

Article

An Approach to the Environmental Impact of Rammed-Earth Dwellings in Historical Contexts and Their Interventions: The Case of the Region of Northwest Murcia, Spain

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Abstract

Dwellings built from rammed earth in historical contexts represent not only a heritage to be preserved but also buildings with a long service life that are still in use by the local population. Changes in urban dynamics and the revitalization of historic downtown areas have led to an increase in renovations of these buildings. However, in many cases, these projects are carried out using materials and techniques that are structurally incompatible and detrimental to sustainability. The aim of this study is to examine earthen residential architecture in the historical context of the Region of Northwest Murcia (Spain), the resources used in their construction, their building systems and their current condition. To this end, an analysis is proposed based on historical documentation, including an assessment of the costs and energy required for their construction, a visual inspection of the current condition of these buildings, and a study of the relevant building regulations. The study of their cladding, eaves, floor structures and partitions in their current state allows for an assessment of the extent of transformation they have undergone and their state of conservation, whilst the study of the regulations provides insight into recent interventions on these buildings. The results point to rammed earth as a technique that, in historic dwellings of various kinds, combined low economic and energy costs with acceptable durability, allowing them to remain in use several centuries later, albeit under the recent threat of interventions using incompatible materials that are shortening their lifespan.

Keywords: rammed earth; dwellings; historical approach; energy; traditional materials; environmental impact; lime-crusted; lime-stabilized



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1. Introduction

1.1. Background

Dwellings built with rammed earth currently account for a high percentage of the world's built heritage [1]. Their presence is not limited to a single geographical or social context but is determined by the availability of local resources, adaptation to the local climate, and cultural factors [2]. The use of this technique is not synonymous with minor constructions; rather, within the same area, monuments, religious buildings, large dwellings and humble homes are all built using rammed earth, a technique that was still in use in inland areas of Spain as late as the 20th century [3].

This technique has variations that use more or fewer resources. They all require formwork made of wooden planks into which the earth is poured. Generally, rammed-earth walls use a mixture of moistened clay, sand, silt, and gravel that is compacted in lifts (layers of compacted soil) [4]. In lime-crusted rammed earth, a portion of lime is added to one or both ends of each layer in contact with the formwork. When the formwork is removed, a continuous lime crust forms, protecting the earthen core from the elements. Lime-stabilized rammed-earth walls, on the other hand, involve adding lime to the earth mixture so its binding effect reduces the need for intense tamping. This variant also typically incorporates small and medium-sized stones, which is why historical records refer to it as “cal y canto” (lime and stone) [5]. Furthermore, in some cases, rammed earth was used in self-build projects, whilst in others, a master builder had to be hired [6], which ensures greater quality and durability due to the professional nature of the work.

The endurance of many of these quite old buildings attests to their good performance. The durability of earthen construction does not depend on stabilisation with modern materials. Rather, factors such as vapour permeability, hygrothermal regulation and long-term repairability—combined with proper maintenance—are key, and also ensure that earthen architecture aligns with the United Nations’ Sustainable Development Goals [7]. In certain historical contexts on the Iberian Peninsula, such as in the Region of Northwest Murcia, buildings over 400 years old survived through successive partial renovations and alterations without the replacement of their original rammed-earth walls. However, the area has undergone interventions involving cement-based mortar coatings and other materials that are incompatible with earthen walls [8].

Growing concern over the excessive consumption of resources worldwide and construction processes that contribute to increased greenhouse gas emissions has directed efforts towards assessing the potential of the existing building stock, as many of these processes are minimized or non-existent when working with an existing building, which is a far more sustainable approach [9].

Consequently, in recent years, there has been growing interest in analyzing the impacts generated by construction throughout a building’s service life, which involves a life-cycle analysis based on the three pillars of sustainable development: environmental, economic and social [10]. This approach has been applied to methods for both new constructions and interventions in existing buildings. In the latter case, a baseline situation is established through a building assessment, and a lifespan is proposed, which in 80% of studies is 50 or 60 years [11]. According to a recent analysis of the scientific literature, earthen construction techniques offer better environmental performance than conventional building materials in terms of embodied carbon and embodied energy [12]. However, this perspective has often overlooked the original circumstances surrounding the construction of buildings of considerable age, as well as the importance of having maintained interventions compatible with their nature over a long period.

Conducting a joint study of the historical context and examining rammed-earth buildings through fieldwork that identifies materials and construction systems is of great importance. In Tlemcen, northern Algeria, a study was conducted along these lines. It included interviews with the local population to assess the extent of intervention and users’ perceptions of this type of architecture. The study demonstrated that rammed-earth architecture is not an obsolete tradition. It also emphasized the importance of maintenance, particularly in cases of water leaks from the roof or seepage through the ground. Additionally, it highlighted the need to systematize vernacular knowledge for application in technical standards [13]. Other recent studies have cataloged earthen houses on a regional scale, providing their dates of construction and current state of preservation [14]. On the Iberian Peninsula, a notable study of traditional architecture combines historical archival research

with fieldwork [15] and inventories of earthen buildings, characterizing their construction techniques [16]. Contemporary earthen buildings in Europe that incorporated standardized materials with a high carbon footprint were compared with vernacular earthen architecture. This demonstrated the latter's connection to the environment through its use of more sustainable materials, such as wood. This comparison encourages future research to explore the historical relationship between these materials [17]. Other materials related to traditional earthen construction include gypsum and lime. In Spain, the close relationship between these materials has been highlighted, and the artisanal production process has been documented from its historical origins to its potential revival today [18].

Therefore, comprehending the construction of these buildings requires examining their historical context and evaluating the conditions under which they were erected, including the materials, techniques, and labor employed. In Spain, this period corresponds to the beginning of the Modern Age, when many towns experienced significant growth until the mid-17th-century crisis [19].

The current socioeconomic context differs greatly from when these buildings were constructed. Since the 1960s, industrialization and the growth of the service sector have driven a significant proportion of the population to major cities and coastal areas, resulting in depopulation in much of the interior of the Iberian Peninsula [20]. In some cases, this has resulted in the abandonment of buildings like these, while in others, new owners reuse them in ways that often fail to consider the values this architecture can convey. Consequently, many buildings have been transformed in recent decades, which have distorted their essence and, at times, accelerated their deterioration. It is therefore worth adopting a retrospective approach from the perspective of economic, energy, and transport costs to understand the reasons that led to a building being constructed in one way rather than another, and which interventions over time have enabled its structure to remain functional today. Furthermore, understanding these processes can help revive traditional construction wisdom and provide valuable insights for contemporary, low-carbon architecture.

1.2. Local Context

An understanding of the local context is essential for analyzing the construction techniques used in the dwellings and the dynamics of the interventions. The Region of Northwest Murcia is situated in south-eastern Spain (Figure 1), in a transitional area between the Castilian Plateau and the Mediterranean coast. This region is of interest because its dynamics are partly comparable to those of the nearby depopulated area. However, it is also changing due to its proximity to thriving cities such as Murcia and Alicante.

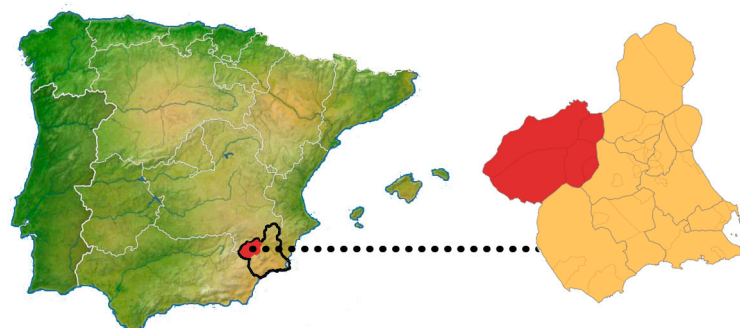


Figure 1. Location of Region of Northwest Murcia (in red colour) in Spain. Map source: wikimurciana.

The significant population growth experienced by this region in the 16th century led to the construction of numerous dwellings, many of which are still partially preserved today, or in some cases entirely [21]. The most commonly used construction technique was rammed earth, a technique previously assumed to be exclusive to the humblest social

classes [22], but it has recently been demonstrated that it was also used in manor houses [23]. The survival of some building contracts for these dwellings owned by the local elites allows us to ascertain their date, location, and construction technique, amongst other details. Consequently, it is possible to trace a construction history and outline an analysis of the resources employed to understand the reasons that led to their construction in a particular manner.

The abundance of gypsum in the area has led to this material being used in numerous building elements: walls, partitions, cladding, and prefabricated components [24,25]. A traditional plaster typical of the area, known as yeso al jaboncillo, involves adding rosin—extracted from pine resin—to the gypsum to increase its durability against atmospheric agents and give it a distinctive sheen [26]. Furthermore, lime can also be extracted locally, as the region contains abundant outcrops of limestone [27]. This material is essential for constructing a lime-crusted rammed-earth or a lime-stabilized wall, but it has not been documented in traditional cladding in the region. As for timber elements, the area is rich in timber resources due to the abundance of pine forests in the mountains.

The crisis in Spain in the mid-17th century also affected the Region of Northwest Murcia, which did not manage to recover until the 18th century, when the arrival of a new bourgeoisie, the beginnings of industrialization, and the boom in trade brought about social changes that also had an impact on building practices [28]. Houses from this period onwards feature a wider range of construction techniques. However, many dwellings from the 16th century and the first half of the 17th century, built using rammed earth, managed to survive the forces of change and are still preserved today.

These trends heightened their transformative potential beginning in the 1960s, a period marked by profound social and economic changes, as well as the industrialization of the construction sector. The widespread adoption of Portland cement, as in other parts of Spain, occurred at this time, leading to the indiscriminate use of this material in measures to address moisture, erosion, or other forms of deterioration, becoming particularly popular in baseboards coated with Tyrolean render (roughcast cement) [29]. The negative consequences for earthen walls [30]—arising from both material incompatibility and loss of cultural identity—prompted the drafting of municipal regulations to protect these buildings. These regulations (approved in 1989) were preceded by a preliminary study within the framework of the so-called Integrated Rehabilitation, an initiative promoted by the General Directorate of Architecture and Housing of the Spanish Ministry of Public Works and Urban Planning, whose objective was to study rehabilitation proposals for historic centers with an integrative and cross-cutting approach. Thus, the historic centers of Caravaca de la Cruz and Cehegín, the two most populous municipalities, were declared Assets of Cultural Interest (Bien de Interés Cultural, BIC) in the category of Historic–Artistic Complex (Conjunto Histórico–Artístico), and the aforementioned protection regulation was drafted for this complex, which has served as the basis for subsequent interventions.

1.3. Objectives

This study primarily aims to analyze historic rammed-earth dwellings and their construction systems. This analysis combines an examination of economic conditions, an evaluation of the energy resources used in construction, and an assessment of the dwellings' current state. The study focuses on historic rammed-earth dwellings, as opposed to dwellings made of other materials in the 16th and 17th centuries, in the three municipalities that experienced the greatest population growth during that period, since smaller population centers developed later. Additionally, the study explores the reasons for the dwellings' durability and the impact of interventions on their state of preservation, which directly affects their lifespan.

2. Materials and Methods

The data collection methodology is based on three pillars: a review of archival documents and literature to understand the historical development of construction; a quantitative study of 100 rammed-earth buildings through fieldwork; and an analysis of current applicable regulations. Figure 2 shows the methodological framework. This allows data to be cross-referenced and organized into a record for each building.

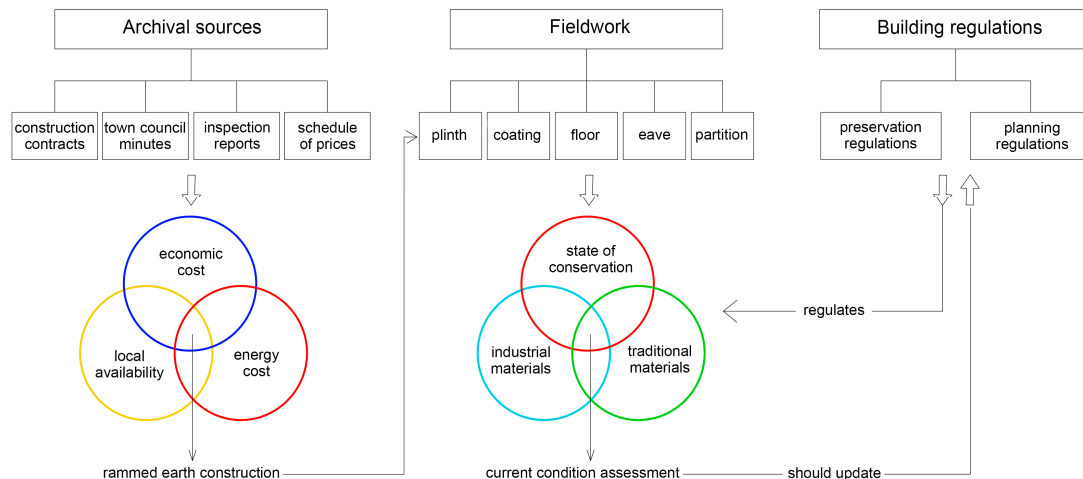


Figure 2. Methodological framework of the research.

For this historical study, four types of archival documents were consulted. First are construction contracts, which outline the agreement between the developer and builder for constructing the building. Dated between 1564 and 1630, these contracts are distributed among the municipal archives of Caravaca de la Cruz, Cehegín, and Moratalla, as well as the Provincial Archive of Murcia. Most have been digitized through the Proyecto Carmesi [31], while others are preserved in physical form at the General Archive of the Region of Murcia (AGRM) [32]. Some contracts have been interpreted through their publication in recent bibliographies [33]. Second are the town council minutes, which document implications beyond the construction work itself and provide information on materials and workers when granting permits. The council minutes have also been digitized. Third are the inspection reports derived from the visits by the Order of Santiago. As the territory was under the jurisdiction of this military order from 1344 to 1840, many actions were subject to its approval. These documents provide information on available resources, the state of preservation of the buildings, and the necessary repairs to those under their ownership. In many cases, they also include cost estimates for the work. These documents originated from the historical archive of Uclés (Cuenca Province), the administrative headquarters of military order. They have been transcribed and published by D. Marín Ruiz de Assín [34]. Price schedules are documents issued by municipal councils to set and standardize the prices of construction materials. The price schedule examined in this study is an unpublished document dated 1627 and held in the Provincial Historical Archive of Murcia (AHPM) [35]. Information from these sources was cross-referenced with local literature and literature on traditional architecture in nearby areas of the Iberian Peninsula [15,36] to assess the uniqueness of the findings.

During the fieldwork, 100 buildings were identified that showed evidence of being constructed with earth. A visual inspection was conducted to identify such cases. This inspection included looking for gaps or peeling cladding on facades, as well as inspecting the interiors of accessible buildings. The selected sample consists of the municipalities of Caravaca de la Cruz, Cehegín, and Moratalla because, unlike other smaller towns in

the region, they experienced population growth from the beginning of the Early Modern Period, as described in [23]. The analyzed period spans from the 16th to the 19th century. Furthermore, historical documentation allowed for a deductive method to be used in the most representative buildings. The main houses, the term used in the documentation to define the dwellings of the local elites, are clearly identified in the construction contracts, allowing for their exact dating. They are currently in an acceptable state of preservation. These three municipalities are referenced in the available historical documents. Identification was carried out through direct visual inspection, supplemented by an analysis of photographs provided by owners who had them. Due to the limitations of this method, it is usually impossible to fully understand all of a building's construction systems. This influences the identification of the five construction systems in this study, particularly the decision to focus the wall analysis on the façade.

Table 1 lists the cases studied by municipality. Classification into 'two stories or fewer' and 'more than two stories' is relevant not only as a typological indicator, but also because regulations permit up to three stories in the historic center. Therefore, houses with two stories or fewer are likely to undergo renovations in the future that could increase their height. The buildings analyzed are classified as good, fair, or poor based on their state of preservation. "Good" refers to buildings that show no obvious signs of deterioration. "Fair" refers to buildings with varying degrees of physical deterioration that do not affect the building's structural integrity. "Poor" indicates advanced physical deterioration and structural problems that compromise safety. This categorization is not broken down in the results because the objective of this study is not to analyze the specific causes of each problem in detail, but rather to demonstrate the condition of the sample and the limitations of the study. Due to the identification method, which is based largely on missing material or localized deterioration, most of the sample consists of buildings in fair or poor condition that exhibit this pathology. The table with more detailed information (Table S1) can be downloaded as Supplementary Materials. A FLIR E60bx thermal imaging camera was used as an additional aid. While it cannot confirm the presence of a rammed-earth wall, it can rule one out when there is doubt. The emissivity and thickness of contemporary materials make them more easily identifiable under infrared radiation.

Table 1. Inventory of analyzed buildings.

Municipality	N	Two Stories or Fewer	More Than Two Stories	State of Preservation		
				Good	Fair	Poor
Caravaca de la Cruz	47	12	35	6	32	9
Cehegín	38	10	28	3	27	8
Moratalla	15	6	9	1	10	4

Regarding current regulations, the planning instruments that directly affect these properties are municipal in nature and developed according to provincial and national law guidelines. These instruments include the General Urban Development Plan, which contains catalog entries for unique buildings, and the Special Plan for Interior Renovation for municipalities that have designated a group of buildings as Property of Cultural Interest (BIC by its Spanish acronym) in the historic complex category [37]. The key aspects studied are the ordinances regarding the form, materials, composition, and color of buildings. Many of these ordinances refer to woodwork, decorative elements, and ironwork, all of which fall outside the scope of this study, which focuses primarily on the material aspects of walls.

The structural elements that were studied interacted with the main rammed-earth wall in one way or another. The wall itself was divided into three parts: the base, the wall

body with its cladding, and the eaves. Where possible, the floor slab and interior partitions were also examined. The data was entered into the form and broken down by material. One section is dedicated to the building's state of preservation. The various interventions that these buildings have undergone affect their expected service life because they can improve or worsen the building's performance, depending on the nature of the material used. A review of the literature on the impact of cementitious materials, cladding, and other impermeable materials was conducted.

A profile has been created using the collected data. This profile contains information gathered directly from the building itself regarding its construction system, materials, and state of preservation. Compiling the 100 profiles allows us to develop statistics on the most common elements and intervention dynamics. Additionally, a map of the study area was created using the National Geographic Institute's LiDAR map to indicate the resources and sources of construction materials (Figure 3). This map corroborates information from historical documents and observations of the buildings, categorizes locally sourced materials, and establishes local relationships between material resources. Unlike the data sheets, this map is not exhaustive. It was created by compiling bibliographic sources, historical documents, and testimonies [31,38,39]. The map's objective is to verify the existence of materials found in the buildings in the vicinity and to serve as a baseline for any future discoveries, such as gypsum or tile kilns, that may be included.

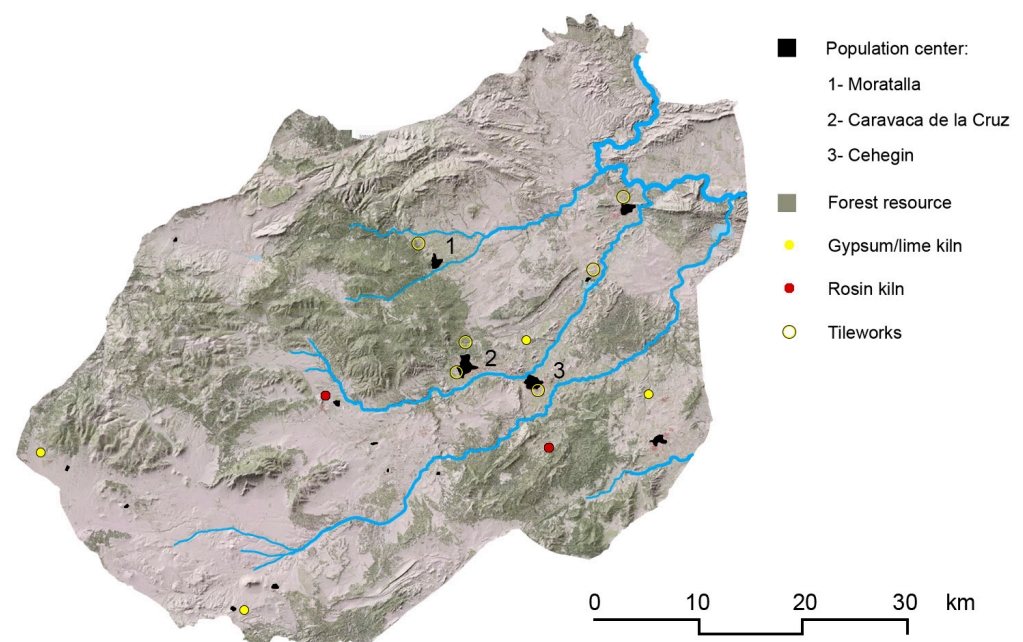


Figure 3. Map of the Region of Northwest Murcia and the local resources and materials used in traditional construction. Created using LiDAR mapping available at <https://nco.ign.es/> (accessed on 15 May 2026).

The data obtained from historical documents has been standardized and presented. For bulk goods such as gypsum, lime, and rosin, the volume is shown in cubic meters, though the original units of measurement are retained in the definitions. To allow for cost comparisons, the maravedí, the smallest monetary unit, is always indicated even though the documents mention larger units, such as the real or the ducado, for large quantities. One real was equivalent to 34 maravedís, and one ducado was equivalent to 11 reales. The qualitative study of the energy resources used should be interpreted as an approximation of the most likely method of producing materials with the available resources at the time. The results are presented in terms of low, medium, and high energy consumption based on the calcination

temperature, time required for calcination, and necessary tools. These parameters were quantified by extracting figures from literature on material production [40–42] and cross-referencing them with data addressing the manufacturing process of traditional materials mentioned in the schedule of price [43,44].

3. Results

Taking a multi-perspective approach to the subject of study makes it possible to categorize the results according to the buildings' origins, historical analysis, extent of interventions, and current material composition and state of preservation in light of current regulations.

3.1. The Construction of Rammed Earth Dwellings from a Historical Perspective

Of the available construction contracts for housing that mention the construction technique, eleven use the term rammed earth, while two refer to a structure made of “cal y canto” (lime and stone). Only the five contracts that specified the cost per unit were used to study the economic cost of constructing a rammed-earth module, since the rest provided the price for the total work. Four construction contracts provide the price of the tiles, while only one mentions purchasing four thousand bricks without providing additional information. Therefore, it is unclear whether the bricks were intended for walls, vaults, or another purpose. The four contracts of the manor houses specify that the walls must be constructed of lime-crustrated rammed earth: “de tapia con su costra, conforme a la costumbre que se tiene en esta villa en semejantes edificios” (made of lime-crustrated rammed earth, just like the other buildings in this town). The Order's inspection reports mention construction work and repairs on rammed-earth buildings. On four occasions, the reports attribute the commander's house's good condition to its maintained lime crust on the rammed-earth wall.

On the other hand, ashlar masonry is only mentioned in the walls of large monuments—there are only two churches in the region built in this way—and in the monumental stone portals of the wealthiest manor houses, whose walls are made of rammed earth. Before the 18th century, brick was only mentioned in construction contracts for churches built for religious orders and in another contract for a building whose intended use is unknown. This is consistent with the 100 case studies, as no pre-18th-century dwelling features a brick wall. However, the brick did appear in 16th- and 17th-century convents. The predominance of earth over brick in rural areas of the Iberian Peninsula has been noted in other publications [15]. According to Felipe II's topographical surveys in 1575 in the La Mancha region, 87% of respondents answered “earth” to the question “What material is your house built of?” compared to 10% who answered “brick”.

A review of the available literature indicates that rammed earth was the most used construction technique for dwellings. Specifically, lime-crustrated rammed earth was used for manor houses and buildings belonging to wealthier households. All buildings were required to have ceramic tile roofs, which explains why the three largest settlements in the region had at least one tile kiln nearby. There is no evidence of flat roofs or roofing made from plant materials in the documentation or from fieldwork.

Figure 3 shows the Region of Northwest Murcia. It identifies forest resources, rivers (along whose banks the *Arundo donax* species grows; this species is used to make reed mats), main population centers, and production or processing sites for traditional materials, such as gypsum plaster, lime, brick, and roof tiles. The location of the plaster, lime, and rosin kilns indicates that their proximity to the raw materials was prioritized over their proximity to urban centers or the buildings they were intended to serve, as these were simple and sometimes temporary structures. This is a characteristic feature of vernacular architecture as opposed to industrialized manufacturing.

A previously unpublished 1627 schedule of prices issued by the municipality of Caravaca de la Cruz was analyzed, providing significant insight into the widespread use of earthen materials in housing compared to other construction techniques. Table 2 correlates the price schedule's data on building materials, their units of sale, and prices with the energy required for their production and transportation. The energy data is qualitative and serves as a rough guide to whether a material involves high energy consumption during manufacturing compared to others. Ceramic products and lime, for example, required high firing temperatures and more than four days, while gypsum required less than two days, and wood required only the use of specialized tools.

Table 2. A 1627 Price Schedule related to the cost of energy for production and transport.

Product	Quantity		Price	Energy	Transport
	Unit	Volume			
"cintilla" (thin decorative brick)	1		10	high	unknown
locally made roof tile	1000		1768	high	<10 km
brick from Mocejón	1000		8228	high	400 km
cahíz * of lime	1	0.22 m ³	68	high	<50 km
cahíz of gypsum	1	0.22 m ³	51	medium	<50 km
432 cm long wood pole	1		17	low	<50 km
200 cm long wood plank	1		17	low	<50 km
1 pound of rosin	1	4.26 × 10 ^{−4} m ³	24	medium	<50 km

* Cahíz was the unit of volume equivalent to 222 L.

The unit listed in the table is the unit of measurement used to determine the price listed in the schedule of rates. Thus, ceramic and wood products are measured in units or thousands of units; lime and plaster are measured by volume, and other products, such as rosin, are measured by weight. This table includes a volume measurement in cubic meters to facilitate comparisons between materials. Transportation costs are determined by the schedule price data itself if the material is imported or by an estimate based on the mapping results in Figure 3.

The schedule of rates provides the price per thousand for "locally manufactured" roof tiles, but not for bricks, which must be imported from Mocejón, a town in Toledo province located 400 km away. Although a contract for a church belonging to a religious foundation [45] did specify locally manufactured bricks, a few years later, the same developer was forced to purchase bricks from Puebla de Don Fadrique, Granada. The absence of these bricks from the price list suggests that they were likely produced only by special order or that the local clay, with its proportions of calcium carbonate and gypsum, was not suitable for local production [46]. Regarding wood, the document specifies that the listed prices are per piece "at the felling site", meaning the pieces were worked on site. The price increased when they were sold in the town. Conversely, reeds are not included under the "construction" heading, but are taxed for fabric production. For instance, a hemp cloth measuring approximately 0.75 m² was valued at two reales (68 maravedís), indicating that the raw hemp itself, before reaching the loom, must have been even less expensive.

The schedule of prices includes the cost of labor, which is a key factor when comparing it to compacted rammed earth construction. At the time, it was common for the price paid to the master builder on masonry projects to include materials. Thus, the price for "building a rammed earth wall" included collecting earth and performing formwork and tamping, as specified in the contracts. Table 3 lists the cost of building a rammed earth wall according

to the price schedule and construction contracts. The price schedule sets a rate of 2.5 reales for a rammed earth module without specifying the type; meanwhile, the rate for a master mason was 4 reales. Available construction contracts confirm that lime-crusted rammed earth walls were built by master masons. This suggests that the cost of a high-quality wall increased not only due to the proportion of lime, but also due to skilled craftsmanship.

Table 3. Labor costs based on the schedule of prices or based on construction contracts.

Work	Source	Price
Master mason's wage	Schedule of prices	136
"for building each rammed earth module"	Schedule of prices	85
Lime-crusted rammed earth module built by a master mason	Construction contract	145
Lime-stabilized rammed earth module built by a master mason	Construction contract	102

Based on the collected data, the cost of a lime-crusted rammed earth wall (60–80 cm thick) was compared to a 30 cm thick hypothetical brick wall. The brick wall was found to be 3.48 times more expensive using local brick and 16 times more expensive using imported brick, based on the contract and schedule of rates, respectively. In practice, brick is sometimes used to complement walls for lintels, piers, and transoms in religious buildings and, less frequently, in residential buildings.

3.2. Results of the Visual Assessment of Dwellings by Construction Systems

The fieldwork reflects the current condition of the buildings based on the proportion of materials found in the studied construction systems. However, the method's reliance on visual analysis makes it difficult to deduce a building's specific renovation and evolution timelines directly from it. The following data has been verified for the 100 buildings studied that feature a rammed earth wall:

A lime-crusted rammed earth wall has been identified in 12 cases. In 46 cases, the lifts are clearly visible. In the remaining 42 cases, it has not been possible to determine the lift height. Alternatively, a high proportion of stones could correspond to a stabilized rammed earth wall with a different tamping technique. Nine buildings in this group are mixed-construction structures featuring masonry (five cases) or brick (four cases) piers.

Figure 4 shows the proportion of materials found in the five construction systems studied. Traditional materials predominate in eaves and floor slabs, with 61% of eaves made of curved ceramic tiles and 67% of floor slabs made of wood. However, wall cladding and plinths show much greater variation. Plinths have undergone significant transformation: 36% are made of roughcast cement, 24% are painted cement, and 28% have cladding. As for wall coverings, 30% have a traditional gypsum plaster finish that allows the wall to breathe, and 6% are uncovered. Cement mortar appears in 49% of cases, either as a one-coat cement render or painted. Fifteen percent have paint over a traditional gypsum plaster. Regarding partitions, 32% feature industrialized materials such as gypsum board or hollow ceramic brick. However, the most significant data pertain to traditionally constructed partitions: three were made of adobe, two of reused ceramic tile, seven of reeds and gypsum, two of ceramic brick, and 29 of gypsum-crete or tapialete, a technique involving the pouring of a mixture of gypsum and earth that hardens without the need for tamping [47]. This technique incorporates horizontal wooden crossbeams that have been found at 80–120 cm intervals in this region.

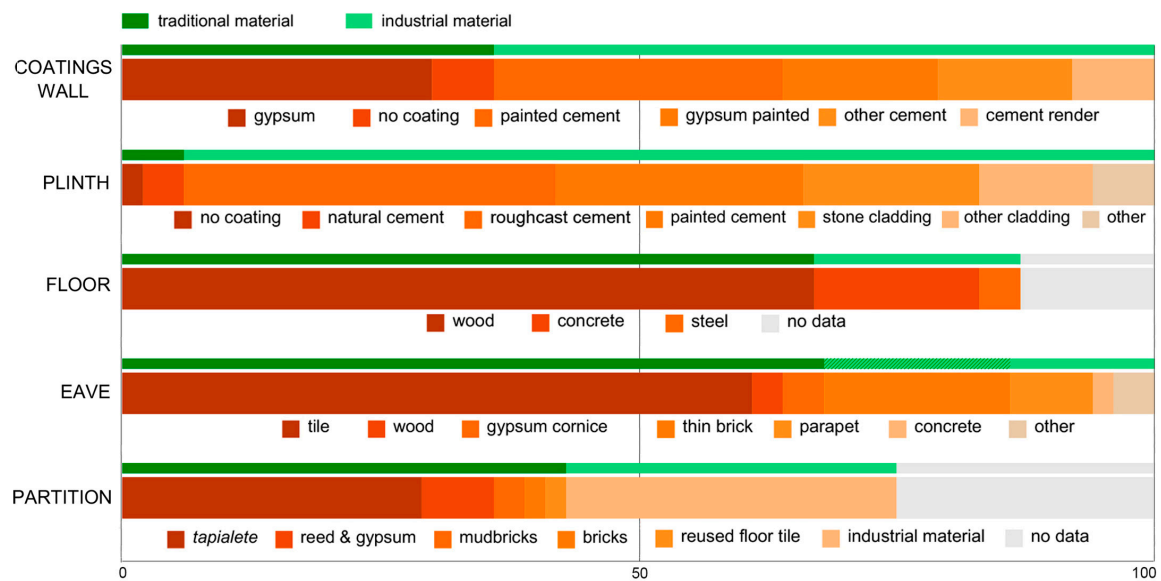


Figure 4. Quantitative analysis of materials in five building systems and the proportion of traditional and industrial materials.

The results can be categorized as either traditional or contemporary materials. Analyzing this ratio reveals the extent of architectural transformation. This is shown in Figure 4 by the thin upper bar for each construction system. Furthermore, analyzing traditional material types and techniques and cross-referencing them with historical documentation suggests which materials were most used in the area. Fieldwork confirms the limited use of brick in historical documents, as it appears only as a Supplementary Materials in four of the 100 dwellings studied. Tapialete (gypsum-crete) and reeds with gypsum partitions are the most prevalent. Figure 5 compares the cost and embodied energy of four typical wall and partition types in the region, combining rammed earth or lime-crusted rammed earth with tapialete or reeds & gypsum partitions. It also compares these with a hypothetical solution of brick walls and partitions. The thicknesses are those found in each system: 70 cm for the rammed-earth wall, 30 cm for the brick wall, 20 cm for tapialete, and 10 cm for the reeds and brick partition. In addition, gypsum coating, gypsum + rosin render (yeso al jaboncillo), and lime coatings have been studied, as well as eaves made of tile or thin ceramic brick.

The economic and energy costs of rammed earth walls are up to three times lower than those of brick walls. Rammed-earth walls without additives have substantially lower embodied energy; however, in lime-crusted rammed earth, the energy comes from producing the lime. In partitions, the embodied energy comes from the gypsum, which gives the reed partition structural integrity and provides cohesion to the tapialete system as a gypsum binder. Regarding coatings, gypsum is the most common in the case studies and the most economical. Lime requires more energy and labor to apply successive layers, while gypsum with rosin plaster shows a clear distinction between cost and embodied energy. While the energy required is not excessively high since rosin extraction does not require high temperatures, labor costs are higher due to the exhaustive polishing process, which sometimes lasts several days [26]. Finally, eaves are more economical when formed with roof tiles since they are cheaper than thin bricks and require fewer pieces for the same volume.

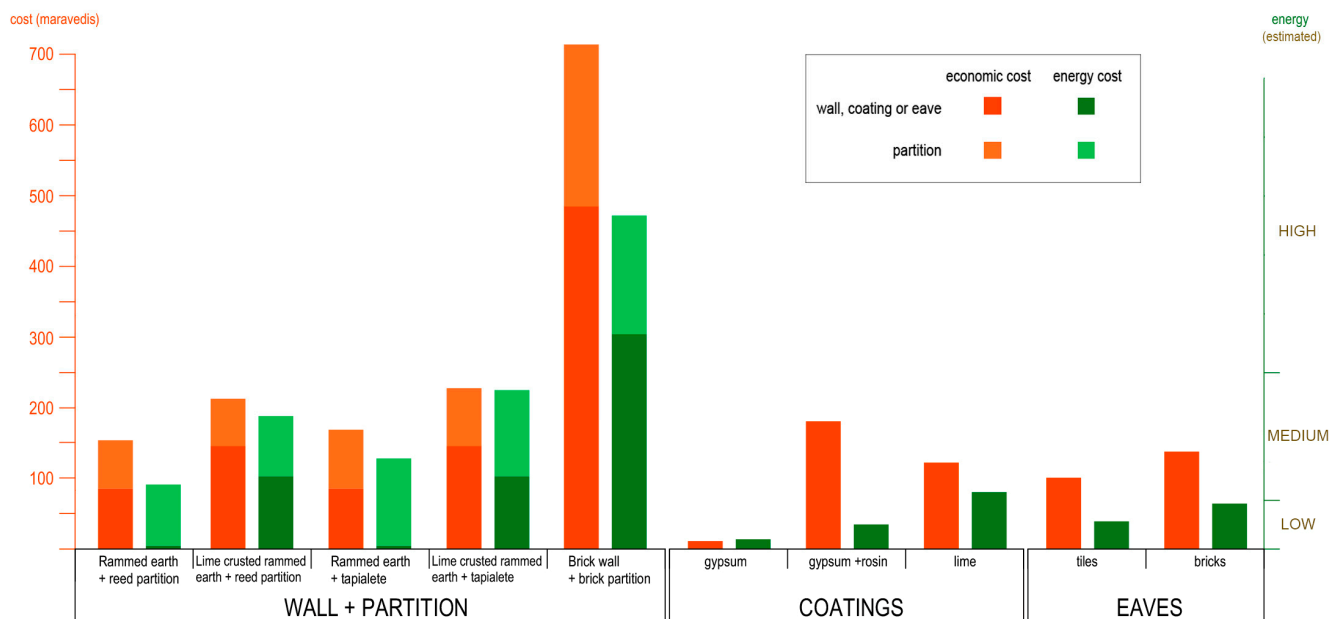


Figure 5. Economic and energy costs of various construction systems during the construction phase of the dwellings analyzed.

Thus, it is evident that vernacular architecture follows a sustainable model characterized by lower costs and reduced energy consumption. In this model, rammed earth plays a central role. Furthermore, when analyzing transformation dynamics, it is insufficient to classify materials as either traditional or contemporary. It is also necessary to distinguish interventions that deviate from vernacular practices yet employ traditional materials. For example, brick walls, lime renderings, and eaves made of ceramic elements other than roof tiles are less common in the architecture of the Region of Northwest Murcia and have higher economic and energy costs.

3.3. Condition of the Buildings and Analysis of Intervention Regulations

Rammed earth walls exhibit a variety of textures and compositions. Simple rammed-earth walls without a facing show little to no significant degradation. In some cases, erosion on the plastered edges and corners is actually more advanced than on the earthen surface. Without a characterization analysis, preliminary hypotheses suggest that the wall may be somewhat stabilized or that the higher proportion of gravel increases durability, which is consistent with some publications [48].

The state of preservation varies in buildings with lime-crusted rammed earth walls. Those that have lost their lime crust were covered with gypsum at some point, as shown in Figure 6. Thus, when the continuous layer of lime on these walls was lost, one or more layers of plaster or, in more recent cases, cement mortar were applied. Starting in the 1960s, plaster coatings gave way to cement finishes that differed from traditional facades. This led to the Special Plans of 1989 specifying that finishes be done “preferably in lime”. Tyrolean cement and imitations of traditional materials were expressly prohibited, and natural stone was permitted for plinths, provided that cladding was avoided. However, at the time, the stone industry was geared toward producing cladding panels a few centimeters thick. Therefore, given the results of the fieldwork and the prohibition on roughcast cement, cladding panels proliferated on plinths.



Figure 6. Replacement of the lime crust with a gypsum coating.

The regulations permit the use of brick, but not on large surfaces, as is currently the case in the region. Furthermore, the authorized colors for facades are “ochre and the natural colors of the area”. The ochre tone is based on a color study conducted in the area before drafting the regulations [24], while “natural color” is an ambiguous term without a precise hue definition. This has led to interventions using paints of various shades, often with low saturation. In other cases, primary colors have been emphasized to counter the stereotype of exclusively white Mediterranean architecture [49]. The vast majority of these paints are acrylic and have been applied primarily to two types of surfaces: traditional plaster and industrialized cement. The first type constitutes 15% of the coatings studied in this work. Of these 15 cases, 14 exhibit cracks, fissures, and material loss affecting the underlying layer (Figure 7). The paint’s impermeable nature prevents the wall and the plaster coating from breathing. The paint offers very little resistance to water vapor pressure due to its thinness, which is why it eventually cracks. In the second case involving painted cement mortar, the plaster degradation is much less severe, and sometimes the plaster remains intact since the paint interacts with the substrate layer.



Figure 7. Cracking and peeling of the acrylic paint applied to the gypsum.

4. Discussion

Findings from historical documentation indicate that rammed earth was a predominant construction technique within the region during the 16th and 17th centuries. This period was characterized by significant urban expansion, which fundamentally shaped the historic centers of these municipalities. The exceptional durability of numerous surviving dwellings may be attributed to the lime-crusted rammed earth method. However, despite its widespread adoption—as documented in contemporary building deeds—this technique should not be assumed omnipresent across all domestic architecture, given

its premium cost relative to simpler rammed-earth variants. Notably, in every archival contract where the commissioning party owned a manor house that remains preserved today, the specifications explicitly mandated a lime-crusted rammed-earth wall alongside the engagement of a master mason. In one instance, the craftsman identified himself as a master stonemason. Collectively, these circumstances strongly suggest a direct correlation between the implementation of lime-crusted rammed earth, the employment of highly skilled labor, and enhanced structural longevity.

A quantitative analysis of 100 case studies does not indicate how many renovations a dwelling has undergone; rather, it shows the extent to which the traditional solution has been preserved compared to industrialized alternatives. Thus, although a building's roof is one of the elements most likely to undergo frequent interventions, the tiled eave solution is present in 61% of cases, including those with a high degree of transformation into other construction systems and those that have not undergone any modern interventions. Conversely, the tiled eave solution is the most effective for protecting an unrendered earthen or traditional gypsum façade. Eave solutions using ceramic thin bricks in geometric patterns consume more material and, according to the 1627 schedule of prices, entail a higher cost than a tile eave. This suggests that the ceramic brick solution is based more on picturesque architecture than on vernacular origins. The low proportion of wooden eaves, which are common in other mixed-construction buildings from the 18th and 19th centuries, is unexpected given the area's abundance of timber resources and extensive use of wood in floor structures and partitions.

Regarding external finishes, the economic and energy costs of cladding systems are substantially higher than those of a rammed-earth wall, with the notable exception of traditional gypsum. A lime-based coating would incur greater expenses than a rammed-earth wall for an equivalent façade surface area, approaching the cost of a lime-crusted rammed-earth wall. This economic threshold explains the historical predilection for lime-crusted rammed-earth walls, as documented in archival sources, and their widespread implementation, as evidenced in case studies. By mitigating the need for costly cladding, this technique proved highly viable; furthermore, its initial adoption may have driven subsequent practices where walls that had lost their original lime crust were sequentially coated with gypsum.

Regarding material degradation, phenomena affecting surface finishes are of critical relevance in earthen structures. Notably, visible pathologies affecting traditional gypsum coatings, frequently associated with painted layers, stand out in contrast to the concealed, internal degradation induced by cement rendering. The former manifests as cracks and fissures that develop rapidly until the vapor pressure of the underlying substrate equilibrates with atmospheric conditions; thereafter, the degradation stabilizes or progresses marginally due to secondary mechanisms driven by rainwater infiltration. Conversely, in earthen walls rendered with cement, damage remains visually imperceptible on the exterior, while internal degradation accelerates due to interstitial condensation and increased moisture retention caused by the impermeable coating. Furthermore, the ochre tones specified in current regulations are inherent to traditional finishes, whereas contemporary interventions attempt to replicate these hues through superficial paint or pigmented cement. Given these contrasting degradation mechanisms, prescriptive standards should regulate material composition rather than merely aesthetic color, thereby ensuring that the material matrix itself yields an authentic, intrinsic tone.

In the national context, the use of cement mortars for cladding, which was common in the latter part of the 20th century, has gradually been phased out in the restoration of historic buildings, as indicated in [8]. The commercial availability of lime mortars is increasing. They have been shown to perform excellently in terms of the breathability

of historic walls, and they are now widely used in such structures. However, they also have limitations, and environmental conditions must be considered [50]. Thus, it might be beneficial to consider a broader range of compatible materials whose use in vernacular practices has been demonstrated. These materials can also help reduce the carbon footprint. Drawing on the work of other authors who have studied their traditional manufacturing processes and identified key ideas for their revival today can help with this, as in the case of gypsum [18].

To achieve this goal, it is essential to collaborate with technicians and workers, revive traditional techniques and provide training in their application. It is also crucial to involve competent authorities to recognize the value of these contributions. Transferring knowledge of traditional rammed earth techniques from workshops to the workforce is also important, especially given historical documentation and findings within the building itself regarding the original technique.

5. Conclusions

A significant number of earthen-built dwellings within the Northwest Region of Murcia remain standing today, although many have undergone subsequent alterations. Archival research reveals that lime-crusted rammed earth was a predominantly accepted construction technique during the consolidation of the region's three main historic centers. Historically, its economic, material, and energy costs were substantially lower than those of alternative construction systems documented in contemporary schedules of prices. Fieldwork identification and visual assessment of the cases recorded in the documentation demonstrate the high durability of this vernacular method, which is currently jeopardized by the introduction of incompatible contemporary techniques and materials.

The convergence of low economic and embodied energy costs, the utilization of locally sourced materials, and verified structural longevity directly aligns these historic dwellings with modern sustainability principles. Consequently, not only does aligning contemporary interventions with these historical tenets foster the conservation of architectural heritage, but it also contributes to sustainable development. This paradigm must be integrated into heritage regulations to govern material composition and technical compatibility, thereby preventing interventions that run counter to the intrinsic nature of the historic building matrix.

To ensure effective implementation of the regulations, they should require some type of testing or evaluation that allows for an understanding of the nature of the construction system. This is of particular interest since the inability to examine the core of the wall has often been the main limitation of this study. Furthermore, it is of even greater interest that regulations address techniques and materials supported by the latest research and incorporate mechanisms capable of being periodically updated to reflect the availability of traditional craftsmen and resources, given the anticipated boom resulting from the most recent trends in architectural intervention.

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