E3S Web of Conferences **382**, 17001 (2023) https://doi.org/10.1051/e3sconf/202338217001
UNSAT 2023

Investigation of the properties and behaviour of ancient and newly constructed mudbricks from the ancient walls of Eleusis

Michail Bardanis[1*], *Theodoros* Marinis[2], *Eleni-Eva* Toumbakari[3] and *Georgios* Dounias[1]

[1]EDAFOS Engineering Consultants S.A., 9 Iperidou st., 10558 Athens, Greece
[2]Conservation Engineer, MSc hired on contract for the Eleusis mudbricks production project, Athens, Greece
[3]Directorate for the Restoration of Ancient Monuments, Hellenic Ministry of Culture and Sports, 12 Karytsi Sq., 105 61 Athens, Greece

Abstract. The paper presents the test results from the investigation of the nature and mechanical behaviour of mudbricks from the ancient mudbrick wall of Eleusis in Attica, Greece. The mudbrick wall remains preserved to date in the site of Eleusis are some of the largest preserved in Greece. Small fragments of mudbricks were taken to the laboratory for experimental investigation. Testing included index tests to classify the soil material the mudbricks were made of, mineralogical analyses of their fines' content, mechanical testing suitable for the nature of the materials and the ability to trim the samples without causing damage and measurements of suction on samples as they were obtained, further dried, or rewetted. The soil material used for ancient mudbrick construction was a silty sand to sandy silt with a small fraction clay content, with marginally plastic to non-plastic fines. Dry unit weight was found to be close to the dry unit weight of fresh mudbrick material after being compacted with a minimum compaction energy of only 45 kNm/m^3 and left to dry to residual water content conditions. Similarly, field water content was found close to the residual water content of these recompacted soil samples. Consequently, unconfined compression strength was found very high corresponding to the residual water content condition, with similarly high cohesion obtained from direct shear tests and a very high yield stress under one-dimensional conditions of loading.

1 Introduction

Earthen materials construction is most probably the most common application of unsaturated soil mechanics principles with the twist that it has been empirically practiced since prehistoric times [1]. Especially when no additives of any kind that alter soil behaviour and index properties (lime, cement etc) are added, earthen materials behaviour depends solely on their behaviour as affected by partial saturation. In recent years, research in earthen construction and especially mudbricks has focused more systematically on the study of their behaviour in the framework of unsaturated soil mechanics rather than pure empiricism, as a result of increased needs for the conservation and repairs of monuments and other buildings made of mudbricks, as well as an increased need to support scientifically alternative methods of construction and building materials towards more sustainable construction [1, 2, 3].

As part of this, an experimental investigation of the Mudbrick Walls in the Eleusis Sanctury was undertaken with the purpose to support conservation of this largely unique ancient monument. This investigation is presented in this paper and involved the study of the physical and mineralogical properties of the ancient mudbricks and sources of material to construct new ones, as well as the mechanical and hydraulic behaviour of samples from ancient mudbricks and newly constructed ones plus mudbricks and small mudbrick walls. Particular points of interest in this investigation was the compaction energy per volume, the percentage of contained dry grass and the time needed to achieve a stable condition of water content, namely the residual water content of the soil material used to build the mudbricks and the mudbrick walls [4, 5].

2 Mudbrick walls in the Eleusis Sanctuary

The Eleusis Sanctuary was one of the main religious centres of the Greco-Roman world. Roman Emperors have been major benefactors of the cult, that grew from a small shrine and a sacred cave (Ploutonion) of the prehistoric (Mycenean) period to a fortified Sanctuary with a citadel (Acropolis) during the archaic period. From the 5th cent. BC onwards, successive expansions of the temple (Telestirion) and the fortifications, accommodated the increasing needs of the religious centre, until its decline during the Christian Era and its formal closure by 392 AD.

The first earlier identified circuit wall to mark the boundary of this site dates in the 6th cent. BC and is known as the Peisistratean wall that still retains visible parts today. The most significant of these remains is the

---

[*] Corresponding author: mbardanis@edafos.gr

wall and tower sections that preserve mudbrick masonry upperstructure with stone base (socle). These consist of two volumes of mudbrick structure, one of 6m maximum height with up to 4 m width, and two smaller volumes (5th cent. BC additions) of less than 1m height (Fig. 1). The typical masonry units have 44-45cm square plan dimensions and 8-10cm thickness, though smaller fragments were used for the interlocking of the masonry bond and the sides.

Nowadays, the state of preservation has been a result of more than 2000 years of subsoil conditions, as the archaic wall was completely backfilled to create the Sacred Court of the classical period on top of it. Major archaeological excavation works of the 1880s uncovered the mudbrick wall sections. The surviving parts remained exposed until the 1930s, when field research was finalised. Temporary and insufficient protection covers led to the degradation of the material until 1990, when more solid shelter solutions stabilised the semi-open condition to its present state of deformed, uniform volumes of soil. Only the vertical sides of the tower and the fissure-like form of joints indicate the original structural form.

The ongoing restoration initiative of the Greek ministry of Culture (Directorate for the Restoration of Ancient Monuments) has focused on restoring the lost wall section between the two main volumes of ancient mudbrick: an approximately 7m long and 4m wide surface is planned to be built with new mudbricks up to a small height as a conclusion of a pilot research and implementation programme.

Apart from the visible evidence, little is known from ancient sources about the mode of production and this type of ancient construction. The research work that gathers most of the scarce indications from historic sources is the 1950s book on ancient Greek building methods and materials by A. Orlandos [6]. From this is derived that the soil was selected, sieved and molded with straw into the mudbricks.

In order to keep the compatibility and reversibility principle of monuments' restoration, it was decided not to use any stabiliser other that the dry cut grass from the seasonal maintenance of the Eleusis site and soil from the site's excavation works in the design concept for the new mudbrick production. The soil from the site's excavation works proved to be practically of the same physical and mineralogical properties indicating that the soil found locally was probably the source of the materials for constructing the ancient mudbricks.

Any industrial additives or any device for compressed stabilised production was ruled out. The quality control of the end-products was decided to rely on the same factors as those influenced by the ancient mason:

- moisture control on the wet mix of hay and soil
- hand-packed by manual tool compression in the mold

The equipment for mixing was acceptably simple but modern. Mechanical hand mixers were used. The molding of 400 mudbrick production with 44x44x9cm average dimensions for the pilot restoration programme could also afford a luxury that the ancient mass production of tens of thousands could not. This luxury was the preservation of each brick in the timber frame mold until full drying of the brick has been completed with an average time of one month in confined drying. The external conditions were also stable inside a shaded covered space, similar in the laboratory and in the worksite.

Fig. 1. Views of sections of the remaining volumes of mudbrick walls (photos taken 2020).

3 Unsaturated soil mechanics background

All fully saturated soils dry when left in atmospheric conditions. Drying is driven by evaporation caused by the relative humidity and temperature of the atmosphere as dictated by Kelvin's law [7]. Drying causes the pressure of the water inside the soil to become initially negative for as long as the porosity, grain-size distribution and mineralogy of the soil maintains the degree of saturation equal to 100%, and then it will become suction once the soil is desaturated (i.e. its degree of saturation becomes smaller than 100%). Drying will continue to a value of water content, called the residual water content [4, 5]. If smaller relative humidity is applied or the material is heated, drying will continue to practically zero degree of saturation corresponding to approximately 10^6 kPa [8]. Degree of saturation, S_r, vs negative pore water pressure/ suction, s, has the general form shown in Fig. 2. Drying generally causes shrinkage leading to a decrease to residual void ratio [4, 5] as shown in Fig. 3a corresponding to a maximum dry unit weight as shown in Fig. 3b. Residual water content, residual void ratio and the corresponding maximum dry unit weight are strongly dependent on initial void ratio and water content [4] as well as structure caused by various factors in natural soils or compaction energy per volume in compacted soils [5].

Mudbricks are constructed with the state properties of the soil (void ratio, water content, and dry unit weight) corresponding to a point either on the full saturation portion of the curves shown in Fig. 2 & 3 or slightly into the portion between desaturation and residual drying conditions (between points A & B in Fig. 3). “Curing” -as unfortunately used for mudbricks in materials’ science- corresponds simply to the completion of drying of the mudbrick soil material to its residual drying characteristics: residual water content, residual void ratio and the corresponding maximum dry unit weight consistent with the initial state characteristics.

Contemplating this simple unsaturated soil behaviour puts mudbrick characteristics investigation and construction parameters into perspective:

- Initial water content and dry unit weight as dictated by compaction energy per volume used will dictate final dry unit weight and water content which will itself dictate final strength characteristics.
- The physical characteristics of the soil used will dictate how prone it is to crack because of shrinkage during drying. Hay/dried grass serves as a natural type of fibre controlling resistance to cracking during drying depending on its content and the soil properties.
- The primary construction specifications are initial water and hay/dried grass content and initial dry unit weight plus, perhaps the most important parameter in terms of construction efficiency, the time that this drying will take place under the specific atmospheric conditions causing this drying.

These characteristics were investigated during the experimental programme undertaken: compaction energy per volume, hay/dried grass content, time taken to drying to constant conditions.

4 Soil properties

4.1 Index and state properties

The index and state properties of the soil from the samples of actual ancient mudbricks are summarised in Table 1. Few “undisturbed” samples were provided plus a number of very disturbed samples in the form of crumbled material at the foot of the walls. Characterization of the soil ranged between SM and CL according to USCS.

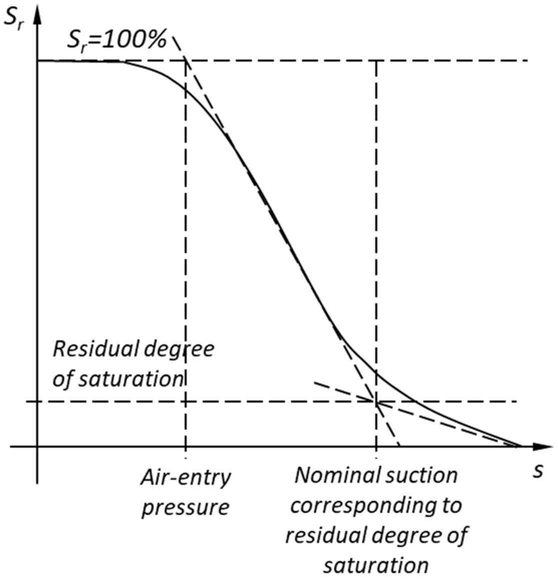

Fig. 2. General shape of the relation between degree of saturation, S_r, and negative pore water pressure/suction, s, during drying (soil-water characteristic curve).

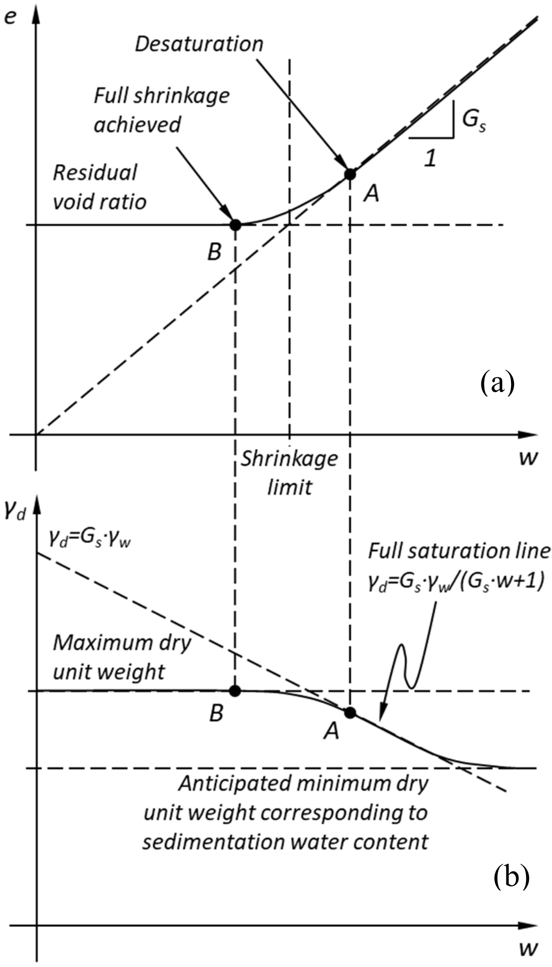

Fig. 3. General shape of the relation between void ratio, e, and water content, w, during drying (shrinkage curve -top) and the way it corresponds to dry unit weight, γ_d, evolution during drying (bottom).

Table 1. Index and state properties of the soil of the ancient mudbricks.

Property	**Range**	**Average**
Clay fraction (%)	0.4-6.3	3.5
Fines (%)	42-54	49
Sand (%)	39-50	43
Gravel (%)	3-12	8
w_L (%)	20-23	21
I_P (%)	3-8	6
G_s (-)	2.65-2.73	2.69
e_o (-)	0.56-0.83	0.71
γ_d (kN/m^3)	14.5-17.3	15.7
w_o (%)	0.6-14.0	3.2

4.2 Mineralogy

X-ray diffraction was used to identify contained minerals in the samples of actual ancient mudbricks. Silica minerals ranged between 42 and 58% with an average of 48%, feldspars between 10 and 14% with an average of 12%, clay minerals between 4 and 16% with an average of 9% and calcitic minerals between 22 and 42% with an average of 31%. Calcitic minerals were mostly dolomite and secondarily calcite. The main clay mineral identified was illite with traces of the other basic clay minerals. Mineralogy of the soil used to construct the new mudbricks was practically the same with calcitic minerals having a larger content and calcite being more than dolomite.

4.3 Compaction characteristics

The compaction characteristics of the soil used to construct the new mudbricks was investigated using the Proctor compaction test [9, 10] with various compaction energies per volume (CEPV) used. Various compaction energies per volume were used in order to identify the compaction energy per volume producing samples with an initial dry unit weight at the optimum water content leading to dry unit weights after drying to residual water content practically equal to that of the samples of ancient mudbricks. Dry unit weight-water content curves for the compaction energies employed is shown in Fig. 4 and final dry unit weight after drying to residual water content vs initial dry unit weight after compaction with various compaction energies at optimum water content is shown in Fig. 5. On the basis of these results, the applied compaction energy per volume to reproduce ancient mudbricks was set at 45 kNm/m^3 and the initial dry unit weight after compaction with this compaction effort to 15.5 to 16.0 kN/m^3 with initial water content of 22%. All new mudbricks both in the laboratory and on site were produced following these specifications.

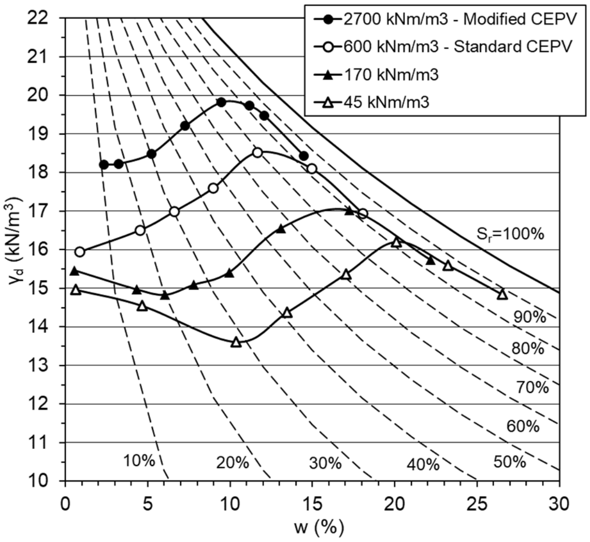

Fig. 4. Dry unit weight-water content relationships for the four compaction energy per volume values used on soil samples without hay/dried grass.

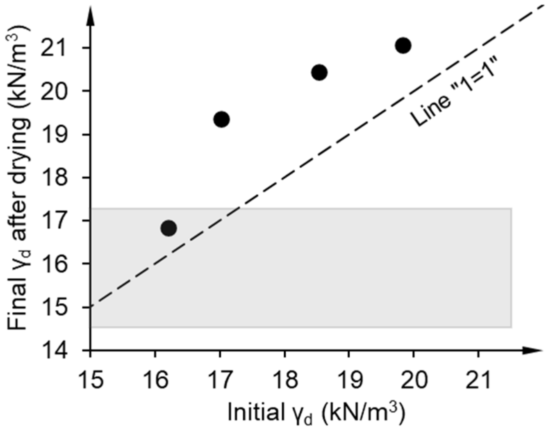

Fig. 5. Final dry unit weight after drying vs initial dry unit weight after compaction with various compaction energy per volume values. Shaded area shows range of dry unit weight of ancient mudbricks.

5 Mechanical properties of samples of ancient mudbricks

Samples from ancient mudbricks were either very small or with a shape not allowing trimming of test specimens with the right dimensions. Nevertheless, a small number of unconfined compression strength tests was performed with q_u ranging between 140 and 580 kPa with an average of 330 kPa. Modulus of elasticity from these tests varied between 18 and 50 MPa with an average of 35 MPa. A single splitting tensile strength test yielded a value of 125 kPa. Finally, a slow direct shear with previous consolidation was performed on two test specimens with their field water content without addition of water in the device cells yielding a failure envelope described by c=40 kPa and φ=65°. Suction of these was measured on the trimmings of the test specimens using a METER Environmental WP4C chilled mirror hygrometer and was found to range between 110 and 120 MPa. Overall, in all samples from ancient mudbricks, suction measured using the same device ranged between 50 and 130 MPa. Given the index properties of the soil material from the ancient mudbricks, these values of suction position the samples on Fig. 2 well into the residual degree of saturation range and on Fig. 3 on water content values well below point B on the graphs. It is also probable that these very high values of suction affected the value of the angle of shearing resistance obtained along with the low applied vertical stresses during the test (low enough to replicate expected vertical stresses in the actual walls -only 6m maximum height). A combination of low vertical stress (keeping the soil in the range where the failure envelope is non-linear with a higher angle of shearing resistance) and very high suction leading to the formation of aggregations of soil particles considerably larger than the actual soil particles contained in the soil is likely to have led to this high value.

6 Properties of newly prepared samples

The soil material to be used for the construction of new mudbricks was found as the top layer down to 0.6m within the archaeological site at the specific locations of archaeological excavation. Cylindrical samples were formed to measure unconfined compression strength and splitting tensile strength for various contents of dried grass. Dried grass came from the same area of the archaeological site and was added air-dried in the dry soil before adding water. Dried grass was scissored to lengths of 5-6cm maximum and dried stem diameters ranged between and 0.05 and 3.51mm. Unconfined compressive strength from 200mm high/100mm diameter cylinders vs dried grass content is shown in Fig. 6.

For 0% dried grass, samples were prepared inside plastic tubes stuck on the porous plate of a pressure extractor. Pairs of samples were used, with one sample having a height over diameter (h:d) ratio of 2 and one sample having an h:d ratio of 1, so that both the unconfined compressive strength and the splitting tensile strength could be measured for various values of suction until the suction in equilibrium with atmospheric conditions is achieved in mudbricks. The pressure extractor can apply up to 1500 kPa of suction. After this value of suction pairs of samples were placed in saturated salt solutions chambers to achieve higher values of suction. Another pair was also left in the atmospheric conditions of the interior of the laboratory. Measuring water content for each suction and total volume of samples using immersion in paraffin wax and subsequent weighing of waxed samples in water allowed determination of the full soil-water characteristic curve, shown in Fig. 7. Unconfined compressive strength and splitting tensile strength vs suction are shown in Fig. 8. Combining Mohr's circles from Unconfined compressive strength tests and splitting tensile strength tests as shown in Fig. 9 (for suction = 200 kPa) [11] allowed the estimation of apparent cohesion evolution with suction and the value of φ_b of the generalised Mohr-Coulomb strength criterion for unsaturated soils [11, 12] (Fig. 10).

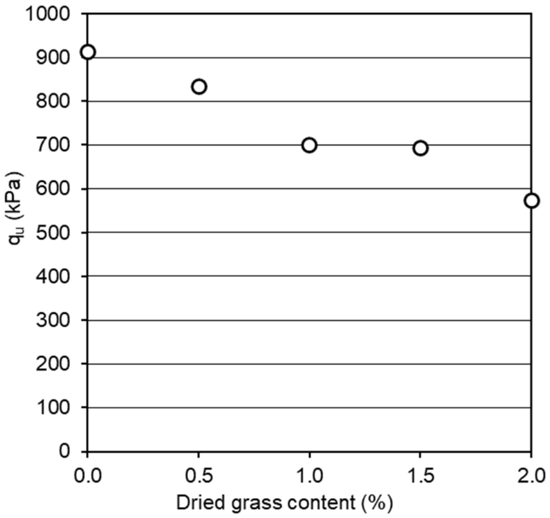

Fig. 6. Unconfined compression strength measured on 200mm high cylindrical samples of 100mm diameter with dried grass content.

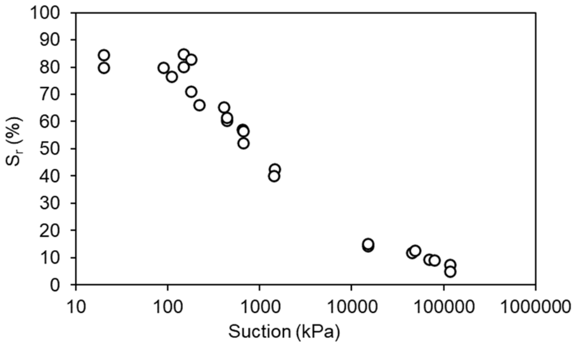

Fig. 7. Degree of saturation vs suction.

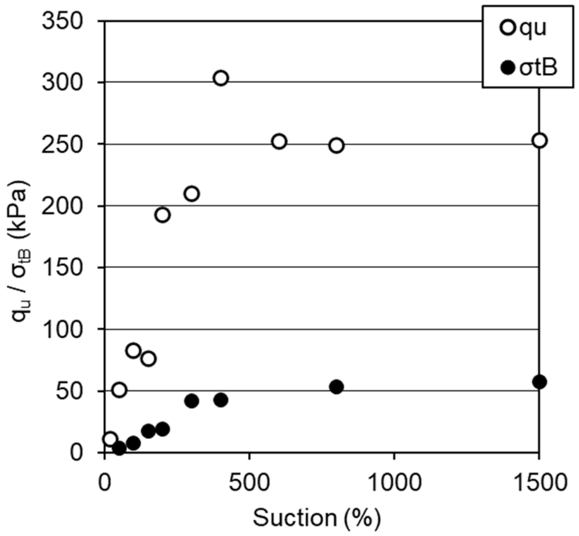

Fig. 8. Unconfined compression and splitting tensile strength vs suction for 0% dried grass.

7 Conclusions

Samples of ancient mudbricks from the walls of Eleusis were tested under various conditions allowed by the

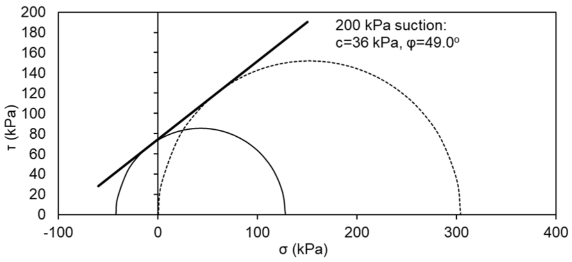

Fig. 9. Combining unconfined compression and splitting tensile strength for suction 200 kPa and 0% dried grass to estimate cohesion intercept and angle of shearing resistance for this suction.

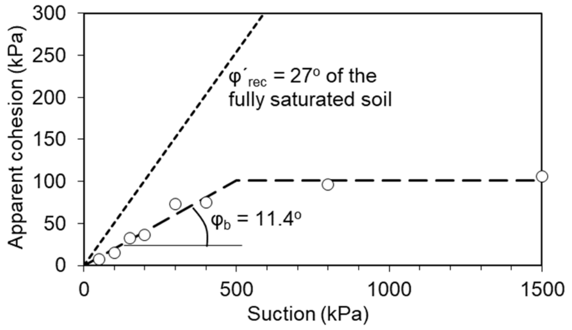

Fig. 10. Apparent cohesion vs suction.

shape and size of the samples. Soil mechanics index properties indicated that the material is a sandy silt to silty sand of low plasticity and the mineralogical analysis indicated that the fines of the soils material are predominantly silica with calcitic minerals, a small amount of feldspar and traces of clay minerals. The state properties of the samples indicated that they were dried to the residual degree of saturation corresponding to the soil and the atmospheric conditions of the site. Soil from the same archaeological site was found to have practically the same index properties and mineralogical composition and was used to investigate the effect of compaction energy per volume, dried grass content and suction during drying so as to reproduce appropriate newly constructed as part of a restoration project under way. A very low compaction energy per volume value of only 45 kNm/m^3 was found appropriate so that samples of the same dry unit weight after drying to residual degree of saturation conditions are produced and a dried grass content of 0.5% per dry weight of soil is appropriate to ensure sufficient tensile strength at early stages of drying and sufficient compressive strength after drying to residual degree of saturation conditions. This part of the investigation was supported by suction and volumetric water content monitoring in newly constructed mudbrick and small mudbrick walls presented elsewhere [13].

8 Acknowledgements

All work presented herein was performed by EDAFOS Engineering Consultants S.A. under contract by the Directorate for the Restoration of Ancient Monuments of the Hellenic Ministry of Culture. All tests presented in the paper were performed in the Soil Mechanics Laboratory of EDAFOS Engineering Consultants S.A. with assistance from the laboratory technicians, Mr Marios Tsoukaladakis and Mr Nikos Kalantzis and Mr Harry Vagenas and Mr Marios Genias (both formerly of EDAFOS), Ms Sofia Grifiza, Ms Ioanna Panagiotopoulou and Ms Marina Kammenidou, Geologists, Ms Marianna Feuillas, Mining Engineer-Metallurgist, and Mr D. Kokoviadis, Civil Engineer, of EDAFOS S.A.. Only exception was XRD tests performed by Dr I. Baziotis of the Agricultural University of Athens, Greece.

9 References

1. P. Jaquin, C. Augarde, Earth Building – History, science and conservation (HIS BRE Press, Bracknell, 2012)
2. D. Gallipoli, A. W. Bruno, C. Perlot, J. Mendes. Acta Geotech. **12**, 463–478 (2017). https://doi.org/10.1007/s11440-016-0521-1
3. P. A. Jaquin, C. E. Augarde, D. Gallipoli, D. G. Toll. Geotechnique **59**, No. 5, 487–490 [doi: 10.1680/geot.2007.00129]
4. M. E. Bardanis, M. J. Kavvadas, in proc. of the 4th Intnl Conf. on Unsaturated Soils, April 2-6, 2006, Carefree, Arizona, United States, https://doi.org/10.1061/40802(189)88
5. M. E. Bardanis, M. J. Kavvadas, Unsaturated Soils: Advances in Geo-Engineering, Toll et al. (eds), Proc. 1st Eur. Conf. on Unsaturated Soils, Durham, UK, 2-4 July, 2008, pp. 381-387.
6. A. K. Orlandos, The Building Materials and Architectural Techniques of the Ancient Greeks, as evidenced by the Authors, the Inscriptions and the Monuments (in two vols) 1955-1958, 2nd ed. in one vol. 1994, ISBN 960-7036-37-9.
7. Thomson, W., 1871, Philosophical Magazine, **42**, pp. 448.
8. D. G. Fredlund, H. Rahardjo, Soil mechanics for unsaturated soils (John Wiley & Sons, New York, N.Y., 517 pp, 1993)
9. ASTM (2020). ASTM D698-12: Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft3 (600 kN-m/m3)). West Conshohocken, PA, USA: ASTM International.
10. ASTM (2020). ASTM D1557-12: Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)). West Conshohocken, PA, USA: ASTM International.
11. M. Bardanis, S. Grifiza, Proc. 3rd Eur. Conf. on Unsaturated Soils, Paris, France, 12-14 September, 2016, DOI: 10.1051/e3sconf/20160909007.
12. D. G. Fredlund, N. R. Morgenstern, R. A. Widger, 1978, Can. Geot. J., Vol. 15, pp. 313-321
13. M. Bardanis, Th. Marinis, E.-E. Toubakari, G. Dounias, Reproduction and long-term monitoring of drying of mudbricks and small mudbrick walls for the preservation of the ancient mudbrick wall of Eleusis, in proc. of the 8th Intnl Conf. on Unsaturated Soils, May 2-6, 2023, Milos, Greece.