PRESERVATION OF RAMMED EARTH STRUCTURES THROUGH TRADITIONAL METHODS: CASE STUDY

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This paper describes the research carried out around a high heritage value construction, the Torre Muza de Benifaió in Valencia (Spain). The tower is a defensive building from the Spanish Arab period, built during the 11\textsuperscript{th} and 12\textsuperscript{th} centuries AD. When the studies began, it was abandoned, in a dilapidated state, and slight information was known. Therefore, following extensive and multidisciplinary work was the starting point to recognizing the critical aspects of its history, damage, and current condition. Particularly noteworthy is the specific characterization of the traditional rammed earth construction system and the materials that made it up. All this was performed based on historical research, laser 3D scanning, and complementary characterization studies (physical, chemical, and mechanical) with the vision of the whole and surroundings. With all this, it was possible to determine the recovery of the walls following the same construction technique, although differentiating their specific execution. These preliminary studies allow a respectful consolidation and recovery of the construction and ensure the compatibility and integration of the materials and the intervention. This paper remarks on the importance of multidisciplinary preliminary studies to develop proper preservation of vernacular techniques and heritage architecture.

Keywords: Earthen Structures, Vernacular Architecture, Preliminary Studies, Arabic Tower, Heritage Construction.

1 INTRODUCTION

Earth as a building material has been used practically worldwide since ancient times. We have examples of these constructions in countries like Egypt, China, India, Syria, Peru, North Africa, the Iberian Peninsula, etc. The construction techniques have adapted to the existing materials in the area, the different types of soil, and the different climates.

According to the characterization made by Houben and Guillaud (2006), there are about twelve different techniques identified throughout the world. These include the earth excavated, poured, or molded, the soil as fill or cover, and rammed earth or adobe. According to Leporelli \textit{et al}. (2021), these techniques can be divided into two types of characterization, depending on whether the structural characteristics or the construction process are considered.

The rammed earth stands out for its structural characteristics within various techniques. It consists of pouring a soil mixture (silt, sand, gravel, and clay) into thin layers (7.5-15 cm) compacted within a formwork. The term “rammed earth” refers to both the material and the construction process (Jaquin \textit{et al}. 2009). Silt, sand, and gravel are simply aggregates, while clay is the binding element of the mixture (Minke 2007). If the mixture binder is only clay, it is
considered “unstabilized” rammed earth. If a cementitious material is added to increase its durability and resistance, it is called “stabilized” rammed earth (Ávila et al. 2022). Lime has been the material used as a binder for centuries, its main effect being the increase in mechanical strength (Bell 1996, Minke 2007, Baldovino et al. 2019).

It is crucial to develop complete preliminary studies to know rammed earth structures’ properties and mechanical behavior to prevent failure (Silva et al. 2014). Moreover, other aspects should be analyzed: constructive, conservation and vulnerability, and risk characterization to perform the diagnosis and propose remedial measures for preservation (Canivell 2012).

This paper presents the research carried out in the Muza (or Mussa) Tower. This is a rammed earth construction from the 12th-13th centuries, located on Benifaió (Valencia, Spain). The paper describes the data collection and characterization carried out: historical, archaeological, physical, chemical, and mechanical for the subsequent consolidation of the tower walls. This working way establishes a research procedure for analyzing and preserving this type of construction.

2 RESEARCH APPROACH AND METHODOLOGY

2.1 Background and Regulatory Framework

According to the Valencian Cultural Heritage Law, the Muza Tower is an ancient defensive construction, holding the top consideration category of the protected heritage building as a “Monument” (Ley 4/1998 1998). This law reproduces what established the previous Spanish Historical Heritage Law regarding these constructions (Ley 16/1985 1985). Furthermore, specific regulations detail heritage values and protected areas (Resolución 12.01.2000 2000, Orden 31.05.2005 2005).

These regulations establish the conditions of the intervention in these buildings: a multidisciplinary team must study all the aspects involved. Besides the architectural, historical, or archaeological values, the previous state damage must be considered in the proposal.

The regulations also recommend and promote traditional techniques and materials for intervention instead of newly created or implanted materials. Among other reasons, technical aspects of materials compatibility are argued, but experts should also consider environmental, social, and economic factors connected with the primary axes of sustainable development.

Likewise, it is necessary to establish, on the one hand, a careful balance between the difference between the restored elements and the original ones to avoid a historical fake and, on the other hand, the necessary integration into the whole (ICOMOS 2003).

2.2 Methodology

With these conditions, needing to afford the Preliminary Studies established by the heritage legislation, there was necessary to take some regulations as a reference. Therefore, the Spanish Standard UNE 41805:2009 “Diagnosis of buildings” (Asociación Española de Normalización y Certificación AENOR 2009), were used to establish the minimum contents of the study.

According to UNE 41805-1 Standard, preliminary studies are the phase before the intervention of prior research. Their key issue is to consider the building as an “integral system” in which various actions interact. For the current state, it establishes the study of five aspects:

(i) The activities carried out from the beginning in the building and its surroundings.
(ii) The different materials and their compatibility: ceramic, stone, wood, mortar, etc.
(iii) Products manufactured on-site (in Muza Tower: rammed earth walls).
(iv) The external damage agents: biological, physical-chemical, environmental, etc.
(v) The damage location considering the construction system and zones.
These studies were carried out before the intervention for one year. As the data were obtained, the researchers established the links and relationships. The preliminary studies developed, based on the regulations applied and previous experience in this type of work, include:

- Graphic surveys, documentary historical and archaeological research.
- Geological explorations, territory, landscape, environmental and botanical analyses.
- Research on construction techniques, dimensional surveys, and building configuration.
- Observation of damage patterns, thermographic, and mechanical characterization.
- Sampling, physical, and chemical analysis and characterization of materials.

![Figure 1. Previous views and plans of Muza Tower.](image)

### 2.3 Preliminary Studies

The graphic and cartographic documentation was one of the first tasks since it is the basis for referencing many of the subsequent studies. For this reason, although the regulations do not indicate it, this part must be available to program the work to perform (Rodríguez et al. 2021).

Different surveys were carried out, from the sketches, direct measurements, photogrammetry, topographic support, and a laser scanner. The restitution was performed with computer technologies that allow 3D-building modeling. This means was proper in rammed earth works due to irregularity in the walls.

The data obtained has been used to define the construction and detail studies of the tower and the walls’ construction, determining the rammed earth characteristics and its dimensions: module, number of boards, needles’ position, etc. It also allows establishing different hypotheses about its construction, especially the interior, where there are more interpretation doubts.

The historical research combined with the technical drawings (photogrammetry, laser scanner, and topography surveys) supports the constructive technique study. As a result, the module of the formwork and the levels were established. The formwork module was two Arabic cubits (94 cm), and the different interior levels were 3.60 m in height (López-Mateu et al. 2015).

Finally, physical-chemical tests were performed to characterize the material. Samples were taken on the interior and exterior walls. These tests included the following determinations:

- Morphological characterization by optical microscopy.
- Scanning electron microscopy with X-ray and FT-IR ray diffraction spectroscopy.
- Granulometric analysis of mortar and insoluble residue after an acid attack.
- Mineralogical chemical characterization and quantitative determination of soluble salts.
In a first assessment, the current state of the Muza tower would be considered reasonable in general, or at least not excessively inadequate. However, after the analyses, a more detailed direct observation revealed that the NW corner and the finish were in poor condition.

The exterior walls were damaged in their lower part by the absorption of water by capillarity directly from the ground. Older repairs with Portland cement mortars had impeded the breathing of the walls. Additionally, the damage caused by the vegetation, mainly the ivy, which had been introducing its roots into the wall itself and in the subsequent repairs, was evident.

In the upper part of the tower, the generalized deterioration due to erosion was very significant, with some battlements having detached. Fortunately, others were still preserved, although partially crumbled and eroded by the action of atmospheric agents.

There were two large cracks in the north corner on the NE and NW faces. These cracks seriously compromised the tower’s stability. Around them, there were partial landslides of wall mass of approximately 2 meters in height. Despite cavities from its former use as a dovecote, the walls did not show significant damage inside the tower.

Figure 2. Pathological, constructive, and dimensional study of Muza Tower.

3 RESULTS

3.1 Intervention Proposal and Development

In the intervention, three action phases were considered: first, urgent intervention; second, interior and surroundings of the tower; and third, the recovery of the environment and new uses (López-Mateu et al. 2015).

Furthermore, these phases could be executed in several sub-phases. They depend on the progress of the task and the budgeting available. It also hinges on the final damage extension and the repair techniques required, which always pose uncertainties in rehabilitation projects.

3.2 Scaffolding Challenge and Analysis Accomplishment

The work that consumed the most resources was the assembly of the complex scaffolding to access both outside and inside of the tower. It was also necessary to prepare the accesses and level the land with the corresponding archaeological surveys.

Once the scaffolding assembly was completed, the team developed a new inspection of the upper and the interior areas of the tower to obtain new data: pictures, measurements, and samples that complement the previous ones. The fact evidence that preliminary studies are “under supervision” until the end, always searching for new pieces of evidence.
3.3 Consolidation, Repair, and Retrofit of Rammed Earth Walls

The masonry consolidation and retrofit tests were carried out at the tower’s base in a specific area provided for this purpose. Different aspects were previously verified, such as the preparation of the traditional formwork or the dosages and mixture consistency. These preliminary on-site tests, including the final patina, were essential to establish the superficial protection.

Next, the masons addressed the upper part of the tower consolidation, placing the necessary propping where the walls were in critical condition. They used it in the battlements and the upper corners, the weakest points of the construction. All the auxiliary elements, such as formwork, falsework, etc. followed the characteristics of traditional ones recognized in previous research.

The walls recovery required the prior demolition of the parts in poor condition. It was necessary to eliminate those disintegrated parts that could compromise the structural stability. The selection of these areas was complex since it needed to balance the prevalence of the conservation of the original fragments and their viability.

![Figure 3. Retrofit detailed plans and a final view of the intervention.](image)

3.4 Materials Criteria Applied and Retrofit Works Management

Where the rammed earth walls had partially or totally lost their volume, they were recomposed or rebuilt using the same traditional construction technique. The wooden formwork followed the original metric characteristics: number of boards, height, width, and slope.

The stones were placed in rows, the biggest ones in the corners, following the way observed in the initial construction. Mortar proportions were: 1 aerial lime, 1 hydraulic lime, 6 aggregate (sand and gravel according to predetermined granulometry), and minimum amount of water.

Cement was not used in mortars or grouts, which meant a slower construction process due to the setting of the materials. However, it preserves the compatibility between materials and avoids chemical reactions. This situation required redistributing working areas on the construction site.

4 CONCLUSIONS

The construction technique of the Musa Tower is the monolithic rammed earth wall “stabilized” with hydraulic lime similar to masonry but made up of wood formwork. The research team identified particular dimensions of these timbering through a combination of multidisciplinary studies. The ancient constructors followed the module of the Arab cubit of approximately 47 cm, called the “black cubit” and configured the construction of the whole building.
This type of modular construction presents excellent resistance and stability, despite the various damages caused by climatic actions in the most exposed areas, such as the upper part and the corners, or dampness in the lower part. It has also been able to resist changes in the dimensions of the access and defensive openings.

In addition, it resists the cavities due to the subsequent use of the dovecote and arbitrary repairs and modifications. Despite this significant resistance to this type of construction, the exhaustive investigation revealed that when the time comes, it is necessary to intervene in a certain way to avoid irreversible deterioration or a partial collapse of such a monolithic structure.

Among the criteria used in the intervention, it was a key issue to use the same traditional technique and materials. It is relevant to retrofit the upper part of the battlements and the last wall levels to unify the finish and protect it from the weather conditions.

This case study shows that preliminary studies are vital to identify the traditional construction techniques and the materials used throughout the process to achieve unity with the whole and, above all, the highest degree of compatibility and durability to the intervention.

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