RAMMED EARTH CONSTRUCTION: A CIRCULAR SOLUTION FOR SUSTAINABLE BUILDING

GIAMMARCO MONTALBANO¹, GIOVANNI SANTI¹, and NAJEM KHOULOUĐ²

¹Dept of Energy, Systems, Territory, and Constructions Engineering (D.E.S.T.e.C.), University of Pisa, Italy
²National School of Architecture of Marrakech (ENAM), Marrakech, Morocco

The building and construction sector is one of the most harmful industries to the environment, responsible for producing high levels of greenhouse gas (GHG) emissions, energy consumption, and waste. Rammed earth, a traditional building technology is deemed as a promising solution to tackle these challenges. In addition, the low level of skill required for rammed earth buildings paves the way for self-built activities. This paper presents the preliminary findings of an ongoing research study focused on the rammed earth construction technique. The primary objective is to assess its sustainability and circularity within the context of Europe and the Mediterranean. The methodology employed is based on an analysis of rammed earth techniques and a review of relevant regulations related to the selected context. The analysis includes case studies of contemporary European rammed earth buildings. They aim to illustrate possible design strategies that incorporate rammed earth alongside well-established construction technologies. These case studies also shed light on how the integration of various construction technologies introduces circularity variables into buildings, thereby influencing their overall sustainability. These variables are contingent upon the techniques, technologies, and performance characteristics of the selected building elements. As a result of this analysis, the paper initiates a discussion on the role that rammed earth constructions can play in the development of sustainable hybrid buildings.

Keywords: Sustainability, Sustainable construction, Circular buildings, Frugal architecture, Vernacular architecture, Raw earth.

1 INTRODUCTION

The growing concern about climate change is placing the concept of sustainability in the spotlight. In this context, the construction sector plays a crucial role in achieving the environmental goals set by the Paris Agreement in 2015. This sector is responsible for approximately 40% of global operational and process-related CO₂ emissions (UNEP 2022), as well as significant consumption of natural resources and the generation of waste. Additionally, the sector must face the increasing of the by 2050 (UN DESA Population Division 2022), which will rise the demand for housing. The scientific community deems the establishment of a circular economy (CE) within the building and construction sector as a key factor in reducing its environmental impact. Here, the choice of building material is fundamental to enable the application of CE practices. Specifically, raw earth, a traditional material used in vernacular architectures globally, is widely recognized as a sustainable option due to its abundant availability, recyclability, and low embodied energy throughout its life cycle, as also the frugal architectures represent. In the European context, only a few countries have ruled the use of raw earth (Jiménez Delgado and Guerrero 2007). The lack of clear regulations and
uncertainty about its mechanical behavior restrict its use. This paper examines the use of raw earth in construction, specifically the rammed earth (RE) technique. It presents preliminary findings from ongoing research by the DESTeC department at the University of Pisa on the sustainability and circularity of raw earth in RE construction.

2 MATERIALS AND METHODS

This qualitative research seeks to investigate the role of the RE construction technique in promoting sustainability and supporting the CE within the European and Mediterranean regions. The analysis encompasses an evaluation of the features of raw earth and RE construction, emphasizing their sustainability and circular potential. A comprehensive review of global codes about earthen construction has been conducted to determine the countries where RE is ruled. However, this paper focused only on European and Mediterranean codes due to the specific context of our study. Two case studies showcasing the use of the RE technique in contemporary European architecture are presented. These case studies are located in different European countries and demonstrate the influence of regulatory frameworks on technological choices. Furthermore, a comparative analysis is performed with an example of Moroccan vernacular architecture. This comparison aims to identify possible connections between contemporary and traditional construction methods and to facilitate a discussion on their contributions to sustainability and circularity.

Sustainability of raw earth as a construction material are well-known. It is natural, locally available, reducing CO₂ emissions from transportation. Using raw earth also allows to reduce construction site waste, since it represents a significant portion of C&D waste resulting from excavation operations. In its natural state, raw earth is infinitely reusable (Bui and Morel 2015). It means that when a raw earth building reaches its end of life, natural raw earth can be completely reused or restored. Additives like cement enhances raw earth properties, but affect earth's low embodied energy making it less sustainable (Arduin et al. 2022). Raw earth holds promise as a sustainable alternative in developed countries like those in Europe; while it is widely used in the construction of low-tech buildings in many developing countries (Giuffrida et al. 2019). The key features of raw earth as a construction material are highlighted and associated with CE practices (Table 1). These would come into play if raw earth were utilized as an alternative to commonly used construction materials like concrete or bricks, which rely on construction techniques similar to those used with raw earth.

<table>
<thead>
<tr>
<th>Raw earth features</th>
<th>Circular economy practices</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completely natural material and easily available</td>
<td>Reduce</td>
<td>In its natural state raw earth has a very low embodied energy. This is due to the fact that the raw earth sourcing and processing do not involve carbon intensive processes.</td>
</tr>
<tr>
<td>Raw earth can be sourced and processed directly on site. Its processing does not produce waste.</td>
<td>Reduce</td>
<td>Earthen constructions that rely only on raw earth use mechanical processes to compact raw earth, without binding it with chemical adhesives.</td>
</tr>
<tr>
<td>Raw earth if not mixed can be recycled and reused multiple times.</td>
<td>Reuse, Recycle, Reduce</td>
<td></td>
</tr>
</tbody>
</table>

2.1 Rammed Earth: Construction Techniques and Features

RE is one of the most used earthen construction techniques. It is a load-bearing and wet construction technique. It allows to build continuous load-bearing walls with a very high density, ranging between 1800 kg/m³ and 2000 kg/m³ (Giuffrida et al. 2019). RE involves compacting
layers of soil between temporary formworks up to the desired level. Each layer has a height of about 8 cm to 15 cm (Bui and Morel 2015, Ávila et al. 2021) and the soil compaction is achieved by using manual or mechanical rammer. Usually, the resulting walls have large thickness ranging from 30 cm to 80 cm. Soils suitable for construction purposes are subsoils, excavated at least 1 meter below the surface (Gomaa et al. 2023), as topsoils can be sensitive to shrinkage and decay (Morel et al. 2021). The average composition of the soil used in RE constructions is a mixture of clay, sand, gravel, sometimes also fibers with different proportions (Ávila et al. 2021, Gomaa et al. 2023). Regarding structural features, two types of RE can be distinguished: unstabilized rammed earth (URE) and stabilized rammed earth (SRE) (Bui and Morel 2015, Ávila et al. 2021). URE consists of pure soil without additives, with clay acting as the binder. SRE involves blending pure soil with artificial additives, commonly cement and lime, to enhance cohesion and mechanical performance. However, the use of chemical stabilizers impacts the sustainability of RE, as they result from energy-intensive production processes, emit high levels of CO₂ and GHG gases, and deplete natural resources (Arduin et al. 2022). These additives increase the embodied energy of RE and complicate reuse due to chemical bonds formed with the soil. In contrast, URE provides a sustainable and circular alternative to the stabilized version. URE's cohesion and mechanical properties can be enhanced physical stabilization techniques. Physical stabilization involves sorting and sifting the raw earth mixture to maintain proper particle proportions. Well-sorted mixtures create denser RE walls by eliminating voids between particles. By focusing on particle size through sorting and sifting, raw earth's mechanical properties can be improved naturally.

### 2.2 Rammed Earth Codes in Europe

In many countries raw earth in constructions is thoroughly regulated. However, in the European and Mediterranean area only a few countries ruled it. Here, the lack of regulations is one of the hinders to the use of raw earth, especially in load-bearing structures (Jiménez Delgado and Guerrero 2007, Giuffrida et al. 2019). In Germany DIN standards\(^1\) rules prefabricated earth products, earth plasters, and earth mortars; while the Lehmbau Regeln rules RE constructions. In Switzerland the Regeln zum Bauen mit Lehmm covers various earthen construction techniques, including RE. In France, the XP-13-901 regulates compressed earth blocks (CEB), but there are not specific rules for RE constructions. Spanish regulations cover RE constructions. UK has specific guidelines for RE buildings design and construction, which became the reference document for RE. In Africa there is the ARSO standard, which include only CEB (Jiménez Delgado and Guerrero 2007). The other countries of the area do not have specific regulations for RE. Overall, the chosen area lacks a common standard for regulating earthen construction, similar to Eurocodes for other common building materials. The analysis of regulations reveals a focus on industrial products, as their standardized dimensions and homogeneity facilitate mechanical property testing. However, RE construction presents challenges for standardization due to the use of roughly processed raw earth, often in its pure state, and the reliance on workers' expertise for manual labor. Additionally, testing the mechanical properties of RE can be difficult due to the variability of soil composition, which affects its mechanical features. Standardizing RE may require specific soils that may not be readily available on-site, affecting the benefits of material availability and low embodied energy. This

---

\(^1\) DIN 18945 for Compressed Earth Blocks, DIN 18946 for raw earth-based mortars, DIN 18947 for earth plasters and DIN 18948 for other earth-based Panels
reliance on specific soils may also increase environmental impact through transportation-related CO₂ emissions.

3 DISCUSSION: CASE STUDIES ANALYSIS

In Europe, there are few new constructions utilizing RE among the new buildings. These projects are mainly located in countries that have ruled this technique. In general, RE is gaining ground in hybrid technologies, which integrate various construction systems. It is also evident in vernacular construction techniques. In countries with stringent regulations regarding building safety and performance and RE is not regulated, the development of hybrid technologies facilitates the incorporation of RE alongside well-established methods like reinforced concrete, steel, or wood. This is particularly pronounced in European countries. This section presents two European RE architectures to illustrate the concept of hybrid technologies. In these projects, RE has different structural functions: load-bearing and non-load-bearing. These functions have a significant impact on the circularity of the building, introducing certain circularity variables, which will be explained. The selected projects are: The Rauch House, a private building designed by Roger Boltshauser and Martin Rauch, and a public RE tower designed by architect De Gouden Liniaal. The Rauch House, built between 2005 and 2008 in Austria, stands out as a prominent RE construction. In this building, RE walls fulfil load-bearing roles, and beams composed of reinforced trass lime mortar connect the slabs to the walls, as illustrated in Figure 1.

1. Rich loam
2. Foam-glass insulation
3. Low fired mud tiles
4. Reed insulation
5. Cork-clay-trass-lime mix
6. Rammed earth floor
7. Reinforced trass-lime mortar
8. T-beam 60/60
9. Foam-glass filling
10. Reinforced concrete foundations

Figure 1. The Rauch House: Detail of the foundations, one of the most interesting to focus on due to the rising damp phenomenon, and of the slab-rammed earth wall joint (graphic elaboration by the authors).

These elements are embedded within the thickness of the walls, serving the purpose of distributing the loads from the slabs' primary structure along the top of the walls. This distribution helps prevent concentrated loads. Foundations in RE buildings are crucial for both structural integrity, especially in seismic areas to be compliant to the regulations, and for addressing moisture-related issues. RE buildings are susceptible to moisture absorption due to their porosity. Consequently, foundations must rely on well-established technologies such as concrete. Concrete enables precise design in response to stress, ensuring resistance. It also helps to separate the ground from the RE walls, reducing moisture absorption. Rauch House utilizes materials that can be reused as the walls and floors are made from natural, raw earth. However, it incorporates elements from other construction technologies, like concrete foundations and trass-lime reinforced beams, making certain parts of the building non-reusable or non-recyclable. Nevertheless, these components represent a small portion of the overall resources used for the building and they can be easily separate from the RE. The RE Tower (2012), is located in the Negenoord, a former gravel quarry situated on the Belgium-Netherlands border. The 12-meter observation tower combines a concrete
core with an RE outer shell. Collaborating with CRAterre, experts in earthen architecture, was essential due to the lack of specific regulations for RE buildings in Belgium and the Benelux area. The wall mixture consists of clay, sand, gravel, and 6% cement. The choice of cement as a stabilizer was made due to the contractor’s inability to certify the material’s strength using more sustainable stabilizers like lime. Structurally, the tower exhibits a cooperative relationship between the earth and the concrete core, even if the RE panels are not meant to be load-bearing. The landings within the tower are connected to the concrete core at one end, while being supported by 80 cm thick RE walls at the other end. The tower’s foundations are built using concrete to raise the RE walls above the ground, as shown in Figure 2, and prevent rising dump phenomena.

![Figure 2. Detail of the foundations and the basement of the tower. It is evident that RE can be utilized in damp environments as well (graphic elaboration by the authors).](image)

The buildings presented here exhibit significant differences. The Rauch House can be regarded as an example of sustainability and circularity due to its use of RE, even though some construction elements are not circular, such as reinforced truss-lime beams and concrete foundations. The Negeenord Tower does not prioritize sustainability, as evidenced by its extensive use of concrete and cement. Therefore, when considering hybrid RE buildings, it is essential to consider that design choices can introduce certain circularity variables into the construction process. The use of concrete components and cement as additives represents the most significant circularity variables found in the cases studied. A comparison between the two recent architectures presented and vernacular architecture and technologies in RE can be drawn. To facilitate this, examples of buildings built in Morocco, specifically in the village of Alnif (Figure 3), are presented².

![Figure 3. Rammed earth architectures in Alnif, Morocco. Left: Rammed earth vertical wall with embedded wooden pillars. Center: Lightweight wooden floor. Right: Overview of the rammed earth wall-floor joint (photos taken by the authors, 2023).](image)

The surveys reveal a strong connection between RE buildings and the utilization of hybrid technologies. However, in these Moroccan examples, it becomes evident that wood was the

²The examples presented are part of a research that has been developed in the field of an international agreement between D.E.S.T.e.C of the University of Pisa and The National School of Architecture of Marrakech (ENAM).
preferred material for building elements stressed by bending and shear, such as slabs. It is noteworthy that a lightweight wooden technological system is combined with a thicker one in RE. This choice not only reflects the relationship between buildings and their surroundings but also demonstrates how regional material availability and worker skills influenced the selection of wood and raw earth. Nonetheless, the combination of wood and RE proves to be a successful approach in terms of circularity and sustainability. These Moroccan examples suggest to deepen the wood-RE relationship.

4 CONCLUSION

Globally, raw earth presents a viable alternative to carbon-intensive building materials. However, in European and Mediterranean areas, the absence of standardized regulations for designing, testing, and validating material properties hinders its widespread adoption. The case studies illustrate how RE can be integrated with existing regulated technologies, despite the trade-off of incorporating less sustainable materials. The lack of common regulations contributes to uncertainty, prompting designers to rely on well-known and standardized construction technologies. This, in turn, facilitates the incorporation of circularity variables into the buildings. Moreover, these circularity variables are subordinated to the techniques, technologies, and performance of building elements, and can compromise the sustainability of the buildings. Lastly, it is worthwhile to explore the historical relationship between wood technology and renewable energy, as exemplified by Moroccan examples. These instances highlight the connection between buildings and the environment, particularly in terms of materials and building technologies. Future research will focus on the relationship between innovative lightweight structures and traditional construction techniques such as RE. The research will be contextualized within the framework of creative frugality in architecture and the building and construction sector.

References


