Rammed earth sustainability and durability in seismic areas as a building material

Adolfo Preciado¹* and Juan Carlos Santos²

¹* Professor and researcher at ITESO University, Guadalajara, México
² Master’s student at ITESO University, Guadalajara, México

*adolfopreciado@iteso.mx

Abstract. Rammed earth is one of the oldest materials of the world and has been used as a building material for centuries due to its availability, low cost benefits, auto-construction and bioclimatic capabilities to sustain extreme weathers. Rammed earth and adobe housing are constructed in earthquake prone areas around the world due to these benefits. These earthen materials are used to mainly build load carrying walls with light cover of timber. These auto-constructed buildings are extremely vulnerable to earthquake shaking due to its heavy mass, strength degradation through time and lack of structural integrity among elements. This is a natural and sustainable material that deserves to be investigated in order to be used again as a main construction material against masonry and concrete housing. It is needed to understand its behaviour under different loading conditions to identify the components that convert it into a highly vulnerable material. The present investigation focuses on the durability of rammed earth as a construction material of housing located in seismic areas of Mexico. It is presented a survey on one existing rammed earth house constructed almost 15 years ago. It was extracted soil of the surroundings of the construction site to investigate by laboratory tests the compressive strength of the material as constructed in day one and compared against the existing one. It was observed that the water content plays an important role in the compressive strength. The new earth specimens with similar water content as the existing wall samples, presented five times more compressive strength. Finally, advantages and disadvantages are highlighted about the behaviour and durability of this sustainable material.

1. Introduction

Rammed earth is one of the oldest materials of the world and has been used as a building material for centuries due to its availability in the near environment, zero-cost benefits, auto-construction and bioclimatic capabilities. These bioclimatic benefits of rammed earth permit to the users to sustain extreme hot weathers in spring and summer, as well as to survive cold seasons in winter. On the other hand, rammed earth and adobe housing have been used a lot in seismic areas around the world due to the aforementioned benefits. These earthen materials are used in Latin America to mainly build load carrying walls with light covers of timber and compressed cardboard sheeting or most of the time with fired-clay tiling roofs (see Fig. 1). Moreover, the availability in nature, relative no-cost and easy access to soil in poor regions convert adobe and rammed earth into a very attractive construction material. Another great advantage of earthen materials is the durability capability which may be
extended from centuries to thousands of years (e.g. the rammed earth material used in the infill of the Great Chinese Wall, V a. C., and the infill of the Teotihuacan’s pyramids in Mexico, II a. C.).

Adobe is a material made of rectangular units of mood which are sun-dried and placed together with mortar of the same material to build walls. A typical technique was to add to the mix of the mood of units and mortar natural materials such as dried-grass, cactus nectar, cattle’s blood and manure. These natural additives were a common practice in the construction of adobe and rammed earth walls to increase the durability of soil against environmental actions such as temperature changes (i.e. deformations inducing cracking), rain protection and strength. Both earthen construction materials, adobe and rammed walls require simple tools which could be made in-situ (e.g. wooden molds and rammer) and non-specialized labor or professional supervision.

Figure 1. Typical earthen house with adobe walls in Peru.

These auto constructed buildings are extremely vulnerable to earthquake (EQ) shaking due to its heavy mass, strength degradation through time and lack of structural integrity among elements (i.e. walls, corners, intersecting walls, openings, and so on). However, adobe and rammed earth are natural and sustainable materials that deserve to be investigated in order to be used again as a main construction material against masonry and concrete housing. It is needed to understand its behaviour under different loading conditions such as vertical due to self-weight and lateral by seismic action to identify the components that convert it into a highly vulnerable material. Adobe and rammed earth have been investigated for many researchers around the world in order to identify the main vulnerability components against EQs and how to retrofit them with natural materials such as injected soil, fibers, waste of construction materials and stabilization with gypsum, Portland cement and lime (e.g. [1-9]).

This investigation focuses on the durability of rammed earth as a construction material of housing located in high seismic areas of Mexico. We present a survey on one existing rammed earth house constructed almost 15 years ago. It was extracted several samples of the existing walls in order to be tested in laboratory under axial loading to identify the relationship between water content and the compressive strength. We extracted soil of the surroundings to investigate the behavior of different specimens with variation in age and water content under axial compression to compare the results with those of the existing construction. Moreover, it is presented a summary of the main advantages and disadvantages of rammed earth regarding vertical and seismic behavior, construction process, material degradation and observed damage under EQs.
2. Construction technique of rammed earth and vulnerability aspects

Rammed earth is one of the oldest construction techniques which involves simple tools such as wooden or metal formwork for pouring the soil mix and a rammer for soil compaction. The stress applied to the soil causes a densification due to the displaced air from the pores, forming a solid wall segment that may be used as a load-bearing element or to define an architectonic space. Compacted earth walls may present different thicknesses ranging from 30 to 60cm depending of the height of the wall and roof system [1]. The general process of the construction of rammed earth walls and needed tools (Fig. 2a) are illustrated in Figure 2. This is the house that we use as a case study in the present research work and was constructed in 2005 (see Fig. 2b). More details about the construction process are explained in the following section. It is worth noting the overall thickness (i.e. 0.40m) of the rammed earth segments of the walls (i.e. 0.40x0.50x0.93m), needed tools, pouring technique and ramming the soil mix by a removable/scaling formwork (Fig. 2).

![Fig. 2](image)

**Figure 2.** Typical construction process of rammed earth walls: a) wooden rammer and mold and b) pouring and ramming process of the mix to form the rectangular wall segment.

There are certain aspects that convert adobe and rammed earth structures into very high structural systems. This is due to the great mass of walls, the brittleness of the material, lack of structural integrity and a rapid degradation of strength due to aging and weathering. These earthen walls need a considerable thickness in order to resist its own weight and vertical load transmission, increasing with this the inertia forces in case of EQ loading. Moreover, due to the low compressive and almost zero tensile strength of earthen structures, it is common to observe the presence of vertical cracks along the height of walls and horizontal cracks by low vibrations induced by traffic or past low intensity EQs.

[10] affirms that the volumetric weight of adobe and rammed earth is of about 1800 kg/m³ and the compressive strength ranges between 2-5 kg/cm², shear strength about 0.5 kg/cm² and Young’s modulus of 3000 kg/cm².

Due to the aforementioned aspects, earthen structures present a poor seismic behaviour even when subjected to EQs of low to medium intensity, ending with a brittle collapse of walls or the complete structure. These collapses through the history have taken around the world the lives of many people, especially in Latin American countries such as Mexico, Peru, Colombia and Ecuador. In general, the seismic behaviour and failure of earthen structures is very similar to the presented by unreinforced masonry (URM) (i.e. relative acceptable compressive strength and low shear/tensile resistance). URM structures present a complex behaviour under seismic conditions due to the heterogeneity and anisotropy of this material and has been studied under vertical and lateral conditions through
numerical simulations and post-earthquake observations in high seismic regions by [11-14]. In conclusion, the poor seismic performance of rammed earth housing is due to several important factors such as the elevated heavy self-weight of this material, brittleness, erosion and bad connections among structural elements.

The nonlinear behavior since low horizontal seismic loading and the anisotropy of earthen materials such as adobe and rammed earth also govern the seismic behavior and failure mechanisms. Regarding the last, this may occur in different manners if the loading is presented at walls in-plane and out-of-plane. Regularly, the in-plane failure is mainly presented by diagonal shear at walls and at the corners of openings such as windows or doors. Another in-plane failure may be present by vertical cracking at wall’s corners or at the intersection with other walls due to the lack of structural integrity by the poor tensile/shear strength (see Fig. 3a). Conversely, the typical out-of-plane failure mechanism is represented by the rapid formation of horizontal cracking followed by the collapse of the wall. Moreover, the EQ vibration out-of-plane of walls may also induce the collapse of the roof system into the interior part of the house (Fig. 3b).

![Typical seismic failure of earthen housing: a) in-plane failure mechanism [8] and b) out-of-plane failure mode [9].](image)

A deep understanding of the main aspects determining the seismic vulnerability of earthen structures (i.e. material, geometry, structural components, in-plane and out-of-plane behavior) represents a key aspect in order to improve their performance through the enhancement of the material and other remedial measures. The main goal of the EQ performance improvement of rammed earth structures is to protect human lives from brittle collapses and to continue using this sustainable material against conventional ones such as masonry and reinforced concrete.

3. Case study

This section presents the construction process of the rammed house which was constructed in a high seismic area as a case study. The house was part of a research project and was constructed in 2005 in the backyard of the Technological Institute of Colima (ITC), Mexico. We decided to construct the house on this site to take advantage of an excavation developed by the ITC. The soil was separated of large size rocks, roots and other garbage such as plastic bags and transported by wheelbarrows to the construction site located about 20m (see Fig. 4a).

The soil to be used as rammed earth was selected by qualitative methods consisting of forming a small soil ball with sufficient humidity and dropped from a height of about 1m. The dropped ball presented no cracks, which means that the soil contains a sufficient amount of fines and sand to present a relative good plasticity to be consistent when subjected to the compression induced by the
rammer. A good soil for rammed earth is recommended to contain a combination of silt, sand and fine gravel. The soil is mixed with water and segments of dried straw (see Fig. 4b). This natural fiber helps to the soil to be more flexible against temperature changes and to avoid cracking when dried, and increases weathering protection. In the foundation, we just excavated a ditch with a width and height of about 50cm, and constructed the walls with earth blocks of 0.40x0.50x0.93cm (t x h x l). In the end, we realize that it should have been better to build a stone foundation at the wall’s foot to avoid humidity by the capillarity effect as depicted in Figure 1.

![Figure 4](image_url)

**Figure 4.** Construction site of the rammed earth house under study: a) soil extraction and transportation and b) soil and dried straw mixing process.

Figure 5a presents the rammed earth house almost finished, where it is worth noting the wall thickness of 40cm, the windows and main door, as well as the perimetral beam supporting the two masonry tympanums of fired clay bricks. Moreover, it is observed the light cover system of compressed cardboard sheeting over a triangular timber roof. All walls and tympanums are plastered with fine soil in combination with a 3% of Portland cement for stabilization. The house has a square plan of 3.5 x 3.5m (12.25m²) and the total height of walls is 1.90m and 2.64m including the finished cover system.

![Figure 5](image_url)

**Figure 5.** Rammed earth house under study: a) installing of the compressed cardboard sheeting and b) actual state of the rammed earth house.

The City of Colima is located in the perimeter of the Pacific macro-plate which is also known as the belt of fire for the presence of very active volcanoes. The very high seismicity is normally induced
by the subduction of the Cocos and Rivera plates beneath the North American plate. This mechanism has induced along the history very destructive EQs of magnitudes higher than 7 Mw and intensities ranging from VII to X that have caused uncountable damages to vulnerable buildings and the lives of persons at the different cities of the state of Colima (e.g. the 1995 Manzanillo EQ, Mw= 8 and the 2003 Tecoman EQ, Mw= 7.5). For more information about these EQs the reader is referred to [15 and 16]. However, these major EQs have occurred prior to the construction of the studied house. During the almost 15 years period of observation of damages on the case study house, have occurred relative minor EQs of magnitudes ranging from 5 to 6.5 Mw with no record of structural damages in the surroundings of the ITC. Due to the lack of maintenance, the house have suffered degradation of the plaster due to heavy rain and weathering induced by the cover openings. The cover was damaged because the house was used a storage room for chairs and other waste as illustrated in Figure 5b. The perimetral timber beam is extremely decayed and also the color of the rammed earth walls have changed due to humidity and aging and was identified the presence of insects inside holes. Regarding structural damage, the walls have presented some partial collapses due to vandalism, but not induced by EQ vibration. The observed cracks at walls are mainly related to the lack of maintenance as aforementioned, material degradation by aging, rain, wind, sun irradiation and so on.

4. Sample extraction and experimental testing

In order to investigate the influence on aging on the material strength of rammed earth walls exposed under extreme weathering and zero-maintenance, we extracted several coarse samples of approximately 25x25x25cm with the use of cutting tools (see Fig. 6a). The objective was to compare the compressive strength of the existing rammed earth walls against the new specimens. To develope this, we extracted soil from the same construction site where the house is located and fabricated in laboratory cylinders of 20cm in height and 10cm of diameter (see Fig. 6b). Firstly, we checked again by the dropping ball test the quality of soil and the samples presented a good plastic behavior. Furthermore, the cylinders were filled up in three layers and compacted with a rammer until reaching a visual compaction as the artisanal technique.

![Figure 6](image)

**Figure 6.** Uniaxial compression study with a universal testing machine: a) observed failure mode on an existing wall sample and observed failure mode on a 60 days specimen.

The existing samples were carved in laboratory and presented final dimensions of about 10x10x10cm and were capped with a layer of gypsum (see Fig. 6a) for uniform loading transmission with the universal testing machine. The new earth specimens were not capped, instead, it was used neoprene retainers at the upper and bottom parts of the cylinders (Fig. 6b). The observed failure mechanisms are depicted in Figure 6, where it is worth noting in both, the extracted samples and new specimens, the typical crushing behavior which is represented by a vertical and semi-diagonal
distribution of cracks. The existing samples presented at ultimate conditions a mean compressive strength of 0.040 MPa (0.408 kg/cm²) for a mean water content of about 0.56% (see Fig. 6a). Regarding the new earth samples, at 14 days it was observed an ultimate mean compressive stress of 0.042 MPa (0.428 kg/cm²) for a respective mean water content of 4.81%. For a less content of mean water \(i.e\). 0.89% at 60 days, it was observed an ultimate mean compressive stress of 0.203 MPa (2.069 kg/cm²) (see Fig. 6b). The existing samples presented a very similar compressive stress as the new specimens tested at 14 days (0.040 MPa, 0.56%), but it was observed a different water content (0.042 MPa, 4.81%). Regarding water content, the specimens tested at 60 days presented an approximated percentage (0.89%) as the existing samples (0.56%), but more ultimate strength of about 508% (five times higher).

5. Conclusions and future research

The most important aspects determining the seismic behavior and failure mechanisms of rammed earth walls when subjected to in-plane and out-of-plane loading were highlighted. The vulnerability of this material is related to the poor performance against lateral loading if compared to its relative good performance in compression if the house has a light timber cover. The brittleness of the material and nonlinear behavior due to its almost zero tensile strength induces a lack of structural integrity among elements. Moreover, the openings may attract a concentration of shear stresses that may induce partial or total collapses. A deep understanding of these vulnerability aspects represents a key aspect in order to increase the EQ performance of rammed earth and to prevent a brittle failure in high seismic areas by the addition of wooden elements at vulnerable parts, natural fibers, stabilizing cements and other corrective measures. We may recommend not to construct houses of more than two storeys in order to reduce the structural vulnerability due to the lack of an effective rigid diaphragm as the induced by reinforced concrete slabs in EQ designed buildings. However, heavy slabs are not recommended to be supported by rammed earth or adobe walls.

A full-scale rammed earth house located in a high seismic area was constructed to investigate the construction process, durability, EQ performance, aging and weathering effects with zero-maintenance. The quality of soil for rammed earth was determined by qualitative procedures. As a further research it is recommended to develope a detailed and quantitative study regarding soil granulometry to identify its usability as rammed earth walls. The house has presented a relatively good behavior against minor to intermediate EQs ranging from 5 to 6.5 \(M_w\). The zero-maintenance and damaged cover, as well as heavy rain and weathering effects have contributed in the fast deterioration of walls and the decay of timber elements and plasters. Moreover, the house has presented some partial collapses due to vandalism. The existing samples shown a reduced percentage of water content, which is related to a decrease of axial compression strength as expected. This relation was successfully compared with the testing of new samples extracted at the construction site of the rammed earth house. At 14 days, the specimens presented a similar strength as the existing ones, but different water content. Conversely, the 60 days sample presented almost 5 times more compressive strength as the existing samples for almost the same water content and it is considered in this research as the maximum time period for reaching the higher resistance. With this relationship among existing samples and new ones, we may conclude that the lower the water content, the higher the strength. However, the higher observed strength at the 60 days specimens \(i.e\). 0.203 Mpa, 2.069 kg/cm²) is reduced if compared to conventional fired clay bricks masonry walls with lime mortar, ranging between 15-20 kg/cm².

Furthermore, it is suggested as a further research to test rammed earth wallettes under diagonal compression in laboratory to study the damage propagation and ultimate strength and to verify/calibrate the results with numerical simulations in order to use the mechanical parameters in the 3D seismic assessment of full-scale houses by the finite element approach. Moreover, to investigate in laboratory the shear behavior of earthen walls by the addition of natural fibers such as coconut, agave, dried straw and other extracts such as cactus and so on. Earthen houses such as adobe and rammed earth constructions are made of sustainable materials which have many disadvantages, but represents a
great opportunity to study them more in detail in order to identify the main aspects representing their seismic vulnerability and to propose remedial measures. These measures are mainly aimed at improving its seismic integrity and shear strength, and with this, to avoid the brittleness behavior and collapses by inducing a relative more ductile behavior. Definitely, this sustainable material is worth to continue investigated due to its construction simplicity, availability, low-cost and excellent bioclimatic benefits.

References
[1] Preciado, A., Ayala, K., Torres, S., Villarreal, K., Gutiérrez, N., Flores, A. and Hernández, V. (2017). “Performance of a self-build rammed earth house in a high seismic zone of Mexico.” Proceedings of the 3rd International Conference on Protection of Historical Constructions (PROHITeCH), July 12-15, Lisbon, Portugal.
[2] Taghiloha, L. (2013). “Using rammed earth mixed with recycled aggregate as a construction material”. Master Thesis, UPC Barcelona Tech.
[3] Burroughs, S. (2008). “Soil property criteria for rammed earth stabilization”. Journal of Materials in Civil Engineering, 20(3): 264-273.
[4] Silva, R.A., Jaquin, P., Oliveira, D.V., Miranda, T., Schueremans, L. and Cristelo, N. (2014) “Conservation and new construction solutions in rammed earth”. Structural Rehabilitation of Ancient Buildings, Springer-Verlag, Berlin, 77-108.
[5] Silva, R.A., Oliveira, D.V., Schueremans, L., Miranda, T., and Machado, J. (2014). “Shear behaviour of rammed earth walls repaired by means of grouting”. 9th International Masonry Conference in Guimarães.
[6] Islam, M.S. (2002). “Research on earthquake resistant reinforcement of adobe structures”. PhD Thesis, Saitama University, Japan.
[7] Islam, M.S. and Watanabe, H. (2004). “FEM simulation of seismic behaviour of adobe structures”. 13th World Conference on Earthquake Engineering, Paper No. 1310, Vancouver, B.C., Canada.
[8] Morris, H., Walker, R. and Drupsteen, T. (2010). “Observations of the performance of earth buildings following the September 2010 Darfield earthquake”. Bulletin of the New Zealand Society for Earthquake Engineering, 43(4).
[9] Varum, H., Tarque, N., Silveira, D., Camata, G., Lobo, B., Blondet, M., Figueiredo, A., Muhammad, M.R., Oliveira, C. and Costa, A. (2014). “Structural Behaviour and Retrofitting of Adobe Masonry Buildings”. Structural Rehabilitation of Old Buildings, Building Pathology and Rehabilitation, Springer-Verlag Berlin Heidelberg.
[10] Meli, R. (1998). “Structural engineering of the historical buildings (in Spanish)”. Civil Engineers Association (ICA) Foundation, A. C., Mexico.
[11] Preciado, A., Bartoli, G. and Ramirez-Gaytan, A. (2017). “Earthquake protection of the Torre Grossa medieval tower of San Gimignano, Italy by vertical external prestressing.” Engineering Failure Analysis, 71: 31-42.
[12] Preciado, A. (2018). “Analysis of behavior and failure mechanisms of old unreinforced masonry constructions under strong earthquakes.” Volume 1, Chapter 1 (pp. 1-25). Masonry: Design, Materials and Techniques, Nova Science Publishers, Inc.
[13] Preciado, A. and Orduña, A. (2018). “Numerical modeling strategies for the seismic analysis of masonry structures.” Volume 1, Chapter 3 (pp. 55-79). Masonry: Design, Materials and Techniques, Nova Science Publishers, Inc.
[14] Preciado, A. and Sperbeck, S. T. (2019). “Failure analysis and performance of compact and slender carved stone walls under compression and seismic loading by the FEM approach.” Engineering Failure Analysis, 96: 508-524.
[15] UCOL (1997). “The macro-earthquake of Manzanillo occurred on October 9th, 1995 (in Spanish)”. University of Colima (UCOL), Government of the state of Colima and the Mexican Society of Seismic Engineering (SMIS).

[16] Zobin, V.M. (2004). “The earthquakes and their hazards: How to survive to them? (in Spanish)”. University of Colima, Mexico.