine sand and 25% coarse sand), 5% hydrated lime (calculated as a percentage of the total mass of soil + sand), 0.5% wheat straw measuring 5 to 15 centimeters (calculated as a percentage of the total mass of soil + sand), and 21% water (calculated as a percentage of the total mass of soil + sand + lime). The variation between fine and coarse sand was due to the observation that fine sand provided better cohesion with the plastic structures, while coarse sand yielded better results in bending and compression tests. Due to the use of plant fibers, samples without lime exhibited mold growth, which necessitated the addition of hydrated lime.

High-density polyethylene (HDPE) demonstrates excellent physical characteristics, even when recycled, and is the most rupture-resistant material in the *Precious Plastic* method. The choice to use HDPE derived from bottle caps is strategic, as it allows for collection in different countries.

The sorting process involved separating HDPE from other plastics, washing the bottle caps, drying them, and shredding the material. The shredded material was placed in a compression mold heated to  $175\text{ }^{\circ}\text{C}$ , with the heating time varying from 20 to 60 min depending on the thermoplastic granularity, mold type, and dimensions. After the molding process, the mold and material were cooled under compression to prevent deformation during cooling. The cooling time also varied from 20 to 180 min based on mold dimensions. No composites were added to the plastic structures. Analyses of thermoplastic shrinkage and material strength will be presented in subsequent phases.



**Fig. 9** Wattle and daub structure with (1) primary timber structure and (2) secondary recycled High Density Polyethylene structure

Due to the hydrophobic characteristics of HDPE, smooth surfaces do not adhere well to earth-based mortar, requiring the structure to have a certain degree of roughness. Therefore, tests are being conducted to vary the shape and surface texture of the contact faces with the earth mortar (Fig. 9).

The investigation will limit its results to observations of prototype behavior and mechanical testing. Future studies in engineering fields are deemed necessary to perform physical and chemical analyses to enhance the use of recycled HDPE as a structural material, particularly considering factors such as the flammability of thermoplastic materials.

## 6 Conclusion

The results of this study highlight the potential of the combined use of mixed-earth techniques and recycled thermoplastics, specifically HDPE, for the development of innovative and sustainable solutions in the construction sector. The ideal soil composition, with approximately 50% sand, 30% silt, and 20% clay, allows an effective application of mixed earth techniques in different geographical contexts, as demonstrated by the samples collected in Palmela, Portugal, and by the compatibility with studies carried out in Brazil. This observation underlines the universality of the technique and its viability in diversified scenarios, while maintaining a link with tradition and empirical knowledge.

In the development of the prototypes, it was essential to adjust the composition of the soil and additives, observing the effects of each variation in the flexural and compressive strength tests. The use of hydrated lime proved crucial in preventing the development of molds in samples with plant fibers, highlighting the need for a careful balance between natu-

ral components and chemical modifiers. The inclusion of fine and coarse sand in specific proportions proved to be decisive in optimizing the mechanical properties and adhesion of the mortar to the plastic structures.

Recycled HDPE obtained from bottle caps has proven to be a highly resistant and efficient material, with a mechanical recycling process that maximizes material utilization and minimizes losses. Although no compounds are added during the molding process, the smooth surfaces of HDPE require texture modifications to improve its adhesion to earth mortar. This finding underlines the importance of continuing to explore solutions to increase surface roughness, potentially through precision technologies such as CAD, CAE, and CAM, and the use of robotic arms.

This study also highlights the complementarity between the plasticity of the earth and the structural versatility of recycled HDPE. This combination promotes unprecedented creative freedom in design and creates opportunities for digitally optimized and environmentally conscious construction processes. However, further research is needed, particularly in the field of engineering, to analyze the physicochemical behaviors of materials and improve the safety, durability, and efficiency of recycled HDPE in structural contexts.

Finally, the lack of precise regulation for mixed earth techniques points to the need for standardization efforts that can consolidate sustainable and safe practices in this area. This work thus contributes to the promotion of a construction system that combines tradition, innovation, and sustainability, with meaningful implications for the development of policies, adoption of environmentally responsible construction practices, and advancement of technical and scientific knowledge in the area.

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**Author contributions** With the exception of point 4, whose laboratory methodology was carried out by Valdomiro Ceolin, all authors contributed to the writing of the text. Valdomiro Ceolin is responsible and author of all the figures in text.

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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