Fig.4 Examples of Moarraque, a method for surface protection of earthen architecture in Isfahan: a) brickwork in David's House; b), c) and d) design, cut and installation of mosaic pieces on earthen walls; diversity of approaches in the early 20th century in e) Sadr Madrasa and f) Harunieh alley (credits: Vahidzadeh et al., 2011)

surface protection for earthen architecture as an intangible heritage at different levels of craftsmanship and workshop-management systems. In the Tchogha Zanbil workshop, craftsmen have used new forms of interaction with apprentices to sustain this tradition. In contrast, the improvement of the social status of art masters in Isfahan through receiving funding from tourism, conservation and traditional society have led to the reproduction of historical patterns of apprenticeship. The generation gap and declining of the quality and quantity of entrusted works in both of the regions were limiting factors, while independent and private workshops have made it possible to continue the traditional art creation. The younger artists working in private workshops of Isfahan show a great tendency to the usage of modern technology in practicing vernacular architectural decoration. The older generation of artists in both regions are willing to document and publish their experiences in the form of classic media. Holding joint educational and research programs, dialogue and cooperation between conservators, younger artists and older art masters, has increased in order to achieve a common language for transferring the vernacular knowledge in its most comprehensive forms to future generations in recent years, especially after the definition of intangible heritage in 2003. There is a slight shift in the debates from recording and understanding the technical properties of traditional architectural materials to the protection of vernacular knowledge as an existential wisdom of interaction with the environment and an alternative lifestyle based on cultural diversity.

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PROTERRA INTERNATIONAL INTER-LABORATORY PROGRAM

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Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Inter-laboratory program, adobe, testing methodology

Abstract

At the end of 2007, the PROTERRA Iberian-American Network began an international inter-laboratory program aiming at establishing test procedures and control parameters for materials and products for earthen architecture construction.

This paper reports the development and presents the results of the first stage of this program, which aimed to define the most appropriate procedure for determining the compressive strength of adobe. For this, two types of sampling and three different dimensions were established. The summary of the work plan, participating institutions, and details relating to the development of work in each laboratory are presented, along with the first considerations based on the results obtained. The test results for the earth characterization, the development of the samples preparation and the procedure for implementing the compressive-strength test are highlighted. At the end, the importance of the inter-laboratory program for the establishment of procedures and for testing products' qualification are reviewed, highlighting those produced with earth, and the effect of the inter-laboratory program at the PROTERRA Iberian-American Network.

This activity, as well as others developed within the scope of the PROTERRA Iberian-American Network, is an example of how it is possible to develop joint activities of international nature, solely with the involvement of interested professional volunteers, and disseminating knowledge gained on earthen architecture and its construction.

1. INTRODUCTION

PROTERRA is a network of international and multilateral technical cooperation that promotes the transfer of technology in earthen architecture construction. PROTERRA began in October 2001 as a temporary research project of four years, from the Iberian American Science and Technology for Development - CYTED, in order to encourage the use of earth as building material, using demonstration projects, publications, courses and other events. In February 2006, when the research project PROTERRA/CYTED was concluded, the PROTERRA Iberian-American Network was created, with almost all members of the project, along with other interested professionals. The aims and directions of action were similar to the ones of the concluded project.

At a first stage, PROTERRA's attention was focused on social housing, whose proposal was to have a group of Iberian-American experts provide technical support for building programs to be developed in different countries. Then, it was understood that the use of earthen construction for social-housing programs had not been occurring. With the formation of an international team of professionals, which already existed in each country, competent professionals could provide the necessary technical support. However, it was necessary to promote and to disseminate the use of earthen materials through other actions, in order to provide scientific support to earthen architecture and its construction, including the development of an appropriate updated bibliography applicable to the current circumstances of each country and region.

One of these actions corresponds to the identification and recommendation of tests, and the parameters for the classification of products, such as adobe and CEB (compressed earth block), as well as masonry walls and other different building systems using earth.

A collaborative program began in late 2007, whose first activity was the definition of test procedures to determine the compressive strength of adobe and the parameters for its qualification. Several papers and published documents described the results or limits of the compressive strength of

a) b)

Fig.1 Samples: a) Cube; b) Cut adobe with the halves reunited (credits: Obede B. Faria, 2008)

adobes, but references to the test procedures were scarce or nonexistent. The following references are highlighted in the Iberian American context, mentioning test procedures and product qualification:

- Building Technical Standard E.080 Adobe (RNC, 2000) establishes the adobe test using cube-shaped samples, whose sides equal the smaller size of the adobe (Fig.1a). Using at least six samples, it sets the breaking strength as the value above which 80% of the results occur. It also indicates that this should be 1.2 MPa at least. No loading speed or test time is specified.
- Faria (2002) adapted from Brazilian standards NBR 6460 (ABNT, 1983) and NBR 8492 (ABNT, 1984) for testing adobe. The samples correspond to two parts of an adobe that is cut in half, and then the halves are reunited with cement and gypsum mortar (4 parts cement and 1 part of gypsum) (Fig.1b). In the test, the loading rate is around 10 MPa/minute.
- Varum, Costa, Pereira, and Almeida (2006) used cylindrical samples with a diameter between 70 mm and 90 mm, and a height of approximately twice the diameter. They do not mention the loading speed or test time.

Since the tests do not present the same procedures, it is not possible to compare the results mentioned in various publications. With the completion of the Inter-Laboratory Program, the PROTERRA Iberian-American Network expects to propose a standardized procedure to determine the compressive strength of adobe that, if adopted by all researchers and professionals responsible for product qualification, could provide consistent data to identify one of the main characteristics of adobe and to establish the requirements for its qualification as a masonry product. This paper presents the results of the first stage of the PROTERRA Inter-Laboratory Program, which consisted of using the same tests procedures, necessary to determine the compressive strength of adobes, in laboratories indifferent countries.

2. METHODOLOGY

The methodology of the inter-laboratory program corresponded to the preparation of the work plan, the invitation of different laboratories to participate in the program, and afterwards, the analysis and discussion of the results, and the preparation of the proposal for an Iberian-American test procedure for determining the compressive strength of adobe. The work plan was comprised of the following stages: selection of earth materials, production and preparation of test sampling, conducting tests and recording the results.

2.1 Earth selection

The use of earth with the following composition was established: the sand content exceeded 55% and the clay content needed to be about 30%. If the earth available did not meet this requirement, its modification was made possible by mixing two or more different soils, until the grain size obtained was as indicated.

For selecting earth materials, the following tests were used to characterize the available soil: grain size composition (sieving and sedimentation), Atterberg limits, bulk density of loose earth, and earth-moisture content. The tests to determine the grain-size distribution and the Atterberg limits (liquid limit – LL, and plastic limit – PL) were carried out in accordance with current regulations in each country, that were used in the laboratories of soil mechanics. For loose soil-density determination tests (Fig.2) and moisture content, the procedures followed by Faria, Oliveira, Tahira, and Battistelle (2008) were proposed.

2.2 Preparation of samples

To assess the influence of the manufacturing and cutting processes of adobe in compressive strength, two types of samples were taken, all of which were cube-shaped: the cube

Fig.2 Determining loose soil density (credits: Obede B. Faria, 2008)

cut from the adobe and the molded cube. In order to do this, the following were produced:

- At least 20 adobe units, made in molds with interior dimensions of 7.5 x 15 x 30 cm;
- At least 20 adobe units, made in molds with interior dimensions of 10 x 10 x 10 cm; and
- At least 20 adobe units, made in molds with interior dimensions of 15 x 15 x 15 cm.

For sampling of each type of cube, the following procedure was proposed:

- Withdrawal, at random, of 10 adobe units for the preparation of the cut samples. Each adobe was cut in half, and each half was cut twice, so as to have eight cubes of adobe with approximately 7.5 cm/side (Cube 7.5) corresponding to the height of the adobe produced.
- Withdrawal, at random, 10 units of cubes with 10-cm sides (Cube 10) and 10 units of cubes with 15-cm sides (Cube 15).

2.3 Execution of tests

10 copies of each of the three samples, including Cube 7.5 (trimmed), Cube 10 and Cube 15 (both molded), were placed in an oven at 100°C for 24 hours, aiming at standardizing the moisture content of the samples manufactured in different regions and climatic conditions. After drying, the bulk density of the samples was obtained through the determination of the ratio of dry mass and volume. The samples underwent compressive tests, with a load of a voltage-increase rate of 0.29MPa/min. Data was recorded on sheets prepared for the automatic calculation of results, according to the methodology proposed by Faria et al. (2008).

2.4 Analysis of the results

Initially, each of the laboratory's results was analyzed separately to identify possible relationships between the values of compressive strength and the size of samples, and the range of values for each sample, using the standard deviation and coefficient of variation. Then, the results obtained among different laboratories were compared by analyzing the behavior of the resistance values and the size of the samples.

3. RESULTS AND DISCUSSIONS

The following institutions participated in the Inter-laboratory program:

- CECOVI-Research and Development Center for Construction and Housing, National Technological University, Regional Faculty Santa Fe, Argentina (1)
- CEPED-Research and Development Center, Brazil (2)
- Department of Science and Techniques for settlement processes, Faculty of Architecture, Polytechnic Institute of Torino, Italy (3)
- Faculty of Engineering, Paulista State University –Bauru campus, Brazil (4)
- Civil Engineering Laboratory, National Technological University, Regional Faculty of Rafaela, Argentina (5)
- The results presented below are not identified by the respective institutions, but as laboratories A through E.

3.1 Physical characterization of earth samples

The establishment of a range of particle sizes for the inter-laboratory program had two purposes: to work with earth of similar grain size and avoid using additions in the preparation of the samples. Initially, some of the laboratories faced difficulty obtaining the specified earth type, even with the possibility of mixing two or more types of soils. The proposed grain-size distribution did not require the addition of straw or other additives in the preparation of the samples. Table 1 shows the results of the grain-size distribution and Atterberg limits obtained by the five laboratories.

Property	Laboratory A	B	C	D	E	Proposed Grain size
Grain size						
Gravel (%)		3				
Sand (%)	65	62	72	71	15	? 55%
Silt (%)	9	23	22	29*	56	
Clay (%)	26	20	6		29	≤ 30%
Atterberg limits			**	**		
LL (%)	25	47			42	
LP (%)	18	21			20	
IP (%)	7	20			22	
Soil composition	2 soils	1 soil	2 soils	2 soils	1 soil	

* Corresponds to the content of silt + clay
** The Atterberg limits for the mixture of two soils were not determined.

Table 1. Grain-size composition and Atterberg limits of the earth materials tested (credits: Obede B. Faria, 2008)

3.2 Production of the adobes and the cubes

The laboratories executed molds for the production of adobes and cubes, according to the following interior dimensions: 7.5 cm x 15 cm x 30 cm for the adobe unit; and two cubes with sides of 10 cm and 15 cm each. The molds were made of wood, except for those executed by Laboratory D, which developed metal molds.

Each laboratory reported how the molds were developed and their use. All described having more difficulty filling the cube molds, due to their lower opening in relation to their height. Release from the molds of the 10-cm/side cube was also complicated, despite the use of sand, ashes or other mold-release agents.

D and E laboratories commented on the difficulty of cutting the dried adobes with a handsaw to prepare the trimmed samples, something that Faria (2002) also noted, since the handsaw lost its sharp edge very quickly. After several unsuccessful attempts, an electric saw blade was used.

Laboratories B and E described the amount of added water to prepare the clay for bricks and cubes, which coincidentally was about 35% (the ratio between the mass of water added and the dry earth mass). A few samples produced in one of the laboratories are shown in Fig.4.

	Parameters	Laboratory A	B	C	D	E
Cube 7.5	Average (kg/m³)	1860	1580	1860	1610	1900
	Standard deviation (kg/m³)	270	60	30	120	20
	Coefficient of variation (%)	14.5	3.8	1.6	7.5	1.0
Cube 10	Average (kg/m³)	1740	1760	1950	1680	1940
	Standard deviation (kg/m³)	70	50	90	50	20
	Coefficient of variation (%)	4.0	2.8	4.6	3.0	1.0
Cube 15	Average (kg/m³)	1750	1730	1950	1750	1930
	Standard deviation (kg/m³)	30	50	20	90	10
	Coefficient of variation (%)	1.7	2.9	1.0	5.1	0.6

Table 2. Bulk Density (ρap) of the samples tested (credits: Obede B. Faria, 2008)

Fig.3 Molds for sample preparation (credits: Obede B. Faria, 2008)

Fig.4 Some steps for the preparation of samples (credits: Obede B. Faria, 2008)

3.3 Physical and mechanical characterization of adobes

Table 2 shows the results of the bulk density of the samples, which corresponds to the relationship between the dry mass and the volume calculated by the measurement of the sides of each sample.

So as to isolate the variables that relate to the type of earth used in each laboratory and the method of preparation of the adobes and the samples, the bulk densities were calculated in relation to the average values of the corresponding samples of the of 7.5-cm/sidecube (Table 3).

Type of sample	Laboratory A	B	C	D	E
Cube 7.5	1.00	1.00	1.00	1.00	1.00
Cube 10	0.93	1.11	1.05	1.04	1.02
Cube 15	0.94	1.09	1.05	1.09	1.02

Table 3. Bulk density of different samples (credits: Obede B. Faria, 2008)

The analysis of the results presented in Table 3 show that the bulk density of the 7.5-cube sample (trimmed) is smaller than that of the cubes of 10 cm/side and 15 cm/side, except for Laboratory A's samples. This shows that despite the difficulty of filling the cubes during the molding process, this did not affect the compactness of the mixture. The values of bulk density of the molded samples are also close to each other.

Table 4 presents the average results of the compressive strength from different laboratories and Table 5 shows the loading rate for each sample type.

	Parameters	Laboratory A	B	C	D	E
Cube 7.5	Average (Mpa)	1.24	0.45	1.24	6.41	5.99
	Standard deviation (MPa)	0.10	0.04	0.25	0.63	0.35
	Coefficient of variation (%)	8.1	8.8	20.2	9.9	5.8
Cube 10	Average (Mpa)	1.21	0.43	1.50	4.67	5.70
	Standard deviation (MPa)	0.20	0.03	0.21	0.38	0.36
	Coefficient of variation (%)	16.5	7.3	13.9	8.1	6.2
Cube 15	Average (Mpa)	1.13	0.43	1.71	4.88	5.42
	Standard deviation (MPa)	0.05	0.02	0.24	0.58	0.24
	Coefficient of variation (%)	4.4	5.0	14.2	11.9	4.4

Table 4. Compressive strength (credits: Obede B. Faria, 2008)

Sample	Effective Load (per laboratory) A	B	C	D	E	Proposed Load
Cube 7.5	163	500	168	380	160	163
Cube 10	289	615	300	490	287	289
Cube 15	650	488	660	1160	653	650

Table 5. Proposed and effective loading rates (kgf/min) (credits: Obede B. Faria, 2008)

Laboratory D did not test 10 units of each sample, as stated in the procedure, since the layer prepared to regularize load surfaces came off during the handling of some of the samples. Laboratories B and D did not meet the proposed loading rates, corresponding to a rate of voltage increase of 0.29 MPa/min, as the available equipment did not allow adjustment. Table 6 presents the results of compressive strength based on the average values of 7.5-cm/side cube samples from the corresponding laboratories.

Type of sample	Laboratory A	B	C	D	E
Cube 7.5 cm	1.00	1.00	1.00	1.00	1.00
Cube 10 cm	0.98	0.96	1.21	0.73	0.95
Cube 15 cm	0.91	0.96	1.38	0.76	0.90

Table 6. Compressive strength off the different samples in relation to the 7.5-cm/side cubes (credits: Obede B. Faria, 2008)

Except for Laboratory C's results, the results show a trend of reduction in compressive strength when increasing the size of the sample. The difference between the average data, except for Laboratories C and D, reaches a maximum value of 10%.

Laboratory B further determined the compressive strength of samples corresponding to half of adobes with an application area of sizes of 15 cm x 15 cm and a height of 7.5 cm. The average values of the compressive strength were 0.59 ± 0.06 MPa, with a coefficient of variation of 11.0%. Comparing this outcome with that of the 7.5-cm/side cube from the same laboratory, there is a 31% higher value, probably due to the lower rate of slenderness of the non-cubic sample.

The results also allowed drawing the conclusions below:

- There was no evidence of a relationship between the grain size and the compressive strength of the samples;
- The high values of compressive strength obtained by Laboratories D and E are unexpected;
- There was no significant variation in compressive strength in relationship to the dimensions of the cubic sample.

4. CONCLUSION

Inter-laboratory programs are carried out in order to obtain and compare test results, by adopting the same procedures, usually with the same raw material. In the case of the PROTERRA Inter-Laboratory Program, the use of the same raw material was discarded, due to the complexity of shipping earth between countries. It was decided to establish the requirements (content of sand and clay) for the selection of the raw materials in the samples, and to establish procedures for characterization, preparation of samples, and experiments. Later, each laboratory should complete a study of the repeatability of results, as there are many other earthen-characterization variables, for example, the mineralogical composition, that should also be taken into account.

The aim of this first stage of the PROTERRA Inter-Laboratory Program was to define test procedures to determine the compressive strength of adobe. The results allowed the establishment of the first conclusions, especially concerning the size and shape of the samples.

Since there were no significant differences in the results of compressive strength resulting the method of sample preparation, or its dimensions, using cubic samples trimmed from adobe prepared with the dimensions of each side as suggested is also specified in the Peruvian standard (RNC, 2000).

Considering the test-loading rate, it was not possible to verify its influence on the results, since it would be necessary to carry out tests with the same materials and adopt different rates. In order to avoid undesirable variables, and until data is available on the subject, the adoption of a loading rate for testing compressive strength of adobes is recommended, keeping a rate of increase in tension of 0.29 MPa/min as indicated in the PROTERRA Inter-Laboratory Program test procedure.

Excluding Laboratory A, which has been conducting trials of adobe since 1997, the other participants had no background in the preparation of samples to test the compressive strength of earthen blocks. The PROTERRA Inter-Laboratory Program provided the establishment of systematic procedure for the characterization of adobes in those laboratories. In addition, Laboratory A continues with the research in adobe using, whenever possible, the test procedures set out from the PROTERRA Inter-Laboratory Program. Laboratory D has also begun a sequence of tests of compressive strength with adobes using different types of earth, while adopting the same procedures.

Therefore, the PROTERRA Iberian-American Network intends to:

- Institutionalize the test procedure for characterizing compressive strength of adobe;
- Follow up with the inter-laboratory program, by putting forward test procedures for small adobe walls, to evaluate the behavior of adobe masonry, including the analysis by the finite-elements method.

Other laboratories are expected to adopt this procedure as well, in order to determine the compressive strength of adobes, and to collect data from different sites. This will improve the knowledge on the physical and mechanical characteristics of adobes, an ancient, but not completely understood building material.

Notes

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(2) CEDED staff members: Célia Neves (coordinator), Ivo Oliveira, Clementino Passos and Adelson Profeta.
(3) Torino staff members: Roberto Mattoni and Gloria Pasero.
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(5) Rafaela University staff members: Mirta Sánchez, Hugo Begliardo, Susana Keller, Saida Caula, Fiorela Morero and Juan Pretti.

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NOVEL MICRO-SCALE TECHNIQUES TO ESTABLISH A LIFE-CYCLE ANALYSIS OF EARTHEN-BUILT STRUCTURES IN SCOTLAND, UK

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Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Micromorphology, image-analysis, luminescence dating

Abstract

The rapid changes in climate predicted for the 21st century presents a clear threat to the continued conservation and maintenance of historic vernacular buildings constructed with earth materials. With custodians of such vernacular heritage requiring a strong evidence base in order to prioritize the maintenance of such fabrics, it is clear that experimental studies considering the decay of earth materials correlated to their provenance or lifecycle in future environments is required.

This paper reports on a set of scientific initiatives designed to facilitate an evidence-based proactive approach, rather than an anecdotal and reactive approach, to the future repair and maintenance of such structures. Since climate change is manifested in different ways according to geographic location, process-led understandings are paramount. Two major techniques are used. First, thin-section micromorphology is an established technique for analysis of microscopic-structural features, as well as more extensive matrices of soils. It allows spatially-related observations to be linked to physical and chemical measurements at scales relevant to exchange processes in these materials. Second, a novel form of luminescence dating, allowing rapid on-site relative chronologies to be established, has been developed to permit temporal aspects and, hence, rates of change in the structures' lifecycle to be determined.

Using these techniques to analyze the wide range of constructional materials across a variety of regional environmental contexts in Scotland allows a multi-way comparative analysis. Sites considered include the dry internal structures of a stone-clad 18th-century merchant's house in Brechin, Angus; water-saturated earth-infill of wall from a house in Leetown, Perthshire, and exterior walling materials rich in cereal husks taken from Fladdabister, Shetland. Preliminary findings show differences in composition, internal matrix features, and relative age of these materials. This provides the basis for lifecycle analysis of these materials to be outlined in relation to climatically-related factors.

1. INTRODUCTION

The present paper outlines several techniques developed to help enable two complementary research projects on Scottish earthen structures that are being undertaken by the authors. The background to these projects spans two major themes. First is the need to understand processes of building decay in a manner relevant for the understanding of conservation needs and the development of conservation practices for historic earthen-built structures in Scotland. The number of past academic studies on such buildings is small and encompasses a wide array of approaches, including field observations of specific buildings (e.g. Walker, McGregor, and Little, 1996), ethnography and folklore (Fenton, 2008), and actualistic experimentation using trial walls, such as that reported by Morton (2011). Second is the overarching issue of climate change and the response of different types of earthen-built structures to such changes. In doing so, conservation needs and priorities for both scheduled (protected) buildings and those that are not subject to legislation can be identified and prioritized. The two research projects are in their earliest phases of development. They span the investigation of building histories, experimental examination of earthen-building materials subjected to predicted future climatic conditions, and development of practitioner-relevant advice.