MATERIAL ANALYSIS – IN SITU AND LABORATORY MATERIAL CHARACTERIZATION

ABSTRACT

As explained in the previous session, Session 3.1 Material Analysis – Earth as a Building Material, earthen materials have distinct chemical, mechanical and behavioral properties. These properties—like those of any other building material—should be measured and quantified so that their behavior and performance can be characterized and better understood. Certain test results can provide parameters for assigning different soil types within classification systems, thus providing indicators for a soil's suitability for both repair and new construction.

In the field of earthen building conservation, material characterization should provide information about both existing and new materials for the purpose of repair and intervention. Analysis of historic materials are conducted to understand why and how these materials have changed (or not) over time, their expected performance in the near future, and how to better protect these materials from further deterioration. For conservation, one of the main objectives of analyzing new materials is to properly establish their compatibility with historic ones, in case new materials must be introduced for the purpose of intervention.

In the last couple of decades, the conservation field has identified, applied and, in some cases, adapted laboratory tests from the construction industry. In comparison, however, to the tests available for industrialized materials such as concrete, the current testing protocols for earthen materials characterization are still not standardized and/or well-established. The procedures used for earthen material characterization and analysis must be formally standardized to be able to form comparisons through time or between sites.

Guillaud (2008) identifies the following properties and characteristics as significant to the performance of earthen materials:

- Particle size distribution – Percentage of different particles (gravel, sand, silt, clay)
- Plasticity - workability and water content
- Cohesion
- Compactability
- Shrinkage
- Porosity, permeability, and capillarity (void indices)
- Erosion resistance
- Chemistry - Salinity, humus content, quantity of oxides, calcium, carbonates, pH, etc.
- Mineralogy – Clay content and type, ion exchange capacity
- Compressive strength
- Bending strength
- Shear strength
- Hardness
- Adherence (especially for renders)
- Expansion and contraction coefficients (freezing and thawing, thermal)

Since the 1st International Conference on the Conservation of Mud-Brick Monuments in Iran in 1972, material testing has been performed at a series of sites and now it is considered fundamental to know at least basic properties to understand material behavior for a site conservator, architect or engineer to design proper interventions. A series of studies on characterization techniques for earthen materials have been published, however fully standardized procedures have yet to be established. Furthermore, there is very little scientific

correlation between the obtained results and the material deterioration mechanisms. Parameters have not yet been defined for the diagnoses of material decay. For example, we can determine the permeability of a material, but we do not know the acceptable range of permeability for a material exposed to humid environments.

It is fair to say, never the less, that despite the gaps in our current knowledge, there is a series of field and laboratory analysis that can be performed to understand material properties, patterns of deterioration and, most importantly, to plan and design interventions. The more practitioners perform these tests and establish correlations to material diagnoses, the better the field to design proper interventions.

Houben and Guillaud (1984) identify six basic groups of tests that can be used to analyze earthen materials: Identification, Developments, Performance, Characterization, Control and Acceptance. These groups also fall into two main types of testing i) On site testing, which are carried out in the field with accessible and inexpensive equipment and, ii) Laboratory testing, which are performed with non-portable sometimes sophisticated equipment and under a controlled environment, providing in some cases important complementary information regarding earthen materials.

Objectives

As a result of this session, the participant should be able to:

- Identify the basic tests for earthen material characterization
- Define the objectives of each test
- Define, explain and justify margins of errors and degree of subjectivity on each test
- Properly characterize an earthen sample
- Write a report for earthen material characterization
- Design and elaborate non-standardized testing

Content

Classroom Lecture

The classroom lecture will introduce the subject of laboratory and in-situ testing for earthen material characterization. During the lecture format, active class participation will be continually encouraged.

To meet the objectives of this section, the instructor will present:

- Introduction
    1. Review the previous session and activities for this session, encouraging student participation
- Theoretical background
    1. Discuss the objectives of testing and the need for proper standardization and defined parameters by showing specific examples
- Testing
    1. Discuss and describe the existing testing methods[1]
        a. Identification, characterization and development tests: Visual examination (color), Grain size distribution, Sedimentation, Plastic and liquid limit; Bulk, Volumetric and Linear Shrinkage; Proctor Test, Bulk density, Mineralogical

[1] An effort has been made to group the most important testing procedures to be performed either in the laboratory or in the field; however they can be thought of as a continuous series of tests.

identification through X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM); Soluble salt content, pH
   b. Performance, control and acceptance test: Optimal moisture content, Water Vapor Transmission, Permeability, Capillarity; Thermal expansion; Compressive, Tensile and Shear strength; Young's modulus of elasticity
2. Laboratory and in-situ testing
   a. Advantages and disadvantages
   b. Results and methods to collect data
3. Explain and emphasize the need for accurate and relevant data
4. Explain and emphasize the need for practical testing methods for practitioners

- Summary
  1. Importance of accurate testing
  2. Importance of standardized testing for the field of earthen conservation
  3. Problems of adopting tests from other fields
  4. Need to design new tests, aiming forstandardization

In situ/field testing

The in-situ or field testing will allow the students to properly characterize an earthen sample and to write a report of the findings. The instruction will give a brief introduction to the in-situ tests emphasizing practicality and importance and will then explain the layout of the field exercise.

Figure 3.2.1 (left) and 3.2.2 (right)
Demos of in situ testing by PAT instructors
PAT course, 1999 © J. Paul Getty Trust

The exercise will need to be located at an earthen site and selected soil samples will be given to the students to perform the following testing[2]:

1. Visual examination: Munssel color chart – ASTM[3] D 1535-80
2. Smell test
3. Needle test
4. Touch test
5. Washing test
6. Luster test
7. Adhesion test
8. Sedimentation[4] - ASTM C940-81, NF P18-369
9. Shrinkage – Three days
    a. Linear: ASTM C 490
    b. Volumetric: ASTM C 474
10. Decantation
11. Fine mortar testing:
    a. Dry strength test
    b. Water retention test
    c. Consistency test
    d. Cohesion test

Figure 3.2.3
PAT students performing in-situ sedimentation test
PAT course, 1999 © J. Paul Getty Trust

The students write up their findings in the form of a report and present to the rest of the class for discussion.

Laboratory session

The assignment will be to properly characterize an earthen sample and to write a report of the findings. Please note that safety training should be provided to the students before the class according the laws of your country. Students will be given pre-selected earthen samples to perform the following testing:

Characterization testing

- Particle size distribution (PSD) – Wet sieving and sedimentation
    1. CRATerre's testing procedures
    2. ICCROM, ARC Laboratory Manual for Conservator's procedure
    3. ASTM D 422-63; BS1377
- Plastic and Liquid limits
    1. CRATerre's testing procedures
    2. ICCROM, ARC Laboratory Manual for Conservator's procedure
    3. ASTM D4318-84, BS 1377
- Clay-identification and characterization
    1. Methylene blue test – AFNOR[5] P18-592
    2. X-ray Diffraction[6] (XRD)
    3. Scanning Electron Microscopy[7] (SEM)

Figure 3.2.4
Demos of PSD test by PAT instructor
PAT course, 1999 © J. Paul Getty Trust

[2] For a detailed explanation of the testing, please see Houben and Guillaud. *Earth Construction. A comprehensive guide.* Intermediate Technology Publications 1994:Yorkshire, pp. 48-53
[3] American Society for Testing and Materials (ASTM)
[4] This test should last at least 8 hours. Data will need to be collected and analyzed later.
[5] Association Française de Normalisation (AFNOR).
[6] X-Ray Diffraction can be performed at soil mechanics laboratories. Data will need to be interpreted by a material scientist with expertise on interpreting results.

- Organic matter quantity identification

Performance testing

- Water content
    1. CRATerre's testing procedures
    2. ASTM D6780 - 05
- Shrinkage
    1. Apparatus, linear: ASTM C 1148-92a
- Water Drop Absorption
    1. ICCROM, ARC Laboratory Manual for Conservator's procedure
- Penetration of Water: Capillary absorption
    1. CRATerre's testing procedures
    2. ICCROM, ARC Laboratory Manual for Conservator's procedure
    3. NORMAL[8] 11/85
    4. RILEM[9] II-6
- Water vapor transmission
    1. CRATerre's testing procedures
    2. ICCROM, ARC Laboratory Manual for Conservator's procedure
    3. ASTM E-96
    4. RILEM II-2
    5. NORMAL 21/85
- Determination of pH
    1. ICCROM, ARC Laboratory Manual for Conservator's procedure
- Behavioral SEM[10]

The students will write their findings up in the form of a report and present to the rest of the class for discussion.

References

🕮 = Essential reading material
💻 = Available online

Achenza, M. La Qualificazione del Materiale. In: I Manuali del Recupero dei Centri Storici della Sardegna. Il Manuale Tematico della Terra Cruda. Maddalena Achenza and Ulrico Sana Editors. Itaca:Cagliari, 2008. Pp. 27-44

Centre for the Development of Enterprise ACP-EU, CRATerre-EAG, ENTPE. *Compressed Earth Block. Testing Procedures*. Guilde Series Technologies. No. 16. CDE:Belgium, 121

Cornerstones Community Partnership. Adobe Material Selection. In: *Adobe Conservation. A Preservation Handbook.* Sunstonepress: Santa Fe. Pp.71-76

Teutonico J.M. (1988). Porous Building Materials and Earthen Building Materials. In: *ARC A Laboratory Manual for Conservators*. ICCROM:Rome, pp. 33-110
🕮 💻http://www.iccrom.org/pdf/ICCROM_11_LabManual_en.pdf

[7] Scanning Electron Microscopy can be performed at soil mechanics laboratories. Data need to be interpreted by material scientist with expertise on the interpretation of results.
[8] Italian standards
[9] International Union of Laboratories and Experts in Construction Materials, Systems and Structures
[10] Behavioral SEM (Scanning Electron Microscopy) can be performed at soil mechanics laboratories. The results are essentially SEM samples exposed to particular environmental conditions and the result is in the form of a time-lapse video.

Bibliography

📖 = Essential reading material

Alesiani, M.; Capuani, S.; Curzi, F.; Mancini, L.; and Maraviglia, B., Evaluation of stone pore size distribution by means of NMR. In: *Proceedings of the 9th international congress on deterioration and conservation of stone*. Venice, Italy, 19-24 June 2000 (2000), pp. 579-585.

Al-Kass, R.; Hadi, M.; Khalil, N.; and Ali, F. Ancient Babylonian bricks: Their technological characterization and simulation. In: *Structural repair and maintenance of historical buildings*. Brebbia, C. A., Editor. Computational Mechanics Publications, Southampton (1989), pp. 71-80.

Alvarez de Buergo, M.; Fort, R.; and Gómez Heras, M., Efficiency of stone conservation treatments by means of scanning electron microscopy. In: *Proceedings of the 8th euroseminar on microscopy applied to buildings materials*. Athens, Greece, 04-07 September 2000 (2001), pp. 503-510.

Anselmetti, F. S.; Luthi, S.; and Eberli, G. P. Quantitative characterization of carbonate pore systems by digital image analysis. In: *American association of petroleum geologists bulletin*, 82, no. 10 (1998), pp. 1815-1836.

📖 Ashurst, John, and Nicola Ashurst. 1988. *Practical Building Conservation: V.2: Brick, Terracotta, and Earth*. English Heritage Technical Handbook. New York: Halsted Press.

Balascio, C. C. Specifying sample masses for gravimetric testing procedures. In: *Transactions of the ASAE*, 34, no. 3 (1991), pp. 930-936.

Bartolini, M.; Pietrini, A. M.; and Ricci, S., Application of fluorescence microscopy to evaluate the vitality of photoautotrophic biodeteriogens. In: *Proceedings of the 8th euroseminar on microscopy applied to buildings materials*. Athens, Greece, 04-07 September 2001 (2001), pp. 511-516.

Benavente, D.; García del Cura, M. A.; Fort, R.; and Ordónez, S., Determination and quantification of pore structure using backscattered electron image analysis in porous building stones. In: *Proceedings of the 8th euroseminar on microscopy applied to buildings materials*. Athens, Greece, 04-07 September 2001 (2001), pp. 517-524.

Bell J. and Boke, H. Comparing the Old and New: Investigating present-day traditional building materials for use in the conservation of the Uch Monument Complex, Pakistan. In: *9th international conference on the study and conservation of earthen architecture: Terra 2003 preprints*. Yazd, Iran, 29 November – 2 december 2003 (2003) pp. 61-74

Boxall, J. and Trotman, P. M. Limewash: water vapour permeability testing. In: *Surface coatings international*, 79, no. 3 (1996), pp. 128-129.

Braudeau, E.; Costantini, J. M.; Bellier, G.; and Colleuille, H. New device and method for soil shrinkage curve measurement and characterization. In: *Soil science society of America journal*, 63, no. 3 (1999), pp. 525-535.

Brown, P. W.; Robbins, C. R.; and Clifton, J. R. *Factors affecting the durability of adobe structures*. U.S. Department of Commerce, Washington D.C. (1978)

Bullock, P. *Handbook for soil thin-section description*. Waine Research Publications, Wolverhampton (1985), 152 p.

Cebeci, O. Z.; Demirel, T.; and Lohnes, R. A. Evaluation of hysteresis in mercury intrusion porosimetry by secondintrusion method. In: *Transportation research record*, 1, no. 1 (1978), pp. 15-20.

Cancino, C. and Matero F., Assessment of grouting methods for cracks and large-scale detachment repair at Casa Grande, Casa Grande Ruins National Monument. In: *9th international conference on the study and conservation of earthen architecture: Terra 2003 preprints*. Yazd, Iran, 29 November – 2 december 2003 (2003) pp. 395-414

Chiari, G.; Giordano, A.; and Menges, G. Non destructive X-ray diffraction analyses of unprepared samples. In: *Science and technology for cultural heritage*, 5, no. 1 (1996), pp. 21-36.

📖 Chiari, G.; Invernizzi, A.; and Bertolotto, G., Investigation and restoration of clay fragmentary statues from Old Nisa, Turkmenistan. In: *7a conferência internacional sobre e estudo e conservação da arquitectura de terra = 7th international conference of the study and conservation of earthen architecture*. Silves, Portugal, 24-29 October 1993 (1993), pp. 228-230.

📖 Coffman, R.; Agnew, N.; Austin, G.; and Doehne, E., Adobe mineralogy: characterization of adobes from around the world. In: *6th international conference on the conservation of earthen architecture: Adobe 90 preprints*. Las Cruces, New Mexico, 14-19 October 1990 (1990), pp. 424-429.

Crabtree, S. J.; Ehrlich, R.; and Prince, C. Evaluation of strategies for segmentation of blue-dyed pores in thin sections of reservoir rocks. In: *Computer vision, graphics, and image processing*, 28, (1984), pp. 1-18.

CRATerre, Doat, P., Hays, A., Houben, H., Matuk, S., Vitoux, F., *Construir con tierra*. Bogota, Colombia: Fondo rotatorio editorial, 1990. (Tome 1, 221 p. / Tome 2, 259 p.)

Crumbie, A. K., Sample preparation of polished sections and microstructural observations with backscattered images in an SEM - artefacts and practical considerations. In: *Proceedings of the 8th euroseminar on microscopy applied to building materials*. Athens, Greece, 04-07 September 2001 (2001), pp. 489-496.

Clark, D. and Walker P., The properties of a soil from Southwest England and its influence on the behavior of rammed earth. In: *9th international conference on the study and conservation of earthen architecture: Terra 2003 preprints*. Yazd, Iran, 29 November – 2 december 2003 (2003) pp. 93-101.

Cyr, M. and Tagnit-Hamou, A. Particle size distribution of fine powders by laser diffraction spectrometry. In: *Case of cementitious materials*. Matériaux et constructions , 34, (2001), pp. 342-350.

Dayre, Michel, and Emmanuel Kenmogne. 1993. Etude des transferts d'humidité dans les blocs de terre crue compactée: Influence de la structure des terres. In: *Terra 93: 7a Conferência Internacional sobre o Estudo e Conservação da Arquitectura de Terra: Silves, Portugal, 24 a 29 de Outubro, 1993; 7th International Conference on the Study and Conservation of Earthen Architecture: Silves, Portugal, 24–29 October, 1993; 7ème conférence internationale pour l'étude et la conservation de l'architecture de terre: Silves, Portugal, 24 au 29 octobre, 1993,* ed. Margarida Alçada, 348–52. Lisbon: Direcção Geral dos Edifícios e Monumentos Nacionais.

📖 Demehati, A. 1990. Contribution à l'étude de correlations et de l'utilité de paramètres de l'identification des sols. In: *Ier séminaire international sur l'ingénieurie des constructions en terre, 30–31 mai, 1er juin 1990, Marrakech.* Casablanca: Laboratoire Public d'Essais et d'Etudes.

Depraetere, W.; Carmeliet, J.; and Hens, H., Moisture transfer at interfaces of porous materials: measurements and simulations. In: *International workshop: historic mortars, characteristics and tests*, Unedited pre-prints. Paisley, Scotland, 12-14 May 1999 (1999)

Diamond, S. Mercury porosimetry: an inappropriate method for the measurement of pore size distributions in cementbased materials. In: *Cement and Concrete Research*, 30, (2000), pp. 1517-1525.

Diamond, S. and Leeman, M. E. Pore size distributions in hardened cement paste by SEM image analysis. In: *Materials research society symposium proceedings*, 370, (1995), pp. 217-226.

Didier, G. and Ghomari, F., Méthodologie d'étude au laboratoire de la tenue à l'eau du matériau terre. In: *6th international conference on the conservation of earthen architecture: Adobe 90 Preprints*. Las Cruces, New Mexico, 14-19 October 1990 (1990), pp. 393-400.

📖 Dix, Linnaea A. 1997. Materials in the laboratory—earthen plasters, mortars, and paints from Mug House. In: *CRM Bulletin* 20 (10): 43–45.

Doehne, E., Environmental scanning electron microscopy. In: *Sociedad española de microscopia electronica*, xvii reunión bienal . Oviedo (1995), pp. 26-27.

📖 Doehne, E. ESEM development and application in cultural heritage conservation. In: *In-situ microscopy in materials research: leading international research in electron and scanning probe microscopies*, Gai, P. L., Editor. Kluwer Academic Publishers (1997), pp. 45-62.

📖 Doehne, E. and Stulik, D. Applications of the environmental scanning electron microscope to conservation science. In: *Scanning microscopy*, 4, no. 2 (1990), pp. 275-286.

Dynamic studies of materials using the environmental scanning electron microscope. In: *Materials issues in art and archaeology II: symposium*. San Francisco, California, 17-21 April 1990 (1991), pp. 31-38.

Ebrahimi, A., Researches of mud – brick and staw – clay plasters in Choga Zanbil sit. In: *9th international conference on the study and conservation of earthen architecture: Terra 2003 preprints*. Yazd, Iran, 29 November – 2 december 2003 (2003) pp. 133-140

Ehrlich, R.; Kennedy, S. K.; Crabtree, S. J.; and Cannon, R. L. Petrographic image analysis, I. Analysis of reservoir pore complexes. In: *Journal of sedimentary petrology*, 54, no. 4 (1984), pp. 1365-1378.

Espinosa, I. V., Study of the materials used in the earthen walls of the city of Granada (Spain). In: *7a conferencia internacional sobre e estudo e conservação da arquitectura de terra = 7th international conference of the study and conservation of earthen architecture*. Silves, Portugal, 24-29 October 1993 (1993), pp. 464-468.

Fiès, J. C. Analysis of soil textural porosity relative to skeleton particle size, using mercury porosimetry. In: *Soil science society of America journal*, 56, (1992), pp. 1062-1067.

Fitzner, B., Porosity analysis: A method for the characterization of building stones in different weathering states. In: *International symposium on the engineering geology of ancient works, monuments and historical sites; preservation and protection*. Athens, Greece, 19-23 September 1988 (1988), pp. 2031-2037.

Fitzpatrick, E. A. and Gudmundsson, T. The impregnation of wet peat for the production of thin sections. In: *Journal of soil sciences*, 29, (1978), pp. 585-587.

Gerard, R. E.; Philipson, C. A.; Manni, F. M.; and Marschall, D. M. Petrographic image analysis: an alternate method for determining petrophysical properties. In: *Automated pattern analysis in petroleum exploration*, Palaz, I. and Sengupta, S. K., Editors. Springer Verlag, New York (1992), pp. 249-263.

Goodhew, S.; Griffiths, R.; Short, D.; and Watson, L., Some preliminary studies of the thermal properties of Devon cob walls. In*: Terra 2000: 8th international conference on the study and conservation of earthen architecture. Preprints*. Torquay, United Kingdom , 11-13 May 2000 (2000), pp. 139-143.

Goudie, A. S. Calcrete. In: *Chemical sediments and geomorphology: precipitates and residua in the near-surface environment*, Goudie, A. S. and Pye, K., Editors. Academic Press, London (1983), pp. 93-131.

🕮 Guillaud, H. Characterization of earthen materials. In: *Terra Literature Review. An overview of research in earthen architecture conservation*. Erica Avrami, Hubert Guillaud and Mary Hardy Editors. The Getty Conservation Institute: Los Angeles (2008), pp. 21-31.

🕮 Hartzler, R. 1996. Acrylic-Modified Earthen Mortar: A Program of Investigation and Laboratory Research into Acrylic-Modified Earthen Mortar Used at Three Prehistoric Pueblo Sites. In: *Intermountain Cultural Resource Center Professional Paper*, no. 61. Santa Fe, NM: Intermountain Cultural Resource Center / University of Pennsylvania.

1997. Acrylic-modified earthen mortar. In: *CRM Bulletin* 20 (10): 50–52.

Helmi, F. M., Deterioration and conservation of some mud brick in Egypt. In: *6th international conference on the conservation of earthen architecture: Adobe 90 preprints*. Las Cruces, New Mexico, 14-19 October 1990 (1990), pp. 277-282., 3 figs.p.

Hill, B.; Roger, T.; and Vorhagen, F. W. Comparative analysis of the quantization of color spaces on the basis of the CIELAB color-difference formula. In: *ACM transactions on graphics*, 16, (1997), pp. 109-54.

Hoseini, S. and Seyed, H., Studying the role of admixture in order to stabilization of muddy mortar against of different humitidy behavior in historical site of Choga Zanbil. Selection of soils for synthesis resistance muddy. In: *9th international conference on the study and conservation of earthen architecture: Terra 2003 preprints*. Yazd, Iran, 29 November – 2 december 2003 (2003) pp. 271-292

Houben, H. and Guillaud, H. Earth construction primer: project, In: *Earth construction technologies appropriate to developing countries*. Universitè catholique de Louvain, Louvain-la-Neuve (1984), 361p.

🕮 Soil identification, Testing. In: *Earth construction: a comprehensive guide*. Chapers 2-5. Intermediate Technology Publications: London (1994), pp. 45-59; 64-70; 131-142.

Identificación del Suelo, Pruebas. Translations: Chapter 3 and 5. In: *Earth construction: a comprehensive guide*. Intermediate Technology Publications: London (1994), pp. 45-59; 64-70; 131-142.

Jerome, P. *Analysis and conservation of mudbrick construction in Bronze Age Crete*. Columbia University, New York (1991), ix + 208p.

Analysis of bronze age mudbricks from Palaikastro, Crete. In: *7a conferencia internacional sobre e estudo e conservação da arquitectura de terra = 7th international conference of the study and conservation of earthen architecture*. Silves, Portugal, 24-29 October 1993 (1993), pp. 381-386.

Kakoulli, I. Materials and techniques of the pre-Hispanic paintings at El Brujo, Huaca Cao Viejo, Peru. In: *Research Laboratory for Archaeology and the History of Art*, University of Oxford, Oxford (1997)

Lavergne, P. J. Field and laboratory methods used by the geological survey of Canada in geochemical surveys. In: *No. 8 preparation of geological materials for chemical and spectro-graphic analysis*. 65-18, Geological Survey of Canada, Ottawa (1965)

León y León, C. A. New perspectives in mercury porosimetry. In: Advances *in colloid and interface science*, 76-77, (1998), pp. 341-372.

Lowell, S. and Shields, J. E. Equivalency of mercury porosimetry and gas adsorption. In*: Powder technology*, 29, (1981), pp. 225-231.

Lucia, F. J. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. In: *American association of petroleumn geologists bulletin*, 79, no. 9 (1995), pp. 1275-1300.

Machel, H. G. and Burton, E. A. Factors governing cathodoluminescence in calcite and dolomite, and their implications for studies of carbonate diagenesis. In: *Luminescence microscopy: quantitative and qualitative aspects*, Barker, C. E. and Kopp, O. C., Editors. (1991), pp. 37-57.

🕮 Matero, Frank. 1997. Managing change: Conservation of surface finishes at Mesa Verde's cliff dwellings. In: *CRM Bulletin* 20 (10): 39–42.

McAlister, J. J. and Smith, B. J. A rapid preparation technique for X-ray diffraction analysis of clay minerals in weathered rock materials. In: *Microchemical journal* , 52, (1995), pp. 53-61.

McCreesh, C. A.; Ehrlich, R.; and Crabtree, S. J. Petrography and reservoir physics II: relating thin section porosity to capillary pressure, the association between pore types and throat size. In: *American association of petroleum geologists bulletin*, 75, no. 10 (1991), pp. 1563-1578.

Mesbah, A., and M. Olivier. 1990. Essais simplifiés pour l'identification des sols. In: *1er séminaire international sur l'ingénieurie des constructions en terre, 30–31 mai, 1er juin 1990, Marrakech*. Casablanca: Laboratoire Public d'Essais et d'Etudes.

Middleton, G. F., and L. M. Schneider. 1987. *Earth-Wall Construction*, 4th ed. Chatswood, Australia: National Building Technology Centre.

Milia, F.; Fardis, M.; Papavassilious, G.; and Leventis, A. NMR in porous materials. In: *Magnetic resonance imaging*, 16, no. 5/6 (1998), pp. 677-678.

Moore, Duane Milton, and Robert C. Reynolds. 1997. *X-Ray Diffraction and the Identification and Analysis of Clay Minerals,* 2nd. Ed. Oxford: Oxford University Press.332 p.

Moreau, É.; Sardini, P.; Touchard, G.; and Velde, B. 2D and 3D morphological and topological analysis of a clay soil. In: *Microscopy, microanalysis, microstructures*, 7, no. 5-6 (1996), pp. 499-504.

Morgan, M. T.; Wood, R. K.; and Holmes, R. G. Dielectric moisture measurement of soil cores. In: *Transactions of the ASAE*, 36 , no. 1 (1993), pp. 17-22.

Moropoulou, A.; Bakolas, A.; Karoglou, M.; and Karamberi, A., Microscopic techniques in the assessment of the ability of macropore plasters to tackle rising damp of historic masonries. In: *Proceedings of the 8th euroseminar on microscopy applied to buildings materials*. Athens, Greece, 4-7 September 2001 (2001), pp. 595-602.

🕮 Mueller, U. Interaction of moisture with earthen building materials from Joya de Ceren . Unpublished, Getty Conservation Institute, Los Angeles (2001) 34p.

🕮 Material analysis of soil samples from Joya de Ceren, El Salvador . Unpublished, Getty Conservation Institute, Los Angeles (2000) 58p.

Mueller, U. and Hansen, E. F., Use of digital image analysis in conservation of building materials. In: *Proceedings of the 8th euroseminar microscopy applied to buildings materials*. Athens, Greece, 4-7 September 2001 (2001), pp. 603-610.

Mullet, M.; Fievet, P.; Reggiani, J.-C.; and Pagetti, J. Wicking technique combined with electrical resistance measurements for determination of pore size in ceramic membranes. In: *Journal of materials science*, 34, (1999), pp. 1905-1910.

Murphy, C. P. A comparative study of three methods of water removal prior to resin impregnation of two soils. In: *Journal of soil science* , 33, (1982), pp. 719-735.

Niebla, E. E., Material properties of adobe and laboratory analyses. In: *Adobe: practical & technical aspects of adobe conservation*. Tucson, Arizona, 26-28 March 1983 (1983), pp. 5-8.

Olson, K. R. Characterization of pore size distributions within soils by mercury intrusion and water-release methods. In: *Soil science*, 139, no. 5 (1985), pp. 400-404.

Ordaz, J.; Alonso, F. J.; and Esbert, R. M., Caracterizacion fisica de adobes de Castilla-Leon (Espana) = Physical characterization of adobes of Castilla-Leon (Spain). In: *6th international conference on the conservation of earthen architecture: Adobe 90 preprints*. Las Cruces, New Mexico, 14-19 October 1990 (1990), pp. 438-442.

Pardini, G.; Vigna Guidi, G.; Pini, R.; Regüés, D.; and Gallart, F. Structure and porosity of smectitic mudrocks as affected by experimental wetting-drying cycles and freezing-thawing cycles. In: *Catena*, 27, (1996), pp. 149-165.

Pareschi, M. T.; Pompilio, M.; and Innocenti, F. Automated evaluation of volumetric grain-size distribution from thinsection images. In: *Computers & geosciences*, 16, no. 8 (1990), pp. 1067-1084.

Pel, L.; Hazrati, K.; Kopinga, K.; and Marchand, J. Water absorption in mortar determined by NMR. In: *Magnetic resonance imaging*, 16, no. 5/6 (1998), pp. 525-528.

Penumadu, D. and Dean, J. Compressibility effect in evaluating the pore-size distribution of kaolin clay using mercury intrusion porosimetry. In: *Canadian Geotechnical Journal*, 37, (2000), pp. 393-405.

Pillai, U. P., and D. McGarry. 1999. Structure repair of a compacted vertisol with wet-dry cycles and crops. In: *Soil Science Society of America Journal* 63 (1): 201–10.

Prost, R., T. Koutit, A. Benchara, and E. Huard. 1998. State and location of water adsorbed on clay minerals: Consequences of the hydration and swelling-shrinkage phenomena. In: *Clays and Clay Minerals* 46 (2): 117–31.

Ranocchia, G. and Rovero, L., Influence of insertion of fired bricks on the mechanical characteristics of adobe brickwork. In: *Ceramics in architecture: proceedings of the international symposium on ceramics in architecture of the*

8th CIMTEC world ceramics congress and forum on new materials. Florence, Italy, 28 June-1 July 1994 (1995), pp. 231-238.

Ranocchia, Giovanna, Fabio F. Fratini, and Carlo Manganelli del Fá. 1995. Earthen building in Tuscany: Characterization of the material used in buildings of the High Valdarno. In: *Ceramics in Architecture: Proceedings of the International Symposium on Ceramics in Architecture of the 8th CIMTECWorld Ceramics Congress and Forum on New Materials, Florence, Italy, June 28–July 1, 1994,* ed. P. Vincenzini, 239–46. Monographs in Materials and Society, no. 1. Faenza, Italy: Techna.

Rao, S. M.; Brinker, C. J.; and Ross, T. J. Environmental microscopy in stone conservation. In: *Scanning*, 18, (1996), pp. 508-514.

Roels, S.; Elsen, J.; Carmeliet, J.; and Hens, H. Characterisation of pore structure by combining mercury porosimetry and micrography. In: *Materials and structures*, 34, (2001), pp. 76-82.

Schilling, M. R.; Carson, D. M.; and Khanjian, H. P., Gas chromatographic determination of the fatty acid and glycerol content of lipids. IV. In: *Evaporation of fatty acids and the formation of ghost images by framed oil paintings. 12th Triennial Meeting*,1. Lyon, France, 29 August -3 September 1999 (1999), pp. 242-247.

Seed, H. B.; Woodward, R. J.; and Lundgren, R. Prediction of swelling potential for compacted clays. In: *Journal of the soil mechanics and foundations division*, 88, (1962), pp. 53-87.

Shekede, L., Wall paintings on earthen supports: evaluating analytical methods for conservation. In: *Terra 2000: 8th international conference on the study and conservation of earthen architecture. Preprints*. Torquay, United Kingdom, 11-13 May 2000 (2000), pp. 169-175.

Silver, Constance S. 1990. Analyses and conservation of Pueblo architectural finishes in the American Southwest. In: *6th International Conference on the Conservation of Earthen Architecture: Adobe 90 Preprints: Las Cruces, New Mexico, U.S.A., October 14–19, 1990,* ed. Kirsten Grimstad, 176–81.Los Angeles: Getty Conservation Institute.

Smith, W. Kiva mural decorations at Awatovi and Kawaika-a: reports of the Awatovi expedition, 5 . In: *Papers of the Peabody Museum of American Archaeology and Ethnology*, 37. (1952), 363p.

Starkey, J. and Rutherford, S. Image analysis of particle shape. In: *Automated pattern analysis in petroleum exploration*, Palaz, I. and Sengupta, S. K., Editors. Springer Verlag, New York (1992), pp. 213-221.

Starkey, J. and Samantaray, A. K. A microcomputer-based system for quantitative petrographic analysis. In: *Computers & geosciences*, 20, no. 9 (1994), pp. 1285-1296.

Stefanidou, M., Estimation of porosity by using different techniques. In: *Proceedings of the 8th euroseminar on microscopy applied to buildings materials*. Athens, Greece, 4-7 September 2001 (2001), pp. 619-624.

Thieme, J. Studies of soil colloids with x-ray microscopy. In: *America's microscopy and analysis*, 49, (2001), pp. 23-25.

Tributh, H. and Lagaly, G. Identifizierung und charakterisierung von tonmineralen = Identification and characterization of clay minerals . In: *Deutsche Ton- und* Tonmineralgruppe e. V., Giessen (1991)

Van Der Merwe, D. H. The prediction of heave from the plasticity index and percentage clay fraction of soils. In: *The civil engineer in South Africa*, (1964), pp. 103-107.

Van Greiken, R. E. and Markowicz, A. A. Handbook of x-ray spectrometry: methods and techniques. In: *Practical spectroscopy*, 14. Brame, E. G, Editor. Marcel Dekker, Inc., New York (1993), p.704.

Wachtman, J. B. *Characterization of materials*. Butterworth-Heinemann, Boston (1993), 480p.

Walker, P., Review and experimental comparison of erosion tests for earth blocks. In: *Terra 2000: 8th international conference on the study and conservation of earthen architecture. Preprints*. Torquay, United Kingdom , 11-13 May 2000 (2000), pp. 176-181.

Wang, Y. and Diamond, S., An approach to quantitative image analysis for cement pastes. In: *Microstructure of cement based systems. Bonding and interfaces in cementitious materials: symposia*. Boston, Massachusetts, 28 November-01 December 1994 (1995), pp. 23-32.

Wardlaw, N. C. and McKellar, M. Mercury porosimetry and the interpretation of pore geometry in sedimentary rocks and artificial models. In: *Powder technology*, 29, no. 1 (1981), pp. 127-143.

Wardlaw, N. C.; McKellar, M.; and Yu, L. Pore and throat size distributions determined by mercury porosimetry and by direct observation. In: *Carbonates and evaporites*, 3, no. 1 (1988), pp. 1-15.

Warren, J. Evaluation, preparation, testing and replacement of materials. In: *Conservation of Earth Structures*. Butterworth-Heinemann: Oxford (1999), pp. 99-111.

Watanabe K., Vatandaust A.; Yasuyoshi, O., Physical, mineralogical and chemical properties of mud brick and mud mortars of the Choga Zanbil, Iran. In: *9th international conference on the study and conservation of earthen architecture: Terra 2003 preprints*. Yazd, Iran, 29 November – 2 december 2003 (2003) pp. 656-666

Willis, K. L.; Abell, A. B.; and Lange, D. A. Image-based characterizations of cement pore structure using wood's metal intrusion. In: *Cement and concrete research*, 28, no. 12 (1998), pp. 1695-1705.

Wilson, F. *Building materials evaluation handbook*. Van Nostrand Reinhold, New York (1984), ix + 358p.

Wilson, M. J. *A handbook of determinative methods in clay mineralogy*. Chapman and Hall, New York (1987), 308p.

Winslow, D. Experimental aspects of mercury intrusion porosimetry. In*: Transportation research record*, 1, no. 1 (1986).

Zhaohui, L.; Giese, R. F.; van Oss, C. J.; Kerch, H. M.; and Burdette, H. E. Wicking technique for determination of pore size in ceramic materials. In: *Journal of the American ceramic society*, 77, no. 8 (1994), pp. 2220-2222.