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Conservation of Defensive Military Structures Built with Rammed Earth

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Abstract: Earth is a complex material with mechanical and physical behaviors that differ from modern building materials. The conservation of rammed-earth (RE) constructions presents specific difficulties that are challenging to overcome. A lack of knowledge about RE due to its abandonment for decades and interventions adopting materials and repair methodologies designed for conventional constructions have led to inadequate interventions. In the case of historic defensive constructions, the doubts and technical difficulties are even greater due to the nature of so-called military RE (with physical and mechanical characteristics which differ significantly from those of civil, more common RE) and, not least, due to the historical and cultural heritage value of these constructions. Some important interventions have been carried out recently, while others are underway or in the planning stage, and there is a constant lack of information and technical data regarding the best ways to intervene. To fill this gap, the state of conservation of defensive RE structures and the results of interventions carried out throughout history in the southwest of the Iberian Peninsula are being assessed. This article sets out a framework for the subject, identifies material and construction techniques and recognises the main causes of RE constructions' deterioration and decay. With special focus on the most frequent damages detected in historic military defensive structures built with RE, it analyses and discusses the most common techniques that have been used for the repair and conservation of these particular structures.

Keywords: built heritage; earth construction; fortifications; repair; building technology; preservation

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1. Introduction

The preservation of heritage has been a concern for communities for some time. The cultural value of monuments and buildings, their social impact and, not least, the intention to increase the economic value of regions, have given rise to various interventions to restore built heritage. Much has been researched and learned in recent decades about how to intervene in built heritage, and it is now accepted that interventions should maintain the identity of the buildings and be as minimal and reversible as possible [1].

Structures of historic architectural heritage, by their very nature and history (material and assembly), present several challenges in diagnosis, repair and conservation that limit the application of actual codes and building standards. Recommendations are desirable and necessary to both ensure rational methods of analysis and repair methods appropriate to the cultural context. The ICOMOS Charter [2] sets out the principles for the analysis, conservation and structural restoration of architectural heritage and continues to be a fundamental reference despite having been created twenty years ago.

The rationale for conservation interventions must be based on a theoretical assessment of the static, physical, chemical and even biological behaviors of each built element and each specific construction and never on simple intuition about unproven facts [3]. Thus, it is a detailed and multidisciplinary analysis of each heritage architectural object that will provide adequate information for decision making regarding intervention techniques. That I,: each construction should "tell" the technician how it should be treated!

When one intends to conserve any architectural element, it is always necessary to address a wide range of issues, which means that the approach taken is not always exclusively of a constructive or structural nature. The intangible values of buildings and construction techniques are now also recognised as important elements to maintain [4]. In the case of defensive constructions, other aspects, such as the function of the construction and its elements, are also added to the constructive problems, which are themselves quite challenging.

With regard to historic defensive military structures built with rammed earth, the issues to be addressed are numerous and specific to each fortification in question. These structures were built with a material that is produced from the raw material earth, excavated from the soil of the site itself or from the vicinity of the construction. As the characteristics of the soil vary from place to place, it is easily understood that the characteristics of the rammed earth produced may also vary significantly from construction to construction. Another aspect has to do with the speed of production and the evolution over time of the construction. Some military buildings were built urgently, prioritizing speed over quality, and most of them were subjected to improvements, extensions and adaptations to new combat techniques, particularly ballistics, which have evolved significantly from medieval times to more recent times [5]. Other issues have to do with the specific nature of military use, which must also be addressed when analyzing these structures as it could be part of the factors that led to their state of deterioration.

In what is specifically regarded as the conservation of earthen architectural heritage, as is the case with rammed-earth defensive structures, two main knowledge gaps can be detected in the literature: a lack of conservation theory as a background for earthen heritage interventions and a need for a clear understanding of the values and significance of a place. These two interlocking aspects contribute immensely to less-conscious conservation actions and the implementation of methodologies that do not follow the basic principles of heritage intervention [6].

In many of the interventions already carried out (some directly followed by the authors), it was possible to note a lack of preparation on part of the team members, sometimes in terms of designing, preparing and monitoring the works and at other times when carrying out the work. Most of the time, many of those involved in the process of repairing rammed-earth constructions were unaware of the specific characteristics of the earth material and product. This lack of knowledge, even in a single phase or team, resulted in inadequate and/or ineffective interventions, with irreparable damage to the rammed-earth heritage or, in other situations, additional costs and time spent in adapting and correcting the measures initially proposed. The use of cement-based mortars and concrete, common in the interventions of the 20th century, has been abandoned, but even so, materials and technologies incompatible with the material "earth" are still being used.

The present study intends to analyse and discuss in more depth some of the questions mentioned above in the context of the application of specific methodologies for the conservation of defensive military structures built with air-lime-added rammed earth. The objective is to contribute to the protection and conservation of these historical heritage constructions without destroying or damaging their material and immaterial value. It proposes the development of analysis, diagnosis and repair methodologies, with intervention techniques duly adapted to the specificity of military rammed earth and duly framed in current cultural, constructive and normative parameters.

2. From Soil to Rammed Earth

2.1. Earth as a Raw Material for Building Purposes

The use of earth extracted from the ground for construction purposes was most likely born out of the intention to build quickly and economically and still achieve a robust construction. Earth is a raw material available on site, requiring very little prior preparation to turn it into a construction material and simple and inexpensive technical means for its application. Although it requires intensive labor (which was not a problem in the past), the transformation of earth into the final product, rammed earth, is not complex, nor does it require high levels of technicality [7]. In fact, earth excavated from local soil was used as a building material by all ancient cultures [8]. Site excavations and archaeological studies in diverse regions of the planet have revealed that earth has been used for construction purposes since the dawn of mankind [9]. Its use was probably not an option or motivated by some technical concept, but rather for the simple and previously mentioned fact that it was available in the place where building was intended to occur.

The experience and knowledge accumulated over the millennia in earth construction have resulted in a very effective response to building needs and high levels of comfort, resistance and durability [7]. Shelters, dwellings, buildings with several floors (sometimes entire cities), fortresses and other defensive structures and temples and religious buildings were built with earth, using a diversity of building techniques, with the richest and most varied formal and aesthetic aspects. It will be difficult to find an inhabited continent, and perhaps even a country, that does not have heritage buildings built with earth [10]. It should be noted that sometimes earth elements, such as walls, are coated and cannot be identified. In other cases, earth constructions were demolished to build new ones using other materials.

Earth is a composite material, a natural mixture of a series of aggregates (stones, pebbles, sand and silt) and a binder (clay), similar to ordinary concrete, which also contains aggregates (stones, pebbles and sand) and a binder (cement). However, there are substantial differences between these two materials. One of them has to do with building environmental sustainability. While concrete, when applied on site, undergoes an irreversible transformation and, therefore, cannot be reused and is difficult to recycle (at least easily and without excessive consumption of energy or resources), the earth used to build a particular wall can often be reused after its demolition or ruin, namely, to build a new one. This stems from the fact that no irreversible transformation takes place, and the water used to mix the earth only dries. However, it also justifies why contact between earth walls and water must to be restrained, to ensure great durability.

As a raw building material, earth is conditioned by its numerous possible mineralogical compositions and proportions. These different compositions and proportions mean that certain types of earth are more suitable for some construction techniques and others are more suitable for other techniques. The characteristics and properties of earth used as building material vary from place to place, which leads to different construction methods using this raw material. Thus, several methods of building with earth are known worldwide, with infinite variants that translate the identities of the places, people and cultures in which they were developed.

In the second half of the 20th century, the French group CRAterre (the International Centre for Earth Construction—School of Architecture of Grenoble) [11] carried out a worldwide survey of the different ways of building with earth, typifying many variants. However, some more can be added, such as the use of earth bedding mortars to produce stone masonries. They prepared a diagram with the 12 main identified methods and structured it based on three "families" of constructive systems: monolithic, masonry and mixed structures. It is within the monolithic constructive system that rammed earth fits.

2.2. Rammed Earth: Materials and Construction Techniques

In a general way, traditional rammed earth can be defined as a product and a construction method. Rammed earth uses earth as a raw material; it is commonly directly excavated from the soil at the construction site (to avoid transportation), where it is crushed, moistened, homogenised by mixing, placed and compacted in layers inside a topless and bottomless wooden box serving as a formwork. When the formwork is filled, it is immediately removed and placed aside for continuity or on the upper layer when the one below is completed. In this way, large blocks of compacted earth are obtained which are produced in situ, sequentially and in rows, constituting monolithic walls. The resulting product is called "common" or "civil" rammed earth (Figure 1).

Figure 1. Example of civil rammed earth being produced in Santiago do Cacém, Portugal. Author: M. Rocha, 2014.

Figure 2 shows a traditional formwork set for the production of civil rammed earth in the south of Portugal. Several other examples of rammed-earth formworks used in the Mediterranean region and in China were collected by Qi et al. [12].

Figure 2. Example of a vernacular Portuguese formwork for civil rammed earth. Author: M. Rocha, 2016.

The traditional production of rammed earth presents several particularities, which give it the following specific characteristics:

- The raw material (earth) typically comes from the place where building is carried out;
- The transformation of earth into rammed earth does not extend much further than changing the location of the material after unpacking, crushing, mixing, placing and compacting it again to increase its homogeneity, compactness and density;

– This compaction is carried out in situ, that is, at the construction site and at the exact location of the building built with the rammed earth, using simple, removable and reusable wooden formworks;
– For compaction, which is achieved with rammers, only mechanical energy is required which, in essence, simply corresponds to "arm strength";
– The rammed earth must be protected from the action of water at its base and at its top; therefore, stone masonry was commonly used for a basement, and walls were protected by a tiled roof;
– Once produced, a rammed-earth wall acts as both a structural element and a partition of the built space;
– A building made with rammed earth can last for thousands of years with simple surveillance and maintenance operations whenever necessary;
– At the eventual end of the building's use cycle, the complementary materials and products can be removed (such as roof structure and tiles, windows and doors and wooden or stone lintels), and the rammed earth can be demolished and the earth reused in another building or left in the open air so that the material returns to the natural environment from which it came

In the case of constructions with defensive military purposes, air lime and sometimes other additions were added to the earth. This mixture with the earth was made before placing it inside the formwork in layers for compaction, taking on the designation of "military" rammed earth (Figure 3).

Figure 3. Example of a military rammed-earth defensive fortress in Paderne Castle, Portugal; some of the visible holes are from the original formworks used. Author: M. Rocha, 2003.

With stabilization due to air lime as a binder, after carbonation, the rammed earth turned into an artificial limestone, with more resistance to weathering and to the action of rainy water. However, the earth used in military rammed earth could not be reused, contrary to civil rammed earth; it could only be easily recycled. Before the recognition of the value of defensive rammed-earth structures, there were examples, such as Alcácer do Sal Castle, where parts of the rammed earth walls were cut and sold as masonry units [13].

To facilitate and speed up the pace of the construction of defensive structures, quick lime, calcium oxide (CaO), was added to the earth instead of hydrated air lime, calcium hydroxide ($Ca(OH)_2$) [14,15]. The use of hydrated lime implicated a previous slaking of the CaO with abundant water that would need time and space for the production of high volumes. Alternatively, the direct mixing of the CaO stone with humid earth would simplify the procedure (less space and time needed) and could also ensure better bonding between the earth fractions and the lime via the caustic action of the CaO when slaking. Furthermore, it would be simpler homogenise the mixture of earth and CaO (small and porous stones) than the mix of earth and hydrated lime putty. On the other hand, the volume of CaO doubled when hydrated to $Ca(OH)_2$ after it was mixed with the humid earth, making the effective lime addition percentage higher than if the material was made directly with hydrated lime. The direct use of CaO in the production of military rammed earth can be most probably identified by the appearance of lime lumps due to a lower level of hydration (Figure 4).

Figure 4. Detail of the presence of lime lumps in the military rammed earth of Juromenha fortress. Author: M. Rocha, 2023.

After the carbonation of the lime, which can take several years and even decades, military rammed earth has a porosity lower than that of common rammed earth and a hardness similar to that of air lime concrete.

The percentage of CaO added is difficult to assess, but it is important to find old documents that can present some data. If not, the available possibility is to evaluate the percentage of calcium carbonate ($CaCO_3$) present in old military rammed earth samples from several constructions. In this case, one has to bear in mind that the earth could contain $CaCO_3$ aggregates and the percentage found may not come only from the binder; the percentage found is the one existing at the time of test, and some fractions of lime could have been washed out during the weathering of the wall throughout its lifetime.

Concerning the production of the military rammed earth, in addition to quick lime, other additions to the earth were carried out where it was made, such as the addition of crushed red ceramic waste (from bricks and tiles) and medium-sized stones (Figure 5). Nevertheless, the intentionality of adding these materials is uncertain. Because they were military defensive structures, these buildings required fast construction and fast reconstruction. For that purpose, the collection of building materials was always conducted nearby, and the available supplies could easily include debris from former constructions destroyed by war.

Figure 5. Detail of crushed red ceramic and medium-sized stones added to the earth in the rammed-earth Juromenha fortification. Author: M. Rocha, 2022.

Defensive military rammed-earth walls were most likely rendered whenever possible. The renders were applied in such a way as to simulate that the wall was built with large ashlar stone masonry, probably causing a greater impact on enemies. So, at least one of the reasons was aesthetic related to military issues. The renders are frequently no longer present; only trace elements show how they were in the past (Figure 6).

Figure 6. Detail of simulated ashlar stone masonry in the rammed-earth Paderne fortification. Author: M. Rocha, 2003.

2.3. Rammed Earth Deterioration

Whether due to extrinsic causes (the action of atmospheric/climatological, telluric, biological, anthropic agents, etc.) or intrinsic causes (the composition of original raw materials, construction type, natural ageing/degradation of materials, etc.), the general state of any built structure is the result of a complex situation composed of favourable parameters (to be preserved) and potentially harmful parameters (to be controlled or eliminated).

One of the most deleterious elements for earthen materials is water, but it is generally a combination of many factors that prompts deterioration processes [16]. It is known that the phenomena of the degradation of buildings comprising earth are mostly related to the action of atmospheric agents and factors of anthropic origin. Moreover, and like any other type of building, the state of conservation of a building made with rammed earth depends on its evolution (construction, maintenance, successive transformations, etc.) and its context (geographical, historical, cultural, etc.); so, the causes that are at the origin of its degradation are usually multiple and often combined [17].

In general, the main deterioration agents of rammed-earth constructions are mechanical actions, erosion, the infiltration and absorption of water and the condensation of water vapour [18]. The presence of weeds and vegetation is also an important factor in the degradation of rammed earth, especially in more exposed constructions, such as fortresses (which do not have roofs), buildings where maintenance is low and/or in areas that are difficult to access.

The consequences of the action of each one of these agents often potentiate the action of the others, and many are correlated; for instance, capillary rising damp and roots from plants may significantly reduce the mechanical performance of rammed earth. The application of new coatings acting as water vapour barriers can imply a concentration of salts and their destructive cycles of action [19], producing a lack of cohesion in the rammed earth substrate. The application of a surface-waterproofing treatment can also cause harmful action [20].

It should be noted that in general, mainly in civil constructions, coating solutions for rammed-earth walls were adopted (e.g., painting the wall with air lime milk—limewashing) which, when carried out periodically, ensured the durability of the walls. The walls of military buildings were often cleaned and cleared of vegetation, actions that ceased more than a century ago, i.e., when these buildings ceased to have a military purpose.

3. Military Defensive Rammed-Earth Structures

3.1. The Use of Rammed Earth in Military Defensive Structures

As mentioned before, the use of earth extracted from local soil for the construction of defensive military structures has been constant throughout human history. Different cultural groups, at different times and in the most diverse places, resorted to this material for such a purpose.

The city of Jericho, Palestine [21], the Great Wall of China in the Jyaiyuguan region [21], the palace–fortress of Alhambra [20], the defensive wall of Seville [22] in Spain, the Fernandina Wall of Lisbon [15], the Lines of Torres Vedras [23] and the Fortress of Juromenha [24] in Portugal are some of the many examples of the use of earth in the construction of defensive military structures. Although using the same raw material, the above-mentioned constructions were built with different techniques. Among these, the military rammed-earth technique stands out as it is the object of the present study.

In the southern half of the Iberian Peninsula, there is a significant number of defensive military structures built with rammed earth. Most of them were built, or rebuilt, during the period of the Islamic occupation of this territory. The Muslim invasion of the Iberian Peninsula was relatively quick, and their presence in this territory was long.

The Islamic presence in the Iberian Peninsula is marked by six major periods [5] in which defensive structures were built extensively: the Emirate of Córdoba (756–912), the Umayyad Caliphate (912–1031), the Taifa Kingdoms (1031–1091), the Almoravid Empire (1086–1146), the Almohad Empire (1147–1223) and the Nasrid Kingdom of Granada (1235–1492). Among them, the Almohad Empire stands out as it was the one during which rammed earth was used the most. Most of these structures remain and still retain enough elements to make their detailed study possible, cross-referencing the information provided by the observation of the physical object itself with the respective historical documentation.

The *Reconquista* (re-conquest of the territory by the Iberian Christian kingdoms) was much slower than the Muslim invasion (Figure 7), and during this period, damage, repairs and adaptations to military buildings occurred; later, during the Christian period, there were various interventions and modifications. Many of these fortifications, such as Juromenha, were later modified during the Iberian Wars of the 17th century (Figure 8).

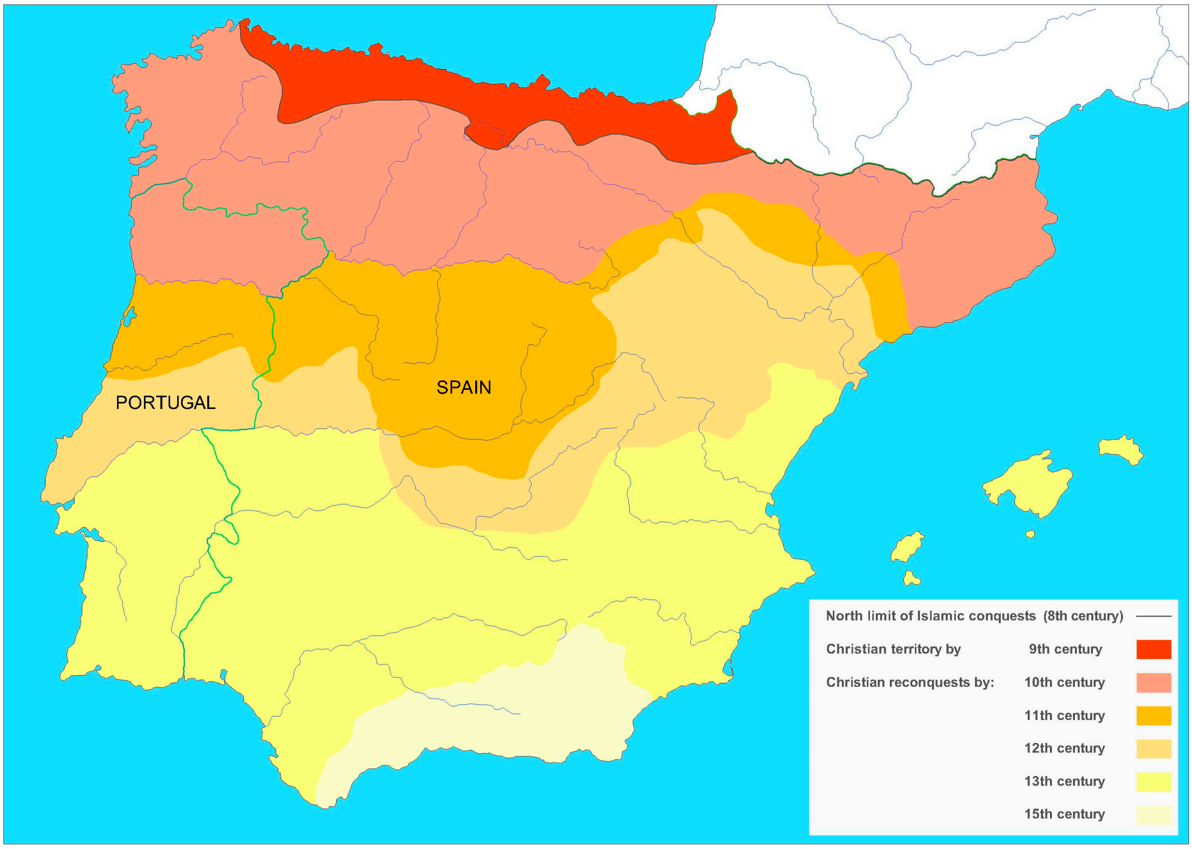

Figure 7. Schematic representation of the stages of the *Reconquista* (Christian re-conquest) of territories occupied by Muslims in the Iberian Peninsula, with the Portuguese territory in the southwest marked with a green line (Author: M. Rocha, 2023).

Figure 8. Example of a military rammed-earth structure built and rebuilt in different historical phases (Juromenha, Portugal). Author: M. Rocha, 2019.

3.2. The Deterioration of Rammed Earth in Historic Military Defensive Structures

The significant number of military defensive structures built and rebuilt with rammed earth during the Islamic occupation of the Iberian Peninsula and still existing at the end of 20th century is an indicator of their importance as heritage elements. Most of them show clear signs of degradation, mainly due to abandonment, but they have lasted for centuries with a reasonable state of integrity. Figure 9 shows the location of some of the most significant ones in the south of Portuguese territory.

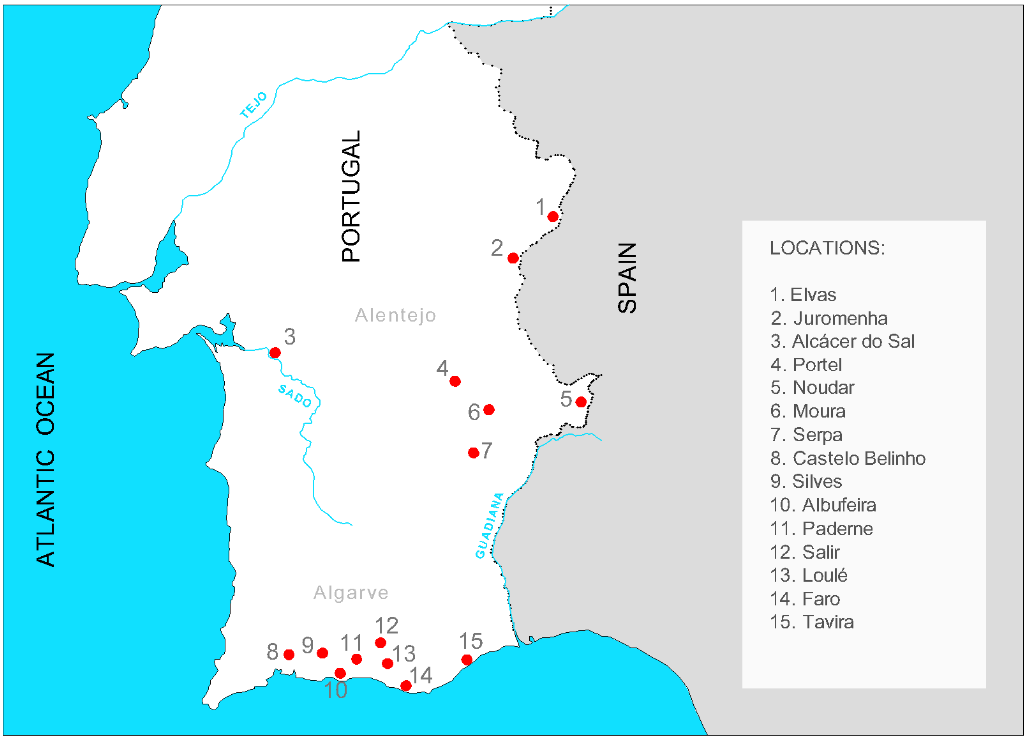

Figure 9. Location of some of the most significant rammed-earth defensive military structures in the south of Portuguese territory (Alentejo and Algarve regions, southwest on the map in Figure 7).

In terms of building preservation, it is interesting to study which factors affect the resistance and durability of this type of structure, especially in the face of threats that are considered more aggressive for earthen constructions. Among them, the action of water, such as heavy and prolonged rain or the capillary rise of water from the ground soil, stands out [25]. Water infiltration and the presence of cracks and fractures enhance the presence of vegetation, which greatly accelerates the degradation of walls and other rammed-earth structures.

There is another important issue to consider with defensive structures: damage caused to walls due to attacks by enemy troops. In order to restore their defensive capabilities, elements damaged by war were reconstructed, sometimes very quickly. These reconstructions were often taken up with the construction of new elements to improve defensive efficiency. In fact, towers and walls of fortifications that reached the 21st century often feature different types of rammed earth and stone masonries. As a result, many fortifications show different types and levels of material deterioration in the same element.

Therefore, the conservation of these historic structures requires that diagnosis and intervention techniques should be very specific for each building.

4. Conservation of Rammed-Earth Historical Defensive Structures

4.1. Analysis and Diagnosis

The ICOMOS Charter mentions in its point 1.3 that "*the value of each historic building is not only in the appearance of individual elements, but also in the integrity of all its components as* *a unique product of the specific building technology of its time and place*" [2]. In the context of the conservation of heritage structures built with rammed earth, it is therefore essential that far-off techniques and/or materials are not applied as they could cause incompatibilities with the pre-existing environment or distort the constructive concept or original architectural or cultural language. To this end, a basic protection and conservation protocol must be established, with tested procedures and technical controls throughout the entire intervention process [26].

Thus, any process of conservation of any element of built heritage must begin with the collection and recording of the greatest possible amount of data about its history, the physical object itself and its surroundings. At the same time, the intervention criteria must be defined based on the general principles set out in the theory of conservation and restoration. It is also of chief importance to proceed with the characterization and evaluation of the operability of the preservation, protection and reinforcement systems for these structures. Moreover, it is fundamental to be aware that among the dangers faced by historical and archaeological sites are those that inexperienced, unskilled or incompetent restorers (and builders) cause during the process of restoration [27].

When analysing the causes of deterioration and loss in a historic building, the following questions must be posed: "(1) *What are the weaknesses and strengths inherent in the structural design and the component materials of the object?* (2) *What are the possible natural agents of deterioration that could affect the component materials? How rapid is their action?* (3) *What are the possible human agents of deterioration that could affect the component materials or the structure? How much of their effect can be reduced at source?"* [1].

Multiplying the sources of information, diversifying and expanding the amount and type of data collected, will allow one to obtain a comprehensive knowledge of the object, not only regarding its material but also its immaterial components. This often provides answers to questions that a simple physical examination fails to provide. No information about the origin, evolution and history of a building that is intended to be conserved should be disregarded, whether related to its physical component or its cultural component: the material object, its use and its functions throughout history are an inseparable whole.

Among the various types of data to be collected, those that make it possible to acquire detailed knowledge of an existing rammed-earth structure stand out in terms of both its components as a constructive system and in terms of its constituent matter.

Diagnosis is an entire investigation process that goes through several stages, from analyzing the symptom of an anomaly to repairing it. Its main target is the detection of the primary causes of the anomaly, which must be eliminated or controlled before proceeding with the repair of the anomaly [28].

The analysis of an earthen construction's pathology makes it possible to distinguish a main set of degradation agents whose effects and consequences are important to know to have a better understanding of the processes according to which they manifest and to be able to act effectively against them [18].

Thus, the initial characterization of an existing rammed-earth structure and the understanding of the causes and processes of its deterioration constitute the basis of a technical diagnosis. As a first approach the building, this diagnosis will open the way to an indication of relevant technical answers to intervene with respect for the building, both for the construction itself and its surroundings. It implies a reading of the object at various levels which does not dwell on the material components of the building and its surroundings but also takes into account its immaterial dimensions, such as its use and history.

One of the specificities of the technical diagnosis of military rammed earth consists of understanding the balance between the presence of water and the structural stability of each building element in question [17] since these are the two main causes of deterioration: the action of water and structural failure. Moreover, generally, one enhances the other (Figure 10).

Figure 10. Action of water and structural failure in a military rammed-earth structure (Juromenha, Portugal). Author: M. Rocha, 2021.

4.2. Rammed Earth Repair and Conservation Techniques

The conservation of military rammed-earth structures attracts increasing interest as it is one of the techniques presenting the highest complexity in conservation practices [21].

A review of the literature reveals that, in general, the intervention techniques applied in the conservation of rammed earth military defensive structures in the Iberian Peninsula are closely linked to three fundamental factors: (1) the original constructive technique, (2) the diagnosis of the pathologies present at the time of the intervention and (3) the intervention criteria specific to the author of the conservation project or the project's objectives [29].

Most interventions cover a wide range of combined conservation, reintegration and reconstruction actions, with varying percentages between these three components. Often, in a single intervention, actions are carried out for the conservation of the rammed earth (cleaning, consolidation, protection, etc.), but also for the reintegration of more or less important gaps in the walls and/or the reconstruction of walls to avoid collapse. In this way, the interventions that have been carried out in rammed-earth fortifications can be classified into four large groups [29], as follows:

(1) The conservation and protection of the walls, in which, accepting certain levels of deterioration, the conservation of the original material is favored over the recovery of the original image of the fortification.
(2) The consolidation of the walls, which corresponds to the superficial consolidation of the walls or, mainly, the filling of large gaps with material similar to the existing material or with other materials to restore the constructive consistency of the built element.
(3) The recovery of volumes in the sense of recovering the profile and the mass of the construction through the reconstruction of some missing parts, which allows for a reading of the original construction before its deterioration and simultaneously decreases the degradation path (Figure 11).
(4) The reintegration or replacement of the finishing surface which, in addition to providing necessary protection against the collapse of walls that were eroded by the action of atmospheric agents, also changes the visual appearance of the building with the creation of a homogeneous and unitary surface.

Figure 11. Recovery of volumes in a military rammed-earth fortress to avoid collapse (Reina Castle, Spain): (**a**) before intervention (unknown author, 1960's); (**b**) after intervention (Author: M. Rocha, 2007).

Often, the approach of a conservation intervention includes tasks from more than one of the above-mentioned groups, depending on the specific element, namely, on large defensive structures.

In order to accomplish a more precise classification of interventions, the selected criteria may be gathered into three categories according to (1) formal constructive, (2) pathological risk and (3) technical reliability responses [22].

The analyses and evaluation of a number of recent actions of repair and conservation of military rammed-earth structures reveal that foreign techniques and/or materials were applied in conservation actions, and they frequently caused incompatibilities (Figures 12–14) with the pre-existing environment and often distorted the constructive concept or the original architectural or cultural language.

Figure 12. Detail of the incompatibility of materials in an intervention for the conservation of a rammed-earth Reina fortification, causing damage to the structure (Author: M. Rocha, 2007).

In addition to the fact that there are few or no regulations for building rammed earth walls, there is no consensus on this technique but a wide variability of proposed values due to the large number of variables related to earthen construction. All these aspects make the regulation of this building technique and its repair and conservation more complex. Even in the majority of references in the literature that propose tests or reference values, the procedures for their verification on site are still scarce and not very precise [30].

Figure 13. Detail of an ineffective intervention for the recovery of volumes in the fortification of Silves, Portugal, simulating rammed earth but distorting the original architectural and constructive concept (Author: M. Rocha, 2016).

Figure 14. Detail of inadequate past intervention for surface repair, with mortar placed inside formworks to simulate rammed earth in the Juromenha fortress, Portugal. Although keeping its integrity for decades, this intervention has a very low visual compatibility (Author: M. Rocha, 2021).

5. Discussion and Final Remarks

In the southwest of the Iberian Peninsula, there is a large number of air-lime-added rammed-earth defensive structures, mainly from the 12th and 13th centuries, which constitute a unique historical legacy. This built heritage is currently recognised as an asset to be preserved for social, cultural, technological and economic reasons. For its preservation, which includes not only material value but also immaterial value, regular maintenance and conservation actions are necessary. On one hand, these actions should not destroy its original characteristics, and, on the other hand, they should contribute significantly to its protection.

However, achieving a conscious conservation of historic rammed-earth defensive structures is a quite challenging task which begins with the issue of the variability in the raw material with which they were built: earth extracted from the local soil. Next, are the uncommon building technique itself and its variation from one location to another, plus the usage of assorted building technologies depending on the circumstances of each location and historical period.

The present study began with an analysis of the raw materials and the characterization of existing military rammed-earth structures and their constructive systems in comparison to more common civil rammed earth. Then, it proceeded with a study of pathologies and the most common anomalies they reveal. Additionally, a reconnaissance of the most frequent damage that this type of military defensive structure suffered throughout history, and still suffers at present, was presented.

Subsequent work revealed that current methodologies and intervention techniques for the repair and conservation of rammed earth fortifications fail in a number of cases, leading to unsatisfactory results, including serious damage in the original structures.

Moreover, considering the diversity of raw materials used in the construction of these structures and the diverse types of interventions throughout history, the establishment of a "universal recipe" for their conservation would be inadequate. Furthermore, constraints, such as a lack of availability of local earth due to archaeology or urban limitations, are problems to deal with.

As result of the analysis of all these issues, it was assumed that a basic protection and conservation protocol must be established which is specific to each structure to be conserved, with tested procedures and technical controls throughout the entire intervention process. The definition of the general framework of this protocol will be part of the future developments of the research project in which the present study is included.

Therefore, in the context of preserving the historic defensive military structures built with rammed earth in the southwest of the Iberian Peninsula, as mentioned above, further research is needed to assess conservation actions, more precisely in terms of material and structural compatibility, as well as with respect to durability.

In the geographical area under study, more than 50 defensive military structures built with rammed earth were listed. Among them, four were chosen to be studied in more detail within the scope of this work: Campo Maior, Juromenha and Paderne in Portugal and Reina in Spain.

Reina, Paderne and Juromenha are Almohad fortifications from the 12th century. Juromenha's structure was modified and added with new rammed earth during the Iberian Wars of the 17th century, and in Campo Maior, rammed earth from this only period was identified. These fortifications were selected because they were considered the most relevant for the ongoing research study, both due to their state of conservation and heritage/historical value, as well as the nature and quality of the conservation interventions recently carried out on them.

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