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ABSTRACT

The contemporary construction industry faces significant challenges, necessitating a response to multiple issues: reducing material resource consumption, minimizing construction waste, transitioning to carbon-neutral building methods, and fostering a circular, local, and inclusive economy. The recycling of raw earth adobes, an ancient architectural practice still employed today, appears to meet all these criteria. This study addresses the potential alterations in the physical properties of high chalk content adobes undergoing multiple cycles of reconstitution. The investigated primary adobes were collected from a recently demolished 19th century barn near Épernay, in the Champagne region located in northeastern France. During the recycling process, the bricks underwent dry crushing, wetting, mixing, molding, and drying. Careful attention was given to reproducibility through controlled water content and manual compaction techniques. Next, physical, mechanical, and thermal tests were performed. The findings indicate that the mechanical and thermal properties remain consistent over several recycling cycles. For example, mechanical tests across three recycling cycles demonstrated that the normalized peak compressive stress is barely affected. In complement, thermal conductivity and diffusivity measurements showed minimal variation across cycles, confirming that recycling did not impact these thermal parameters. The substitutability of raw earth, defined as the ability of the recycled material to reach levels of performance comparable to the original, is evidently robust. In view of these promising results, future research works should explore the possibility of combining raw earth from recycled adobes with additives such as plant-based ash, with the potential goal of improving its durability, mechanical strength, and moisture resistance.

1. Introduction

The amount of waste generated by cities continues to rise, leading to critical issues, including limited landfill space, inadequate

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disposal methods, environmental pollution, inefficient recycling facilities, and suboptimal waste collection systems [1]. According to the World Bank, urban waste generation is projected to increase by 70 % by 2050, reaching an estimated 3.4 billion metric tons per year if current trends continue [2]. Notably, construction and demolition debris account for a significant proportion, estimated at approximately one-third of the total waste generated in urban areas [1,3]. This phenomenon not only exacerbates the strain on existing waste management systems but also poses a significant threat to environmental sustainability and urban livability.

In response to these challenges, regulations worldwide are striving to enhance circularity by promoting the reuse and recycling of construction and demolition materials [4,5]. Initiatives such as the European Union's Circular Economy Action Plan and various local policies aim to divert construction waste from landfills and encourage practices that prioritize resource recovery and material reusability [6]. However, recycling is not clearly defined and encompasses a diverse range of practices that differ significantly in their sustainability outcomes [7–9]. This variability highlights the need for more precise criteria to evaluate the effectiveness of available recycling methods.

The complexity of recycling practices is further underscored by the diverse range of materials involved and the varying degrees of energy input required for their processing. For instance, some materials, such as metals and plastics, can be recycled efficiently with high recovery rates. Others, such as composite materials, still face a number of obstacles that hamper their recycling [10]. As a result, several authors have focused on assessing recycling quality and the sustainability of different recycling practices [4,8,10]. According to Morel et al. [11], most conventional building materials are extracted from bedrock and geological deposits and undergo chemical modifications during manufacturing, which hinders their ability to be recycled at low energy costs. In contrast, earth architecture utilizes materials sourced from the subsoil, enabling them to be completely recycled without loss through the value chain, a seamless alignment with the principles of a circular economy [12].

Research has indicated that while both conventional and earth-based building materials are deemed recyclable, their recycling quality differs significantly. Studies have shown that the embodied energy associated with the recycling of conventional materials can often be higher than that of earth-based materials, primarily due to the energy-intensive processes involved in extracting and processing these materials [13].

It is crucial to recognize that recycling quality involves multiple parameters [8]. In this paper, we will focus on substitutability, which is regarded as a primary parameter for assessing recycling quality. Substitutability refers to the extent to which a recycled material can fulfill the same functions as the original material without the addition of other elements [8,10]. The recyclability of Compressed Earth Blocks (CEB) after three recycling stages has been investigated by Bruno et al. [13] and Audren et al. [14]. They observed a slight decrease in the size of the largest particles in untreated earth; however, the performance of CEBs remained consistent after three recycling stages, indicating that earth exhibits high substitutability potential.

Building on this foundation, the present work aims to assess the reuse potential of another earth-building technique: adobes made from uncommon earth, specifically highly chalky soils, such as those found in the Champagne region of France [15]. The process of constructing new adobes from ancient ones involves two main steps: dry crushing and water addition. However, chalk is particularly sensitive to both processes, tending to turn into powder during dry crushing and becoming a slurry upon water addition. This sensitivity raises concerns about the reproducibility of its properties across successive recycling cycles, especially regarding changes in particle size distribution (PSD).

To investigate these concerns, vernacular chalky earth bricks underwent destruction-wet remolding cycles, and the resulting

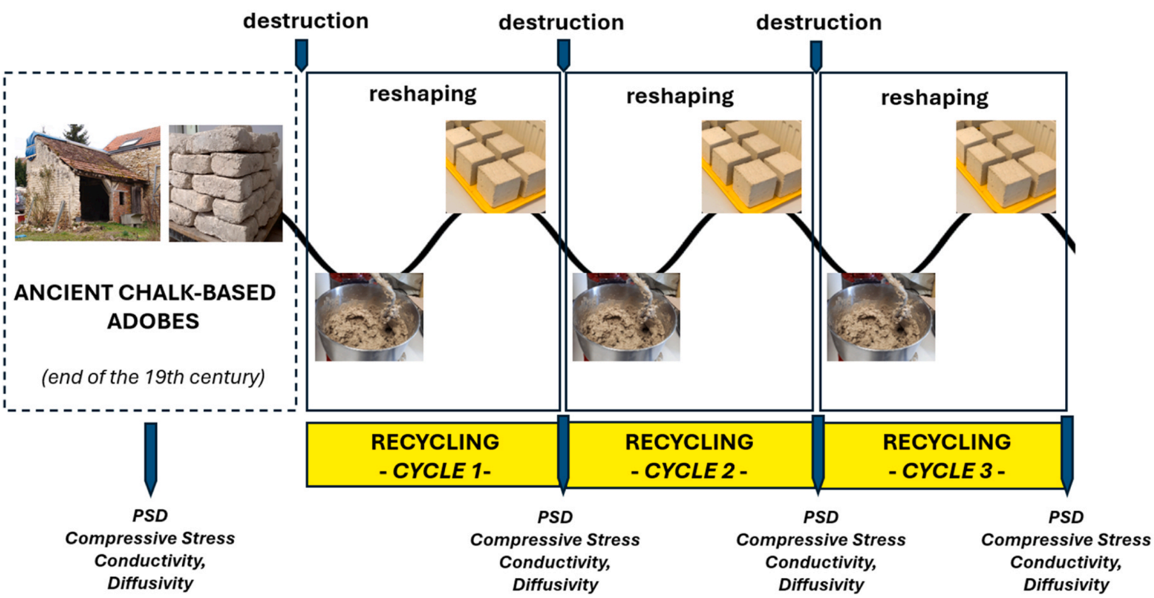

Fig. 1. Synopsis of the consecutive recycling cycles and multiphysical measurements of chalky adobes.

changes in particle size distribution, compressive strength, and thermal properties—such as conductivity and diffusivity—were investigated. The overall workflow which comprises the successive stages of destruction/reshaping/multiphysical characterization is presented in Fig. 1.

By examining these aspects, this research aims to contribute valuable insights into the recycling potential of adobe materials, further promoting sustainable building practices within the framework of circular economy principles. Through a better understanding of the properties and performance of recycled adobes, the study seeks to inform future construction methodologies that prioritize resource efficiency and environmental stewardship.

2. Materials and methods

2.1. Ancient adobes

To support our study, bricks were collected, near Epernay, in the Champagne area (Grand-Est, France), from a barn built in the late 19th century and recently demolished. These bricks were considered as the primary adobes (Fig. 1), and they were found to have width (W) = 139.2 mm (± 8.4 mm); height (h) = 85.1 mm (± 6.2 mm); and length (L) = 264.5 mm (± 12.6 mm). The surface texture is rough with apparent centimetric inclusions and holes. Most of the vertices appear to have been damaged, which may be attributed to the demolition process (removal of mortar joints), transport (shocks) and ageing (erosion). The material used for the earth bricks was categorized as water-sensitive loamy soil [16], following the guidelines outlined in the French Ministry of Transport's technical manual for road earthworks, known as the "Guide des Terrassements Routiers" [17]. We sourced approximately one hundred of these bricks (see Fig. 2), which were analyzed for granulometry, mechanical, thermal, and hydric performance. The results, recently published by Polidori et al. [16], revealed a clay content of 14 % and a very high limestone concentration of 71 % across all granulometric levels. For example, gravel-sized particles turned out to be composed entirely of chalk, which was also present in sand-size particles as aggregates of calcite crystals or fragments of mollusk shells (also composed of calcite). The analysis, based on the Scheibler method, showed that the included chalk is highly pure, containing 95 % calcium carbonate, with the remaining 5 % composed mainly of insoluble materials [16]. At the loam/silt sizes, smaller chalk aggregates and microfossils (coccoliths and foraminifera) were observed (see Fig. 3). Finally, the clay-sized particles (below 2 μm) also contain calcite, corresponding to nanograins of chalk mudstone and fragmented coccoliths.

2.2. Adobe manufacturing process

One of the key aspects in the comparative study of adobe recycling cycles was to ensure adequate reproducibility in the manufacturing process of successive samples. Masons could choose between two different modalities: soaking ancient bricks collected from demolition until their water content is sufficient for proper workability or crushing the ancient adobes and adding water to accelerate the creation of a paste. The latter was preferred since it appeared to be the most likely to affect the properties of adobes throughout successive reusing cycles, mainly because of the risk of altering the particle size distribution. Consequently, the laboratory process involved four stages: crushing with a hammer into coarse pieces (largest dimension between 5 and 10 cm), wetting, mixing, molding, and drying of the samples (see Fig. 4). Special attention was given to achieving a high level of reproducibility in the manufacturing process. A single operator performed both the destruction and molding of the bricks. For this purpose, a kitchen mixer set to a low mixing speed was employed to homogenize the mixture of crushed adobes and water, while minimizing the impact of the mixing process on particle size distribution. For each cycle, an identical water mass ratio of 26 % was added to achieve good plasticity and enhanced workability in manufacturing the new adobes. This water content closely aligns with the value of 25 % reported in the literature for optimal plasticity [18,19].

Specific 3D-printed prismatic molds of dimensions 10x10x10 cm^3 were used to obtain the new samples (see Fig. 4c). Although the earth bricks under study are uncompressed, manual compaction within the mold was necessary to ensure that the material occupied

Fig. 2. Bricks collected from a 19th century barn near Épernay (Grand Est, France).

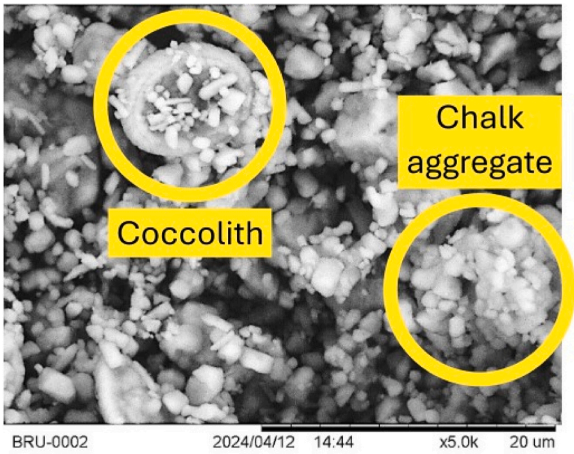

Fig. 3. Evidence of chalk aggregates and coccoliths in the mother brick from SEM.

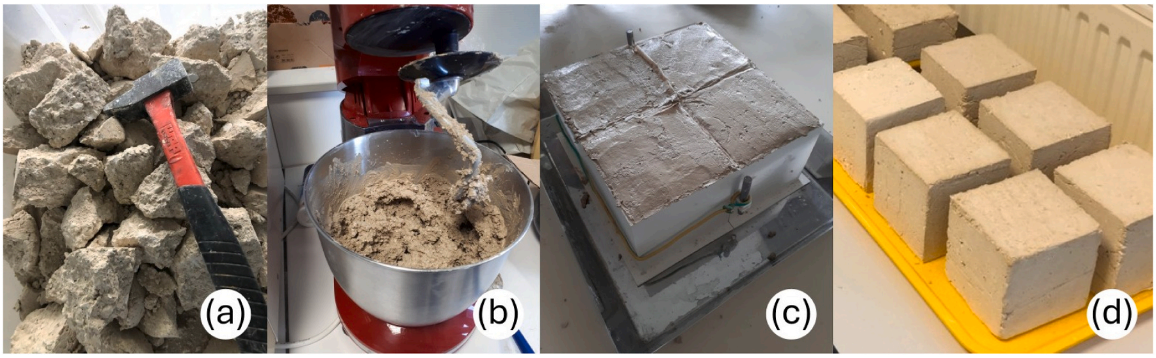

Fig. 4. Adobe manufacturing process: (a) crushing; (b) wetting/mixing; (c) molding; (d) drying.

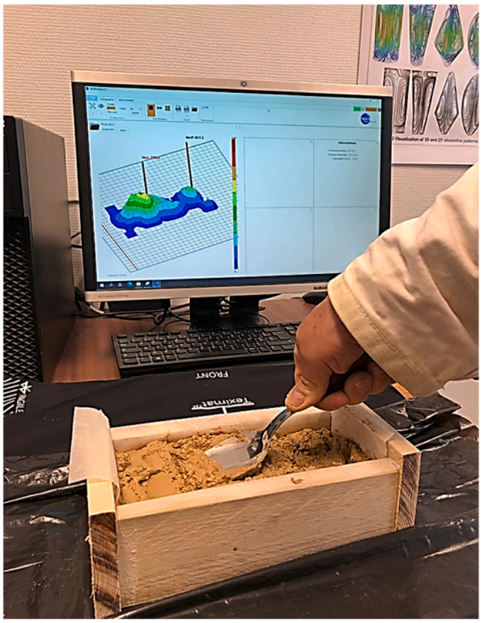

Fig. 5. Methodology for experimental determination of manual pressure threshold in mold filling.

the entire prismatic volume and achieved the desired brick shape, as required for upcoming experimental tests. Assessing the manual compaction threshold was a critical parameter, as it directly impacted the compressive strength of the resulting adobe. For this purpose, a pressure mat was placed below the mold during compaction (see Fig. 5), revealing that the manually exerted pressure did not exceed 7.4 kPa. This value was significantly lower than the pressures generated by mechanical or hydraulic presses used for compressed bricks, which were estimated to be between 25 and 100 MPa, respectively [20].

Table 1 summarizes the physical properties of the samples tested across different recycling cycles. For comparison, data from the primary adobes were also included, although a direct comparison between recycled and initial bricks was not feasible due to the unknown fabrication methods of the latter. It was evident that the manual compaction of recycled bricks, although seemingly negligible compared to the values used for compressed bricks, was nonetheless stronger than that of the old bricks. This was indicated by a decrease in porosity from 34.6 % to approximately 25.5 %, and consequently, an increase in dry bulk density from an average of 1435 kg/m^3 to an average of 1643 kg/m^3 . The maximum relative difference between dry densities across cycles did not exceed 0.6 %, and the maximum absolute variation in porosity remained below 0.8 %, confirming good reproducibility of the manufacturing conditions across cycles. Additionally, the average dry density of 1643 kg/m^3 falls within the typical dry density range for adobe masonry, which varies between 14.13 and 25.07 kN/m^3 [21]. Moreover, this average value is close to the 1780 kg/m^3 reported by Rojat et al. [22], who classify this level of compaction as good. For all cycles, cubic samples measuring 10x10x10 cm^3 were produced. Experiments were conducted under ambient conditions (22°C and 55 % RH). For the sake of reproducibility, five samples per cycle were mechanically and thermally tested.

2.3. Particle size distribution

To better understand how the recycling cycles might alter the properties of adobes following successive demolition and reshaping processes, a preliminary granulometric analysis was conducted. Particle size distribution analysis was performed on randomly selected samples, with a set of sieves covering a range from 10 mm to 25 μm. To ensure reproducibility, each experiment was repeated three times.

2.4. Compression tests

Compression tests were performed using a Zwick Roell Z050 (Ulm, Germany) testing machine equipped with a 50 kN load cell (see Fig. 6a). These tests were conducted under controlled indoor conditions, with a room temperature of 23°C and 50 % relative humidity. The compression rate was set to 8 mm/min following NF XP P 13–901 specifications, resulting in specimen fracture within 1–2 minutes. To ensure statistical reliability, compressive strength analysis typically averages results from 5 to 10 samples [23]. In this study, seven adobe specimens having cubic shape 10x10x10 cm^3 were tested.

2.5. Thermal analysis

Thermal properties were assessed using the thermal characteristics analyzer ISOMET 2114 (Applied Precision, Ltd., Bratislava, Slovakia) based on heat flux pulses applied at the material surface (see Fig. 6b). Five specimens were analyzed to determine the thermal conductivity and diffusivity of the adobes.

3. Results and discussion

3.1. Particle size distribution

The granulometric study was conducted using wet sieving and nine sieves with mesh sizes ranging from 10 mm to 25 μm in descending order. The resulting average curves are shown in Fig. 7. The initial observation is that all the curves, whether associated with the primary adobe or the recycled ones, exhibit a similar, classically sigmoidal shape. Inherent in crushing the old adobes to fabricate new ones, the granulometry is significantly altered, with an increased percentage passing through the sieves by approximately 10–15 %. Subsequently, across the crushing cycles, a successive yet more limited reduction in grain sizes is observed, as the

Table 1
Mean physical properties of adobes - data for ancient adobe from Polidori et al. [16].

	Ancient Adobe	Recycled Adobe		
		Cycle 1	Cycle 2	Cycle 3
Manufacturing process	*Unknown*	*Known*	*Known*	*Known*
Absolute density (kg/m^3)	**2240**			
Dry density (kg/m^3)	**1435**	**1640**	**1649**	**1639**
Porosity (%)	**34.6**	**25.8**	**25.1**	**25.4**
Moisture content (%)	**2.0**	**1.3**	**1.7**	**1.6**
$CaCO_3$ content (%)	**71**			
Clay content (%)	**14**			

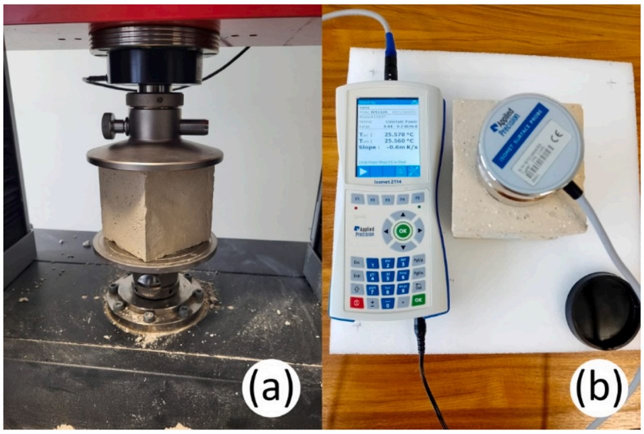

Fig. 6. Mechanical (a) and thermal (b) setups used.

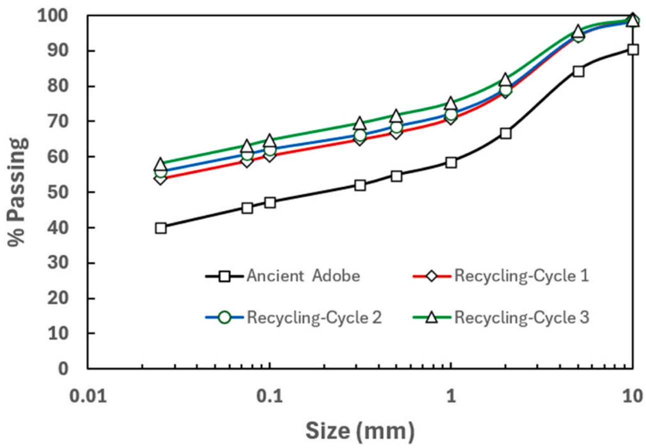

Fig. 7. Particle size distributions of investigated bricks across recycling cycles. The ancient, primary adobe curve is plotted for reference.

fraction of fines in the material increases. This confirms the initial hypothesis that for adobes with a high chalk concentration, recycling from crushing tends to reduce the size of stone aggregates by separating or breaking them, due to the low resistance of this specific geomaterial. The outcome, stemming from laboratory test campaigns, may have been more nuanced in real on-site conditions. Indeed,

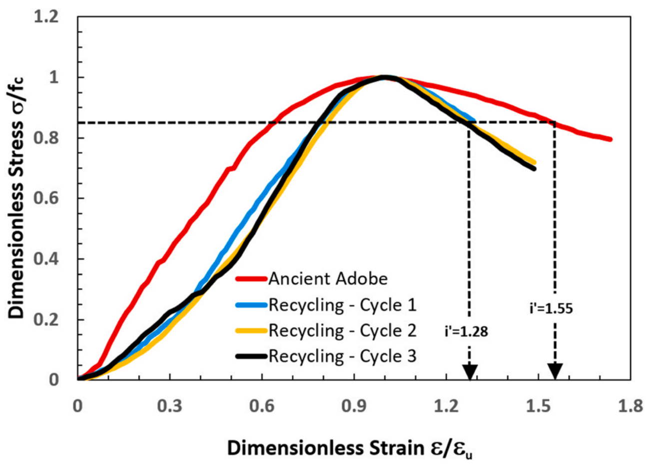

Fig. 8. Normalized stress-strain evolution.

masons may choose between two different modalities: crushing or soaking ancient bricks collected from demolition until their water content ensures proper workability. If soaking was chosen, it is likely that the granularity would be less affected. Naturally, to support our study of the impact of post-recycling on adobe properties, we have placed ourselves in the most unfavorable situation, i.e. crushing.

Therefore, the question arises regarding whether the alteration in chalk grain sizes affects the properties of the new adobes, potentially influencing the overall cohesion with clays present in the geomaterial.

3.2. Compression stress

From a mechanical perspective, for a comprehensive analysis of the stress-strain curves of both ancient adobes and newly reconstituted adobes, we initially opted for a normalized representation, as shown in Fig. 8. The y-axis designates the dimensionless compressive stress defined as σ/f_c where f_c stands for the maximum compressive stress and the x-axis designates the dimensionless strain $\varepsilon/\varepsilon_u$ where ε_u is the strain associated with f_c. All curves resulting from the three recycling cycles adhere to the same standardized law of overall behavior.

This normalized representation is particularly suitable for comparing the ductility of different materials, as it scales the curves uniformly along both axes [24]. Ductility refers to a material's ability to deform without fracturing, thus characterizing its plastic behavior before failure. Imanzadeh et al. [24] introduced a new ductility index denoted as i' in the post-peak region, associated to the value of normalized strain when the normalized stress drops to 85 % of its maximum value. A condition of $i' = 1$ indicates brittle failure, where the material hardens steadily and then fractures abruptly upon reaching its peak strength. Fig. 8 shows that the recycling process does not significantly affect ductility, as all three normalized stress-strain curves exhibit a consistent ductility index of $i' = 1.28$. For reference, the reformed samples demonstrate lower ductility compared to the ancient adobe ($i' = 1.55$). This observation can be attributed to a 14.5 % increase in dry density and an approximately 15 % increase in the mass of fine grains of the reconstituted adobes. Consequently, it can be stated that the observed difference in curvature during the consolidation phase reflects varying compaction of the granular soil matrix. Besides, this higher compaction improves the closure of natural microcracks in the porous material stabilized with the clay binder for the reconstituted adobes.

In this investigation, the mean peak stress was determined to be $f_c = 1.38$ MPa for the three recycling cycles, with a maximum relative difference between cycles not exceeding 1.5 %. The corresponding results are shown in Fig. 9. Thus, it can be affirmed that reusing adobes, even when derived from highly chalky soil, does not induce modifications in their mechanical properties.

The peak stress value for ancient adobes in Fig. 9 is purely indicative. Indeed, direct comparison between the ancient adobes and the newly fabricated ones cannot be considered scientifically robust, in view of the obvious differences in geometry, construction method, density, or porosity. Furthermore, the old adobes have been dismantled, transported several times, or cut up, resulting in non-negligible damage contributing to their fragility.

3.3. Thermal conductivity and diffusivity

The results concerning the measurement of thermal conductivity and diffusivity are presented in Fig. 10, along with the corresponding standard deviations on a highly expanded scale. Firstly, it is observed that results closely align across the three recycling cycles. The mean values recorded and the maximum relative differences between cycles are respectively 0.717 W/(mK) and 1.4 % for conductivity, and 0.430×10^{-6} m^2/s and 4.8 % for diffusivity. These differences fall within the range of standard deviations, indicating that recycling has no impact on these thermal parameters.

It is noteworthy that the average value calculated for thermal conductivity aligns with the typical range for adobes, i.e. 0.5–1.2 W/(mK) as suggested by Rempel and Rempel [25], or 0.46–0.81 W/(mK) mentioned by Adam and Jones [26] for adobe blocks having a density range of 1200–1700 kg/m^3. The diffusivity and conductivity measured on the primary adobe are slightly lower, which is also linked to the compaction process that reduced the material's porosity and increased its dry density.

4. Discussion

Particle size evolution is observed under the effect of crushing [13,14]. A perspective of this work would be to study the recycling of raw earth elements with gentler processes. For example, we can draw inspiration from site practices that involve exposing extracted earth to weathering (rain and freeze-thaw cycles) for an entire winter to make it easier to work with [27]. This would likely limit the particle size fraction changes caused by crushing.

The results obtained in our study are consistent with those of two previous studies [13,14], which report that the mechanical, hygrothermal, and durability performances are retained after 3 recycling cycles. The substitutability of raw earth, i.e., the ability of the recycled material to perform the same function as the original material, seems perfect.

The bonding of raw earth materials is typically ensured by the presence of clay and a small amount of water, which generate suction forces. A significant increase in the water content of the material, leading to pore saturation, results in the loss of material cohesion [23]. Therefore, the cohesion of the material is reversible: the ease of recycling this type of material lies in this reversibility. Moreover, the use of raw earth presents a strong originality compared to earth treated with hydraulic binders, fired earth, concrete, steel, aluminum, or glass. Actually, although these processed materials display higher water and/or mechanical resistance than raw earth, their recyclability is made very difficult due to their irreversible bonding [13,14,28,29].

On the other hand, clays, which are responsible for cohesion, are not affected by the recycling cycles [14]. The material retains its cohesive properties indefinitely. Therefore, it has the capacity, for identical implementation, to reproduce the same microstructure

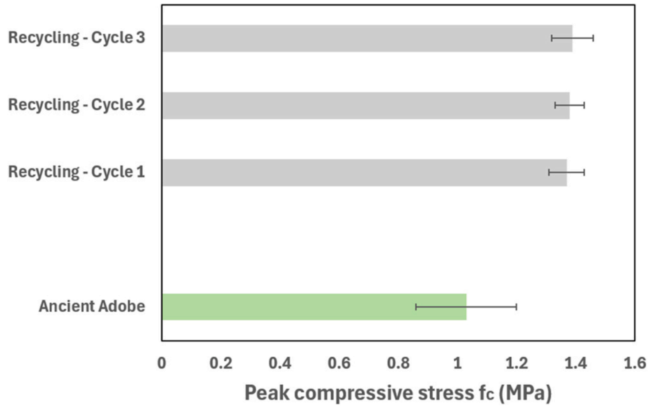

Fig. 9. Peak compressive stress for primary and recycled adobes.

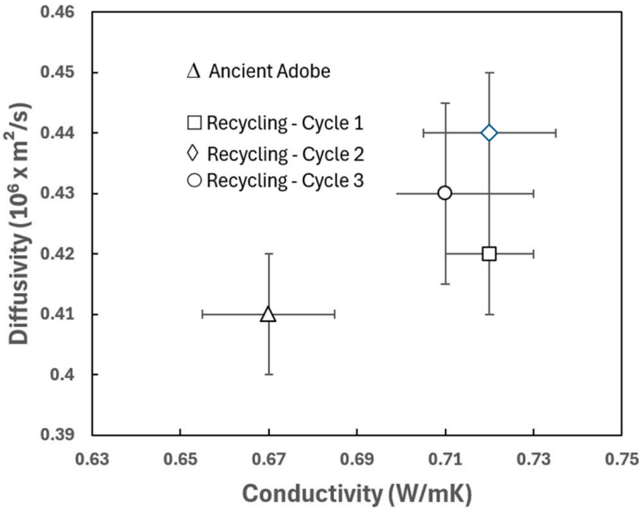

Fig. 10. Thermal conductivity and diffusivity for adobes.

indefinitely and thus to provide the same level of mechanical, hygrothermal, or durability performance. The substitutability of construction materials is generally measured only for the first recycling cycle. However, recycling of conventional building materials typically produces irreversible changes, leading to an imperfect level of substitutability and therefore a limited number of recycling cycles [29]. This eventually generates waste that can no longer be used to perform the same functions. In this case, recycling only postpones the moment when the material becomes an ultimate waste. Conversely, the substitutability of raw earth is good during the first recycling cycle and remains virtually unchanged over time, a major originality among other construction and demolition waste. Similarly to steel, aluminum, and glass, raw earth can be considered an infinitely recyclable material [29].

Finally, recycled adobe offers significant environmental advantages, primarily due to its low embodied carbon, energy efficiency, and waste reduction potential. Unlike recycled concrete, which requires high amounts of energy for processing and transport, adobe is earth-based and lacks cement, minimizing greenhouse gases emissions. Recycling adobe involves breaking down and rehydrating materials without energy-intensive heating, further reducing carbon output and energy costs. Waste reduction is another benefit, with adobe recycling especially effective in areas where adobe is traditionally used, as it minimizes the need for new material production and landfill use. Overall, recycled adobe contributes to sustainable construction by reducing embodied carbon, cutting energy consumption, and managing waste, making it an eco-friendly option for specific climates and building contexts. Raw earth can therefore be regarded as an infinitely recyclable material with a low-impact recycling process. This material has therefore great potential for meeting the challenges of the circular economy.

5. Conclusions

Today's construction industry is facing major challenges and needs to respond to several issues: reducing consumption of material resources, cutting construction waste, moving towards carbon-neutral construction methods, and promoting a circular, local, and inclusive economy. The recycling of raw earth adobes, an ancestral form of architecture still in use today, seems to meet all these criteria and may constitute an environmentally responsible and interesting alternative. For the time being, demolition of adobe buildings in the Champagne area result in adobes being taken to landfill sites or used to fill quarries, whereas they could be used as a resource. The question raised in this study concerned the possible changes in the physical properties of these high chalk content adobes when they are reconstituted several times. By ensuring a highly reproducible brick manufacturing process, this study shows that mechanical and thermal properties are maintained across multiple recycling cycles. Specifically, variations in particle size distribution of the chalk composition from repeated crushing do not seem to affect the recycling process.

However, several limitations should be noted in the context of the present study. First, the work described herein was conducted in laboratory conditions, whereas raw earth adobes are meant to be manufactured in uncontrolled outdoor conditions, directly on-site. The resulting drying conditions may therefore influence the performance of newly made adobes, both thermally and mechanically. Next, recycled adobes should be evaluated in terms of durability in real life climatic conditions. In this context, further research should focus on the long-term durability and performance of recycled adobes.

Future research should also aim to explore the possibility of combining raw earth from recycled adobes with additives such as plant-based ash or natural fibers, with the potential goal of improving their durability, mechanical strength, and moisture resistance, thereby expanding their application in construction. Ash could form additional binding compounds, thus increasing the material's strength, and natural fibers may further improve the overall mechanical performance. These additions would make adobes less prone to erosion and cracking, given that adobes made solely from recycled raw earth may be susceptible to moisture damage in humid conditions. Ultimately, recycled adobes might be applied in new and creative ways, including interior finishes, insulation, or incorporation into composite materials.

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CRediT authorship contribution statement

Adrien Aras-Gaudry: Writing – review & editing, Methodology. **Fabien Beaumont:** Resources, Investigation. **Guillaume Polidori:** Writing – original draft, Conceptualization. **Ouahcene Nait-Rabah:** Resources. **Fabien Bogard:** Data curation. **Sebastien Murer:** Investigation. **Erwan Hamard:** Writing – review & editing. **Christophe Bliard:** Investigation, Data curation. **Gilles Fronteau:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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