Earth building in Spain

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Abstract

This paper is a review of the state of use of the earth building in Spain nowadays. We present researching organisations, modern projects carried out or the existing manufacturers for compressed earth blocks. Besides, we offer an overview of the Spanish general building regulatory system to find that earth construction is not included in it, although there is a pair of non-regulatory guides that could act as national reference documents and whose provisions we examine. Although earth as a construction material is unknown for most people, a growing interest is noticed in two ways, for rescuing the heritage and as a rediscovered environmentally friendly building material. In these areas, we find the problems of how to carry out the conservation works of the great built heritage, usually adobe and rammed earth, as well as the lack of skilled people at all levels, from designer to masons, because it is a forgotten technique.

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1. Introduction

Earth building in Spain has been used from ancient times. Generally speaking, we can say that it stopped being used in the middle of the XIX century. Nowadays, it is ignored and even underestimated, in part due to the fascination for modern materials such as concrete, bricks or steel. We can find examples in almost all parts of the country, but in the central area it is especially easy to find examples in any small town. It is noticeable in the Tierra de Campos district, shared by the provinces of León, Zamora, Valladolid and Palencia. A map of Spain showing the areas with most spread use in earth building based in Rohmer [1] can be found in Fig. 1. Traditional earth buildings, such as dovecotes or huts, found in the rural areas of Castilla-León can be known through Ponga [2]. An illustrated study of the traditional techniques most commonly employed in central Spain was made by Maldonado and Vela [3]. It is found that usual systems employed in Spain were adobe and rammed earth walls, followed by wattle and daub walls.

Spanish earth construction heritage is, without any hesitation, very important, and is present in all kinds of buildings: houses of the rich and poor, secondary edifications in rural areas, or huge monuments. Reviewing UNESCO’s world cultural heritage list, the importance and remote tradition of earth construction in Spain is confirmed, because we can see that five of our earthen monuments have been included in the list, such as the historic centre of the city of Córdoba, or the Alhambra, Generalife and Albaicín in Granada.

Some monumental earthen buildings, because of their historical importance, have been subjected to extensive conservation works, almost always through public funds and adhering to strict criteria in consideration of the special material that is the earth. A remarkable example is the Murallas de Niebla, in Huelva. It is a 1600 m long rammed earth fortification built in the
middle of XII century. As detailed by Guarner [4], the repair consisted in the elimination of the eroded outer layer of the walls to make a new layer in rammed earth on one side. The soil was obtained from the vicinity, being similar to the original. It was mixed with sand and pea gravel, and this mixture stabilised with slaked lime. Before and during the repairs, the quality of the earth was checked making tests for compressive strength, granular composition or plasticity. On the other hand, the heritage of small constructions is not so lucky and remains at a secondary level, without the importance of being historic. It has been abandoned mainly due to the depopulation suffered in rural areas. It is not difficult to find entire towns in which earth buildings are suffering from weathering year after year. But little by little the heritage of small buildings tries to recover its value and a big effort is being made for conserving and promoting it. This conservation trend is partly due to urban society demand for traditional architecture for tourism. For the conservation of modest earth buildings, one must face the problem that it is usually unknown how to make repairs at affordable costs. To a certain extent, this is caused by the lack of skilled masons and because technicians used to ignore this material. It is easy to find incorrect repairs, such as the typical cement-rich renders covering unstabilised walls. These renders are not flexible enough to adapt to natural wall movements, so they crack easily allowing rain water to enter and being trapped inside the wall due to the low porosity of the rendering. The use of earth or lime based renders would be more appropriate.

During the last few years, a growing interest has been appearing too in earth as a modern construction material for being considered a sustainable material. Some of the reasons for this are the manufacture energy savings compared to clay bricks, the less cement used compared to concrete blocks, the transport savings if soil comes from the construction site or vicinity, and the natural appearance and colours that help buildings integrate into the landscape. Most of few cases of new projects on earth in Spain were conceived from these thoughts.

Spanish research on earth construction, the main problems to face for using it today, an overview of Spanish building codes with reference to earth normative, or the few activities on earth existing in Spain are some of the issues reviewed in this article.

2. Earth construction organisations

Earth construction organisations network is not very strong in Spain. We are far away from the situation found in other developed countries such as USA or Australia. Besides, different groups usually work independently. In this sense, we must emphasise the labour being carried out by ARQUITERRA. This is an internet distribution list (http://www.elistas.net/lista/arquiterra), for all interested people, with more than 500 members. Next we comment on the main organisations working on earth in Spain, but it is noticeable that there are some other entities trying to spread knowledge about earth construction through workshops and short courses that they organise. This effort is very important nowadays when there still exists general ignorance and contempt for this means of construction.

A national research centre working on earth as a construction material was the Instituto Eduardo Torroja de...
Ciencias de la Construcción (IETcc). A project called “Materials, Technologies and Low Cost Dwelling Prototypes” was developed there two decades ago. The objective was to prove that the earth is a viable construction material for today, sustained by the existing know-how and built heritage. The studies carried out were mainly focused on the earth weathering resistance. After a soil classification phase, series of samples with different dosages of several stabilisers were made, testing them for mechanical strength and weathering (drip test). Results were shown by Díaz Romeral [5]. There are not many activities related to earth building in the IETcc currently, but the project was a good experience because it represented the beginning in Spain of the need for the study of earth as a construction material from a scientific point of view. The nowadays called Navapalos Center – Inter-Acción was a usual collaborator in that project. Inter-Acción is an association whose objective is trying to avoid the decay and disappearance of the rich Spanish architectural heritage. Navapalos-Center is a centre researching in earth construction founded in 1984 in Navapalos, an abandoned town in Soria. From then until now, more than ten Navapalos International Work Meetings have been celebrated about “earth as a building material”. A variety of subjects have been exposed in the meetings, such as some cases of repairs of old buildings, selfbuilding projects, improvement of materials, soils and blocks characterisation, analysis of existing normative or knowledge about traditional architecture. Inter-Acción partnered with other prestigious earth construction research centres, like Plymouth University (United Kingdom) and CRATerre-EAG (France), in the elaboration of an earth construction glossary of 500 words in five languages, divulged by the German association Dachverband Lehme e. V. Another contribution for spreading earth building knowledge is the summer courses that they organise, offered in Navapalos. Inter-Acción manager is the German architect Erhard Rohmer, who is the Chairman of the Spanish Scientific Earth Architecture Committee of ICOMOS.

If we had to say which is the main concern about earth building in Spain, we would answer the need for conservation of the rich architectural heritage. This problem was specifically treated in the 1st Congress “Earth: Construction and Restoration”, 2001, and 2nd Congress “Earth: Heritage Restoration”, 2002, organised by Architects Without Borders Castilla y León among others. Another congress devoted to earth construction was celebrated in Madrid in 2003. It was the II SIACOT, Latin American Earth Construction Seminar. A variety of papers were exposed, all of them around one of these four themes: nowadays construction or technical, historic and design subjects.

Most participants of the II SIACOT were gathered some days before for the celebration in Segovia of the 2nd PROTERRA meeting. PROTERRA (http://www.ceped.br/proterra/) is a research project dependent on CYTED, the Latin American Program of Science and Technology for Development. This project has the objective of trying to develop a legal framework for the standardisation of earth construction. Two problems were specially discussed in the meeting: terminology and normative documents. About the terminology, it was decided to compile and define the diversity of words used for the same things in different countries and their regions, for the Spanish and Portuguese languages. About the standardisation problem, they agreed on the need for carrying out easy to understand explicative brochures about existing norms, and to work in the calculation methods. At the moment, they are considering norms from USA (New México), Peru and El Salvador. The 2nd PROTERRA meeting and 2nd SIACOT were organised by CIAT.

CIAT is a representative example of the interest in earth construction at university. It stands for Research Centre for Traditional Architecture. It is managed by lecturers from the Departamento de Construcción y Tecnología Arquitectónica of the Universidad Politécnica de Madrid. It is a centre for the research and spread of knowledge about earth construction as a traditional material. Summer courses are taught there in “Architecture and Earth Construction”. Other universities are devoting efforts in earth construction too. Professor Gabriel Barbeta (http://gabibarbeta.eresmas.com/) from Departamento de Arquitectura e Ingeniería de la Construcción, Escuela Politécnica Superior of the Universidad de Gérona, spends part of the lectures of the elective subject “building and ecology”, to teaching earth. Professor Albert Cuchi from Departamento de Construcciones Arquitectónicas, Escuela de Arquitectura del Vallés of the Universidad Politécnica de Cataluña, devotes part of another elective subject to earth too. In the Escuela Politécnica Superior of Arquitectura of the Universidad Alfonso X el Sabio, Madrid, professor Santos Garcia deals with earth as a subject for building materials. Also in master’s degrees about architectural restoration and ecological construction, some classes are devoted to it, as are the cases of Escuela Técnica Superior of Arquitectura of the Universidad Politécnica de Madrid, Universidad de Alcalá de Henares or the Universidad de Valladolid. Here, an earth group has recently organised (summer 2004) the congress entitled “Earth architecture. Tradition and innovation”, in Cuenca de Campos (Valladolid).

3. General building and earth building normative in Spain

In order to understand the role played by earth as a building material and its possibilities for use, we must have an overview of the building regulatory system in
Spain. It is made up of different groups of norms that will soon be replaced by the Technical Building Code. The Basic Building Norms (“Normas Básicas de la Edificación”, NBE), whose main purpose is to defend the safety of people, are mandatory and concerning actions on buildings (NBE-AE 88), steel structures (NBE-EA-95), load-bearing brick masonry walls (NBE-FL-90), fire protection, bituminous material roofing, and thermal and acoustic conditions in buildings. The second main group of building norms in Spain are the not mandatory Technological Building Norms (“Normas Tecnológicas de la Edificación”, NTE), giving advisable technical solutions for the usual building practice, and grouped in site fitting, foundations, structures, facades and partitions, services, roofs and finishes.

On the other hand, any use of concrete is regulated through EHE-1999, Structural Concrete Instruction, and EF-96 for floor slabs. Materials acceptability conditions and specifications for products (such as lime, cement, or concrete blocks) and systems are also regulated, through a variety of documents, in some cases as mandatory. The Spanish standardisation body, AENOR, is responsible for UNE standards to which building regulations are continuously referring to. There is also an Earthquake-resistant Construction regulation (NCSE-02).

All this normative system will be modified by the Technical Building Code (“Código Técnico de la Edificación”, CTE), requested in the Building Ordering Law 38/1999 November 5th (“Ley de Ordenación de la Edificación, LOE”). For the first time, a single mandatory document will state minimum requirements for all kinds of building structures and throughout the building process. The first part of the CTE establishes basic quality demands for the basic requirements. The Basic Documents (“Documentos Básicos”, DB) conform the second part of CTE, containing procedures, technical rules and examples of solutions whose proper use guarantees the fulfilment of the requirements. They are not exclusive since other procedures can be applied. There are five groups of DB, one of them for safety of structures.

Structural Eurocodes are European norms, in the form of EN or ENV, that demonstrate the European convergence in regulations. With time they become integrated into the national regulatory system, this means that, in Spain, each code would become a UNE norm. Masonry structures are covered in Eurocode 6, and earth as a construction material is not regulated through it, as we do not find it included in the list of materials of Section 3.1.1. of Eurocode 6 [6]: Types of masonry units.

Both before and after the CTE, earth construction in Spain is not prohibited, but as it is not regulated, there exists logical reluctance in its use. It is not included in any NBE neither in NTE structures nor Eurocode 6. Before the CTE, there is neither an obligation to comply with a masonry structures code, nor even to comply with a building structures code. After the CTE, not in use at the moment of writing this paper yet, the designer must justify the requirements of the first part, but the DB Structural Security: Masonry Structures, does not provide for earth building, so other procedures should be employed to guarantee the fulfilment of the requirements, with the disadvantageous lack of data that imply the use of non-conventional materials.

Another problem encountered by new earth building projects is due to article 19.1.c of the Building Ordering Law (LOE). It establishes the development company obligation of having an insurance policy called the 10-year insurance coverage (seguro decenal), for compensating, during ten years, possible material damages caused in the building by problems in their structural elements that directly jeopardize its resistance and stability. For evaluating building risk before underwriting it, insurance providers are assessed through the Technical Control Organisations (Organizaciones de Control Técnico, OCT) that are extremely conservative and very reluctant to assess non-conventional materials and construction methods. Because of such circumstance, earth building initiatives encounter a big problem in purchasing the mandatory insurance, and at the moment only non-dwellings or self-built projects not needing a mortgage are free from the 10-year insurance coverage requirement.

In spite of this situation, where earth construction is not found among the general building regulations in Spain, there are two publications that deserve attention. One of them written in 1970 has the purpose of setting the specifications of all kinds of masonry units, including the use of adobe and rammed earth. It is the piet no. 70: Obras de fábrica, IETcc (1970) [7]. The other, more particularly focused on rammed earth, comprises solely earthen wall construction in general, MOPT (1992) [8]. They are not mandatory national reference documents that make the processes of soil selection, design, construction and control easier.

Both are devoted to unreinforced load bearing earth walls, and do not include earthquake resistant design, unlike for example the Peruvian adobe norm [9] or New Zealand national standard for earth construction [10–12]. The procedure followed for structural design of load bearing earth walls in IETcc (1970) [7] is the same one for all the rest of masonry materials included, and is the one later adopted with minimum changes for the NBE FL-90 (brick and mortar mandatory code). Comparing with other more conventional materials, earth has the disadvantage of the lack of datum that usually comes in the form of tables making the calculation processes easier. Examples are the absence of safety

1 www.aenor.es.
factors, wall compressive strength values, distances for control joints or the wall deformation factor. The document contains also rules of quality, and material, workmanship and testing specifications. Some notes of the information given are found summarised in Appendix 1.

Basis for rammed earth design and construction, MOPT (1992) [8] is the result of years of work carried out by its authors in Latin America, above all with rammed earth, although it comprises load bearing walls made of unbaked earth in general. To a certain extent, it solves the lack of datum that was found in IETcc (1970) [7]. It gives guidelines for the architectural and engineering design, and soil characterisation as well as construction solutions and execution control. Some notes on this publication appear in Appendix 2. Engineering design is inspired in the same method than brick and mortar mandatory Spanish code (NBE FL-90).

In general terms, we can say that provisions in Spanish documents are in agreement with other national or international documents. Engineering design in N. Zealand standard [10] is based in their national masonry code too, following limit state criteria. As in the MOPT (1992) [8], procedures for compression, flexion and shear are offered. On the contrary, the Zimbabwe standard for rammed earth [13] wall design offered is basically consisting in minimum requirements of 300 mm wall width and slenderness from 8 to 16 depending on restrain conditions and stabilisation of walls. Width given in N. Mexico rammed earth standard [14] is 45:7 mm for exterior walls, while in IETcc (1970) [7] is 500 mm for unsta tioned rammed earth and 300 mm for stabilised. In NZS 4299:1998 [12], it is of 250 mm for standard grade earth buildings of any kind. Maximum slenderness for un enforced earth in low sismicity areas following N. Zealand standard is 10, while usual slenderness proposed in MOPT (1992) [8] is smaller, 8 for adobe and 6 for rammed earth.

Tests for strengths usually need simple or laboratory compression devices, but in Zimbabwe rammed earth standard [13], a minimum strength requirement must be satisfied through a tension spring device, being of 1.5 N/mm² for one storey and 2.0 N/mm² for two storeys dwellings. Compressive crushing strengths given in Australian documents such as Bulletin 5 [15] or SA & Walker (2002) [16] are 2.0 N/mm², being only from 0.6 to 1.8 N/mm² the rank of usual strengths given for unsta tioned rammed earth in MOPT (1992) [8].

For soil testing, we have UNE standards, making possible the study and characterisation of soils. Though not specific, they are applicable in earth construction, and come mainly from commissions 103, geotechnic, and 77, soils. As there is not a UNE collection of earth building standards, on the contrary, they are distributed in different groups, we consider it interesting writing down our own proposed list, found in Appendix 3. Most of these UNE standards were formerly Transportation and Soil Mechanics Laboratory Standards (“NLT: Normas de ensayo del Laboratorio del Transporte y Mecánica del Suelo José Luis Escario”). There are still NLT standards that can be seen in Appendix 4. About soil stabilisation, there should be applied PG 4 [17], articles 510 (in situ soil stabilisation with lime), 511 (in situ soil stabilisation with bituminous products), and 512 (cement stabilisation of soils).

4. Current activities related to the earth building practice

4.1. Construction of buildings

4.1.1. Luis Salazar house

It is a two storey dwelling with an attic in Urueña, a village in Valladolid, Castilla-León. Finished in 2002, it has roughly 100 m² in plan. Partition walls and some of the outside walls are made of rammed earth, the rest of the walls being of adobe (Fig. 2). The owner wanted a rammed earth house as they were the traditional houses in town. There were some disagreements between owner and architect during the design, besides, as Urueña is a historic-artistic site, very restrictive appearance requirements had to be overcome. Foundations were not dug because the house was built on the rock, on a limestone masonry plinth. Many difficulties were encountered in all stages. Desired to be a rammed earth house, but because plenty of problems appeared during the construction, it was decided to finish it in adobe made by a brick masonry mason. Soil for rammed earth was collected from an abandoned ruined traditional dovecote and it was stabilised with 5–10% slaked lime. Adobes were acquired from Vezdemarbán (Zamora) (0.15 € each) and Villafrechós, Valladolid (1 € each). No testing was made apart from simple field test for soil. Roof was made as

Fig. 2. Luis Salazar house in Urueña (Valladolid), made of rammed earth and adobe masonry.
traditionally, ceramic tiles on an earth mortar on the roof sheathing, with the only innovation of using TIVEK films under the mud mortar. Floor slab was made of pine wood, unusual for new houses in Spain. Concerning administrative aspects, owners found the inconvenience of not getting a bank loan to build the house because it was not possible to subscribe the mandatory 10-year insurance coverage (Law 38/1999, LOE) because they did not find a capable insurance provider.

4.1.2. Houses in ecovillage Amayuelas

Amayuelas is a small town in Palencia province, Castilla-León, where a ecovillage project was carried out trying to revitalise this rural area through environmentally friendly activities. Ten two storey small houses of about 30 m² in plan were made in 2001 for housing as well as for rural tourist accommodation (Fig. 3). Ground floor has got a 50 cm thick rammed earth load bearing wall stabilised with sand and lime, on a masonry 40 cm high plinth. First floor walls are made of adobe masonry in some houses and compressed earth blocks masonry in others, whose thickness is of a block length and a half. Compressed earth blocks are stabilised with cement. The most exposed wall, the one to the West, has got an exterior brick masonry sheet made at the same time than the rammed earth, in one side of the forms, as explained by Basterra and Jove [18]. All the rest of walls are rendered with straw and lime earth mortar.

Roofing is made with the traditional ceramic tiles on a 6–8 cm thick earth mortar on the roof sheathing, with the use of TIVEK films under the mud mortar, mixed with ARLITA and straw.

4.1.3. “La Tenada de Covachuelas”

It is a rural tourist accommodation located in Covachuelas, Segovia. It is a two storey residence and rural house with basement, finished in 2001 and built on the remains of an old stone masonry sheephouse. The stone masonry wall was maintained, and a second floor was added made of a double sheet wall, the exterior sheet of compressed earth blocks masonry, and the interior of brick masonry, filled in the middle with sheep wool for isolation. Nearly 4000 blocks were manually produced by the owners with local soils and cement using a manual press GEO-50 of Altech International. Simple field test and laboratory tests were conducted for checking the suitability of the local soil. Besides, different dosages of different stabilisers were studied although finally only cement was used. The building is an example of eco-building, with use of solar energy, recycling of used water, bioclimatic design and use of Earth-friendly materials. The architect, Gabriel Barbeta, is known for being one of the few architects working on compressed earth blocks in Spain. Main difficulties arose in finding a contractor willing to use non conventional materials and designs.

4.1.4. Theatre of Balaguer

Municipal theatre in Balaguer, Lérida, Cataluña, was finished in 1992. It is made of a 50 cm thick rammed earth wall in U shape. The walls have got 14 cm high brick layers insertions. Reinforced concrete beams are found above the foundation system, in the top of the

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2 http://www.cdrtcampos.es/amayuelas/.

3 http://www.latenada.org/.
walls and in the middle, being good for attaching equipment of the stage. Soil was mixed with 10% white cement (dry weight), for being “poor concrete” according to Spanish regulation, although walls were executed following rammed earth techniques and water content, not the concrete practice. Maximum wall height is 16 m. As explained by Cuchí, A. 2000 [20], the design, calculation and construction of the walls were possible because of the existence of an earthen built heritage that was a reference. Rammed earth is traditional in the area, where some builders are still making agricultural warehouses. The traditional cement dosage is 5%, but it was raised to 10% to be able to classify the material as a poor plain concrete and be able to follow the current concrete regulation, as it was not possible to build a public building without complying with the regulation.

4.1.5. Domingo Chorpos house

Located in Arroyomolinos, Madrid, it was finished in 1996. It is a three storey single-family house with peculiar design with curved shapes and following bioclimatic criteria. The architect is Gabriel Barbeta. Walls are made of “eco-concrete” consisting of a mixture of local soil and granulated cork (32 shelves to 20), cement (8% volume) and water, poured in a concrete-similar consistency and compacted with a concrete vibrator. Wall thickness is 40 cm. Special forms were required for the curved walls, consisting in metal planks and wooden posts. They were 1.25 cm high and were removed after 24 h. Bamboo canes were inserted in the recently made wall pieces for helping the union with the following wall piece. They faced difficulties in finding a tile builder specialist given the unusual roofing design.

4.1.6. “Pinariega” house in Navapalos

It is situated in the abandoned town of Navapalos, Soria, Castilla-León. It consisted in the reuse of an old building of about 15 × 15 m in plan where local schools were situated. It is a rich example of vernacular architecture (Fig. 4). Walls are a combination of stone masonry, adobe masonry and a wooden frame filled with adobe. Adobe units were manufactured with local soils following traditional sizes and with barley straw added. Their compressive strength was 1.4 N/mm². The project was promoted by Inter-Acción, shown in one of their international meetings publications [21]. Costs of a pure rehabilitation were so high that it was decided to combine conservation techniques with usual techniques. Main difficulty faced was a noticeable lack of experience in masons, so training was needed, and labour costs were therefore high.

4.1.7. Steve Graham house in Valdemaluque

Steve and family acquired recently a 130 years old house in a town in Soria (Castilla-León) called Valdemaluque. Their desire is to make of it a rural tourist accommodation. The house is an example of the traditional architecture of the area. They want to maintain its originality as much as possible, although important works need to be carried out and it will be difficult. The house is about 12 × 12 m in plan with an auxiliary building attached to it. It is a two storey house. The first floor wall is built on a stone masonry plinth, and is a load bearing wall shared by wood posts and adobe masonry, while the second floor is made of a wooden frame filled with smaller adobes. Nearly 5000 compressed blocks were made with local soil. The work has just begun after a very hard period of finding an architect capable of assuming this unconventional project, shown in http://www.nodo50.org/valdemaluque/home-en.htm.

4.2. Earth product manufacturers

4.2.1. CANNABRICK blocks

CANNABRICK is the name of the solid compressed earth blocks manually produced in a press in Paulencia, Granada. They are stabilised with lime and contains industrial hemp fibre. They can be used in loadbearing walls and provides thermal and acoustic isolation. Main uses are buildings in a rural environment, tourist lodgings, cave-dwellings or stables. Block size is 300 × 140 × 100 mm. Price 0.87 €/unit (2003). Manager is architect Mónica Brümmer.

4.2.2. BIOTERRE blocks

Solid compressed earth blocks obtained by hyper-pressure in hydraulic press to 10 MPa. At the present time, the blocks manufacture is labour intensive, not fully mechanised. Soil composition and soil particle distribution are previously selected. They contain cement, lime and puzzolanic additions. Main uses are houses, usually in double sheet walls, the inner made of brick and mortar and the outer sheet of compressed earth
blocks, to be able to comply with regulations. Dimensions are 295 \times 145 \times 90 \text{ mm}. Price is 0.7 \text{ €/unit (2003)}. Manufacturer is GRUP PLANA S.L., in Les Planes d'Hostoles, Gerona, whose manager is Albert Venturada. They are applying for a DTI (technical document of suitability), the certification required for new building materials without standards.

4.2.3. Adoberos

In Calzadilla de los Hermanillos, a town situated in the South-eastern part of Leon province, it is easier now to find adobes for restoring old houses. Thanks to L. Rueda and A. Santamarta who have recovered the old method of making adobe bricks. Also in Villafrecho's, Valladolid, when good weather prevails, you can find J. Martín and his son making adobes for sale.

5. Summary

- Spain is very rich in earthen built heritage, being of historic importance as well as simply small rural and urban buildings. Adobe, rammed earth and also wattle and also daub, were the three most used traditional construction methods. These earthen buildings are usually in a terrible state of decay, and owners prefer to demolish them instead of repairing them. On the other hand, the repairs are commonly inappropriate, except for some monumental buildings.
- Earth construction is ignored and even undervalued nowadays, although a growing interest is appearing, from conservation desires or for being considered a good material in ecobuilding. Some national and international meetings about earth building have been organised in Spain. People interested work independently, and there are only a few research bodies or information centres.
- There are only a few new buildings made of earth in Spain, most of them residential buildings, and with a remarkable use in compressed earth blocks. There are two compressed earth block manufacturers, both following labour intensive procedures.
- One of the main problems that new earth buildings have to face is the lack of skilled people, at all levels, from architects to builders. In spite of the fact that earth construction was very popular some decades ago, today it is forgotten, and almost nobody knows how to use it.
- Although we have got a couple of useful earth building guidelines, this construction material is not included in the general building regulations of Spain, so all stages of the building process become unfamiliar.
- Insurance providers set very restrictive conditions for subscribing the mandatory 10-year insurance coverage for dwellings, so there is one more obstacle for the appearing of new cases.

Acknowledgements

We thank the contribution of all people who allowed us to visit their homes or spent their time to be interviewed by phone, making possible the case study.

Appendix 1. Some notes about earthen walls from IETcc (1970) [7]

Definitions

Adobe: Unburned sun-dried clay units, whose dimensional stability and control of shrinkage cracks can be achieved by adding organic fibres. Similar to bricks in shape, but bigger sizes. Can be stabilised with lime or cement.

Rammed earth: Monolithic masonry units made with earth, loam, straw... where consolidation is achieved by mechanic means, without chemical processes that changes materials nature.

Classes of rammed earth walls

- Mud rammed earth: Made with very high water content giving the earth high plastic consistency. Fibres can be added for avoiding cracks.
- Strengthened rammed earth: Soil grading can be improved, but has to be suitable. Low but optimum water content, 10–14% in proctor test. Ball drop test can be used for checking water content during construction.
- Stabilised rammed-earth: Stabilisers such as bitumen, lime or cement are added to improve particular properties.
- Calicostrado rammed-earth: Lime plaster is poured in the forms before a new earth layer is added.

Execution guides

For rammed earth, maximum particle size is 20 mm. Wall pieces must not be more than 2 m long and 0.8 m high. Earth layers height should be up to 10 cm, vertical joints must not be coincident. Before placing the earth, forms must be dry and coated with a releasing agent.
Adobes must be laid dry using high plastic mud mortars, joint thickness as less as possible.

**Construction specifications**

Minimum wall thicknesses for stabilised, strengthened and mud rammed walls are 30, 50 and 70 cm, respectively. Adobe walls must be wider than one adobe length. Walls must be constructed on a concrete brick or stone plinth of more than 25 cm height. Special points in adobe walls as corners, wall bases, etc. must be reinforced with well bonded stone or brick masonry.

**Compressive strength for rammed earth**

Compressive strength can be tested by a method consisting in compressive rupture of 10 cubic specimens 30 cm sided, made with the same soil and conditions than the rammed earth wall. Characteristic strength would be calculated following the formula:

\[
\sigma_k = \sigma_m (1 \pm 1.64\delta), \quad \text{con} \sigma_m = \frac{1}{n} \sum \sigma_i
\]

and

\[
\delta = \frac{1}{\sigma_m} \sqrt{\frac{1}{n} \sum \frac{(\sigma_i - \sigma_m)^2}{n}}
\]

where \(n\) is number of specimens tested and \(\sigma_i\) each specimen rupture value.

**Soil selection**

On the other hand, Table 1 shows recommendations for soil selection for rammed earth.

<table>
<thead>
<tr>
<th>Classes of rammed-earth</th>
<th>Soil gradinga</th>
<th>Plasticity</th>
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</thead>
<tbody>
<tr>
<td>Mud rammed earth</td>
<td>Clay + siltb 30–60%</td>
<td>–</td>
</tr>
<tr>
<td>Strengthened rammed earth</td>
<td>Fine gravel: 10–20%</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Sand: 10–40%</td>
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<tr>
<td></td>
<td>Silt: 20–40%</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Clay: 10–40%</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Clay + siltb &lt; 45%</td>
<td>–</td>
</tr>
<tr>
<td>Stabilised rammed earth</td>
<td>LL &lt; 40%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand &gt; 33%</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>10 &lt; LP &lt; 25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clay + siltb &lt; 30%</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>12 &lt; LP &lt; 20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IP = 6–22%</td>
<td></td>
</tr>
</tbody>
</table>

a Particle sizes are: clay \(d < 0.002\) mm; silt \(0.002 < d < 0.5\) mm; sand \(0.5 < d < 5\) mm; fine gravel \(5 < d < 20\) mm.  
b Tray washing method for separating the fine fraction of a soil, through successive washings of the earth in a tray until water comes out clean.

**Appendix 2. Some notes about earthen walls from MOPT (1992) [8]**

**Probable earth wall values**

Some probable earth wall values of interest for the design are given, such as thermal properties, permeability, water absorption, linear shrinkage, acoustic isolation or Young modulus which are shown in Table 2.

**Simplified calculation method**

A simplified calculation method is proposed safe enough for the usual cases of small or medium sized buildings. It is based on the same method from IETCC [7], being the one in FL-90 (brick and mortar masonry load-bearing walls mandatory regulation). For its application, six conditions must be satisfied: uniform loads distribution, walls should be laterally braced, bond beam in all walls, stiff roof for avoiding transmission of lateral forces to the walls (structural diaphragm), compatibility in walls-foundations deformation, and weather resistant material.

**Crushing strength**

Three alternatives are proposed. For important projects, it is advisable obtaining laboratory characteristic strength. For low risk projects, approximate but safe values of allowable working stresses mentioned in Table 3 could be used. For most cases, a crushing strength could be chosen from Table 4 and then checked with the real strengths obtained from in situ testing of units by simple means (lever device). A certain tensile strength due to flexion can be considered, being of 1/10 of compressive strength. Besides, strength in wet environment would be 1/2 of the dry.

**Design strength**

For obtaining design strengths, factors of safety from 3 to 8 are applied to crushing strengths, depending on execution control and environment, see Table 5.

<table>
<thead>
<tr>
<th>Probable earth wall values following MOPT (1996) [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity coefficient 0.58 W/m K</td>
</tr>
<tr>
<td>Specific heat 836 J/kg</td>
</tr>
<tr>
<td>Global transmission coefficient (50 cm wall) 0.93W/m² K</td>
</tr>
<tr>
<td>Thermal dilation coefficient 0.0012 mm/m K</td>
</tr>
<tr>
<td>Permeability index 1/1,000,000 cm/s</td>
</tr>
<tr>
<td>Water absorption 5–8% (dry weigh)</td>
</tr>
<tr>
<td>Linear shrinkage coefficient 3 mm/m (unstabilised)</td>
</tr>
<tr>
<td>Acoustic isolation (50 cm wall) 58 dB (f = 500 Hz)</td>
</tr>
<tr>
<td>Young modulus 1000–7000 N/mm²</td>
</tr>
</tbody>
</table>
Resistance and stability conditions

Conditions for checking compression, flexion and shearing are given. For compression, a slenderness factor must be obtained from Table 6 once the slenderness is got from virtual height and virtual thickness. It must be noticed that design strengths used in the calculation are obtained factoring the crushing strengths of adobe units or rammed earth cubic samples, the document does not provide for a wall or masonry strength explicitly.

Walls bracing

Long walls must be laterally reinforced through other walls, buttresses, or other means. Proposed distances between braces are shown in Table 7, depending on the construction method, wall slenderness and wall openings.

Common case

For most common cases of one storey dwellings without cantilever elements, with uniform loads, without stabilisers and using suitable soil, a very simple calculation method is proposed. It is a question of verifying that the stresses produced in one meter wall section are lower than work stresses mentioned in Table 8, using a simple calculation of the normal loads that should bear on it.

Soil identification

They offer a soil identification system based upon carrying out seven very simple soil tests. Depending on

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Allowable working stresses for unbaked unstabilised earth walls following MOPT (1996) [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compression (N/mm²)</td>
</tr>
<tr>
<td>Interior walls without contact with wet environments</td>
<td>0.2</td>
</tr>
<tr>
<td>Exterior walls or walls in contact with wet environments</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Compressive crushing strengths following MOPT (1996) [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kind of stabilisation</td>
<td>Rammed earth&lt;sup&gt;a&lt;/sup&gt; (N/mm²)</td>
</tr>
<tr>
<td>Unstabilised</td>
<td>Low strength</td>
</tr>
<tr>
<td></td>
<td>Medium strength</td>
</tr>
<tr>
<td></td>
<td>High strength</td>
</tr>
<tr>
<td>Portland cement stabilisation</td>
<td>Low dosage</td>
</tr>
<tr>
<td></td>
<td>Medium dosage</td>
</tr>
<tr>
<td></td>
<td>High dosage</td>
</tr>
<tr>
<td>Lime and cement stabilisation</td>
<td>Low dosage</td>
</tr>
<tr>
<td></td>
<td>Medium dosage</td>
</tr>
<tr>
<td></td>
<td>High dosage</td>
</tr>
<tr>
<td>Lime stabilisation</td>
<td>Low dosage</td>
</tr>
<tr>
<td></td>
<td>Medium dosage</td>
</tr>
<tr>
<td></td>
<td>High dosage</td>
</tr>
<tr>
<td>Bitumen stabilisation</td>
<td>Better testing</td>
</tr>
</tbody>
</table>

<sup>a</sup> Samples 5 × 5 × 5 cm cut from a wall.

<sup>b</sup> For a adobe unit.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Safety factors for obtaining design strength following MOPT (1996) [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exterior walls or walls in contact with wet environments</td>
</tr>
<tr>
<td>Considerable laboratory execution control</td>
<td>6</td>
</tr>
<tr>
<td>Rest of cases</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Slenderness factors following MOPT (1996) [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slenderness</td>
<td>18</td>
</tr>
<tr>
<td>Slenderness factor</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Need for bracing following MOPT (1996) [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum distances between braces (m)</td>
<td></td>
</tr>
<tr>
<td>Slenderness</td>
<td>Wall without openings</td>
</tr>
<tr>
<td>Adobe</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Rammed-earth</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Usual working stresses following MOPT (1996) [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable working stresses (N/mm²)</td>
<td></td>
</tr>
<tr>
<td>Stress type</td>
<td>Dry and interior wall</td>
</tr>
<tr>
<td>Adobe slenderness = 8</td>
<td>Compression</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
</tr>
<tr>
<td>Rammed earth slenderness = 6</td>
<td>Compression</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
</tr>
</tbody>
</table>
their results, one can get “possible uses” and “possible stabilisers” from an “Assessment and Uses Table”. Besides, recommended granulometric distribution curves are given, with zones of stabilisers to use.

Appendix 3. UNE norms of application in earth construction

- UNE 103401:1998. Determination of the shear strength of a soil with the direct shear box.

Appendix 4. NLT standards of application in earth construction

Following we show a list of NLT norms of application in the earth building practice. We left out the considerable list of standards concerning bitumen stabilisation of soils.

- NLT 103/72. Water content of a soil by the alcohol method.
- NLT 110/72. In situ density by the oil method.
- NLT 114/99. Soluble salts content in a soil.
- NLT 301/96. Maximum density and optimum moisture content of soil-cement mixtures by ramming.
- NLT 302/96. Soil-cement specimens wet-dry test.
- NLT 303/96. Soil-cement specimens freeze-thaw test.
- NLT 305/90. Simple compressive strength of materials with hydraulic binders added.

References