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Reproduction and long-term monitoring of drying of mudbricks and small mudbrick walls for the preservation of the ancient mudbrick wall of Eleusis

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Abstract. The mudbrick wall remains preserved to date in the site of Eleusis are some of the largest preserved in Greece. Following an extensive investigation of the properties of existing mudbricks, material of similar properties from the archaeological site of Eleusis was used to reproduce mudbricks of similar density with the ancient ones after drying with various concentrations of dry grass also from the archaeological site. Actual mudbricks were reproduced and brought to a final equilibrium condition under climatic conditions practically similar to those in Eleusis. Others were used to trim samples and measure mechanical properties to compare with original mudbricks, others were instrumented with suction and volumetric water content sensors in order to monitor mudbrick drying under climatic conditions and others in order to build small mudbrick walls with mortar from the same soil used to make the mudbricks. These small mudbrick walls included the mudbricks with internally installed suction and volumetric water content sensors and were also constructed with similar sensors in the mortar. This allowed monitoring of drying of the mortar until each whole mudbrick wall came to equilibrium and was then subjected to uniaxial compression under load control. Monitoring of mudbricks and mudbrick walls indicated that the higher the dry grass concentration, the higher the drying rate of the mudbricks; the lower the dry grass concentration the higher the probability of mudbrick cracking during drying; minimum required time for mudbrick and mudbrick wall drying for the particular soil used in the ancient mudbricks is not less than 5 weeks. Finally, uniaxial compression under load control on both samples trimmed from dried mudbricks and mudbrick walls indicated that uniaxial compression strength decreases with increasing dry grass concentration and mudbrick wall strength should be expected in the order of 70-80% that of the cubic samples trimmed from dried mudbricks and subjected to load rate control compression.

1 Introduction

Earthen materials construction is probably the most common application of unsaturated soil mechanics principles with the twist that it has been empirically practiced since prehistoric times [1]. 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]. As part of this, an experimental investigation of samples from the Mudbrick Walls in the Eleusis Sanctuary was undertaken with the purpose to support conservation of this largely unique ancient monument. Results of the mechanical and hydraulic behaviour of samples from ancient mudbricks and newly constructed ones has been reported [3]. Particular points of interest were the compaction energy per volume, the dry grass content 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. This paper focuses on the presentation of the experience from building new mudbricks with various dry grass contents, small walls built out of them, monitoring of suction and volumetric water content inside them and the loading tests performed on the actual small walls built and specimens trimmed from mudbricks.

2 Mudbricks' reproduction and instrumentation

Using soil material from the archaeological site of Eleusis, already investigated and found practically with the same physical and mineralogical properties of the soil of the ancient mudbricks [3], whole-size mudbricks

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(44×44×9cm) and half-size (22×44×9cm) were constructed by compacting in wooden moulds. The soil material used is a sandy silt to silty sand of low plasticity [3] Compaction energy per volume (CEPV) used was 45 kNm/m^3 as found by an extensive experimental problem investigating physical and compaction characteristics of the soil material [3]. Initial water content was 22% and three different dry grass contents were tested: 0, 0.5 and 1.0%. Dry 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.

To obtain better understanding of the behaviour of mudbricks and especially the time that their drying is completed in the atmospheric conditions of the environment outside the laboratory where they were kept (protected from rain and direct sunlight but fully exposed to atmospheric temperature and relative humidity), one of three whole-size mudbricks per dry grass content tested, were instrumented with sensors measuring suction and volumetric water content. Temperature and relative humidity of the atmosphere was also monitored. All sensors were connected to an automatic logger set to take readings every 15 min. Sensors used were (numbering compatible with Fig. 1):

1. METER TEROS12 volumetric water content sensor
2. METER TEROS21 suction porous block sensor
3. METER ATMOS14 temperature and relative humidity sensor in its
4. radiation shield
5. METER ZL6 data logger.

In 0% and 1.0% dry grass content mudbricks, one suction and one volumetric water content sensor were installed in the middle of the mudbrick. One layer was first compacted to mid-height of the mudbrick using a falling weight compactor with a pad surface area, moving weight and weight lifting height achieving the compaction energy per volume of 45 kNm/m^3. Once the first layer was prepared, the sensors were pushed in and then the second layer was built to complete the mudbrick. Sensor cables were directed to the middle of the side of the wooden mould and stabilised there in order to avoid the possibility of accidental removal of sensors destroying the mudbricks. The instrumented 0.5% mudbrick had only a suction measurement sensor so that one channel of the 6 channels of the one logger available would remain available for the temperature/relative humidity sensor. Once all mudbricks were built, they were exposed to the atmospheric conditions outside of the laboratory in central Athens (Fig. 1a). They were protected from direct sunlight and rainfall. Half-size mudbricks were built in the same way (shown in Fig. 1b after completion of drying and before used to build the mudbrick walls).

3 Mudbricks' monitoring

Once mudbricks were constructed, their monitoring started. Suction evolution with time is shown in Fig. 3a, volumetric water content evolution with time is shown in Fig. 3b, and temperature and relative humidity evolution of the atmoshpere drying was taking place in is shown in Fig. 3c. A detail of the suction evolution with time at the beginning of drying until stabilisation was first observed is shown in Fig. 4. As drying starts, suction increases rapidly (Fig. 3a) and with a rate initially observed analogous to the dry grass content (Fig. 4) indicating that the higher the dry grass content, the higher the rate of drying. This seems to become less clear as suction values increase above 300 kPa

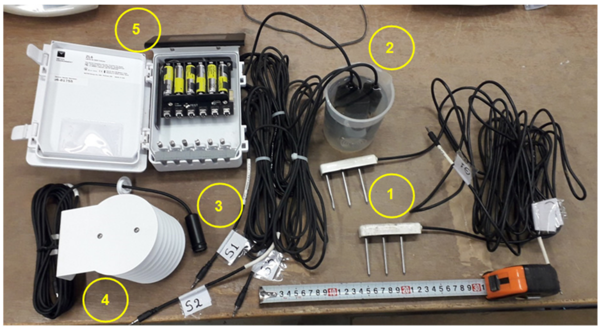

Fig. 1. Sensors installed in the mudbricks and mudbrick walls along with the logger used (explanation according to numbers in the text).

Fig. 2. a) Whole mudbricks positioned in atmospheric conditions for drying (arrows denoting mudbricks with sensors installed -pointing to sensor cables coming out of the samples), and b) half-size mudbricks.

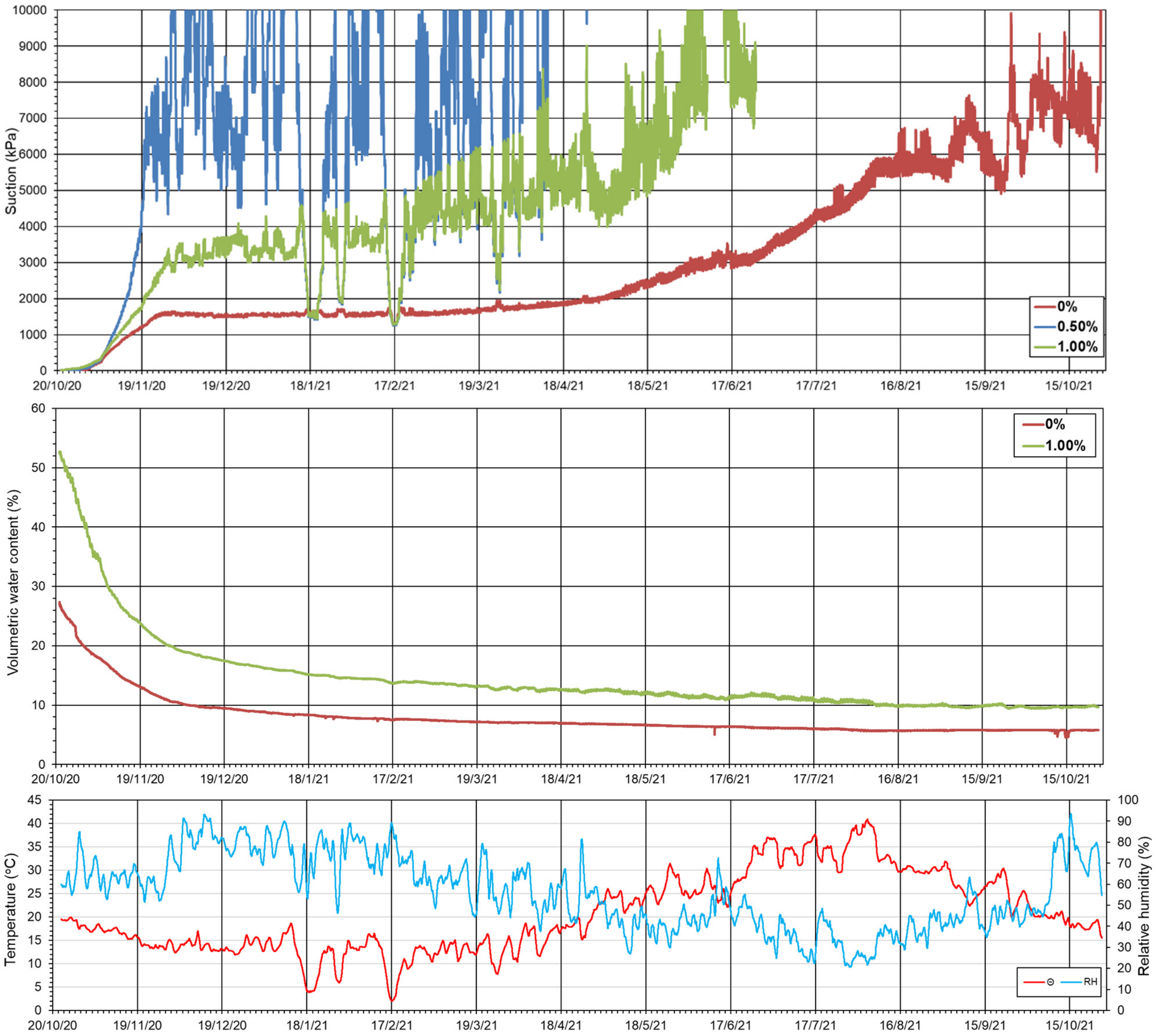

Fig. 3. a) Suction evolution with time, b) volumetric water content evolution with time, and c) temperature and relative humidity with time during drying of instrumented mudbricks.

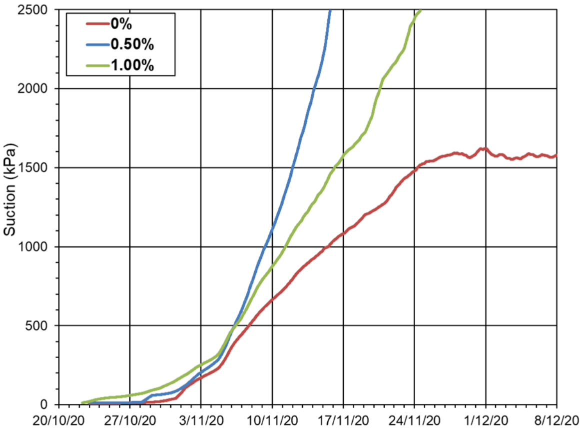

Fig. 4. Suction evolution with time in mudbricks for the first 7 weeks of their dying.

(2.5 weeks of drying in Fig. 3a and Fig 4) probably because the dry grass seems to affect the actual measurement of the sensors. It is noted that suction was corrected for temperature according to published correction equations [4]. Observations on suction development rate led to a better study of the distribution of dry grass diameters on a representative mass of the dry grass used which is shown in Fig. 5. Most dry grass has stems of diameters that would allow air to flow freely inside the samples, serving as a conduit of air with practically similar relative humidity with that of the

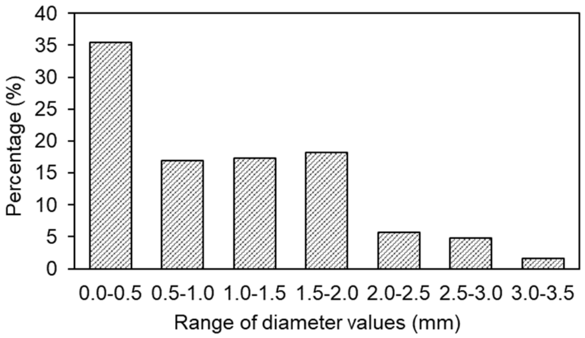

Fig. 5. Distribution of range of diameter values of dry grass stems used in the construction of the mudbricks and samples.

atmospheric air in which mudbricks dried. At the same time however, this flow introduces also micro-fluctuations causing the suction sensors to start having very large scatter in their measurements (something which is not observed in the mudbrick with no dry grass as shown in Fig. 3a). On top of this, dry grass also seems to offer additional tensile strength at the early stages of drying. No mudbrick with dry grass exhibited cracking during its drying, contrary to all three mudbricks with no dry grass that cracked. Cracking initiated at the end of the first week of drying. Finally, irrespective of the dry grass content in the mudbricks and scatter of suction measured in mudbricks with dry grass, suction stabilised after 5 weeks of drying. This should by no means be considered a generally applicable value and should be expected to be a function of soil material, atmospheric conditions, dry grass type and stem diameter and size of mudbricks.

4 Tests on specimens trimmed from mudbricks

One mudbrick out of each three prepared with different dry grass content were sawcut to create sets of specimens to be tested in compression under various methods of loading. Given that the loading of actual small mudbrick walls would be load-rate controlled, specimens were loaded to failure in compression with three methods: i) load-rate control compression on cubic specimens (the most directly comparable compression method to the compression of the small mudbrick walls), ii) displacement-rate control on cubic specimens (a popular loading method in soil mechanics to compare with the previous set of tests popular in material science), and iii) displacement-rate control on cylindrical specimens (a loading method on geometric proportions of samples relevant to actual soil mechanics investigation of the mechanical properties of the soil material used in the mudbricks studied [3]). The results from these tests are summarised in Fig. 6, where they are also compared to unconfined compression strength from displacement-rate controlled tests on cylinders of 200mm height and 100mm diameter prepared in steel moulds with the same compaction energy per volume used and reported in [3]. Not surprisingly, load-rate controlled compression on trimmed cubes led to the highest values of compressive strength obtained, with tests from displacement-rate controlled compression on trimmed cubes leading to practically identical values of compressive strength with that obtained from displacement-rate controlled tests on cylinders of 200mm height and 100mm diameter prepared in steel moulds, and displacement-rate controlled compression on trimmed cylinders leading to the lowest measured values of compressive strength. The latter seems logical, as these samples have practically "suffered" the highest disturbance of all types of specimens prepared. All types of load application and sample geometry verified that compressive strength of mudbricks dried to residual water content decreases with dry grass content, despite the obvious effect of dry grass in increasing the tensile strength at the early stages of drying.

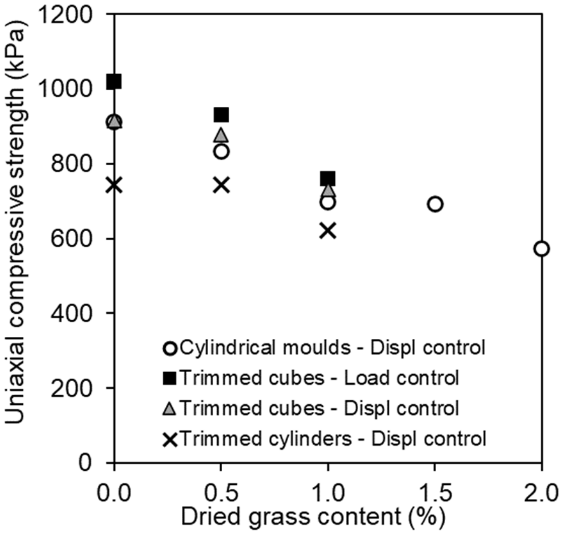

Fig. 6. Evolution of strength with dry grass content for various shapes of samples and load application methods.

5 Small mudbrick walls' construction, instrumentation, monitoring and compression

Following drying to residual water content of all mudbricks and the completion of the mudbrick drying monitoring stage, three small mudbrick walls were built; each for each of the dry grass contents used in the mudbricks: 0, 0.5, 1%. Fig. 7 goes through the procedure used to build each mudbrick wall for the 0% dry grass content mudbrick wall: a) Bottom row of half-size mudbricks placement (arrow indicating TEROS12 sensor installed in fresh soil mixture used as mortar), b) first horizontal layer of mortar just applied, c) first whole mudbrick with sensors positioned (heavily cracked in the case of 0% dry grass only, requiring d) finer fraction slurry prepared to fill cracks), leading eventually to a complete small mudbrick wall as just built (Fig. 7e). Walls would be left for their mortar to dry to constant conditions just like the mudbricks, and then subjected to load-rate controlled compression to failure (Fig. 7g). The same soil material used for the construction of the mudbricks was also used as mortar to build the walls. Irrespective of dry-grass content in the mudbricks, no dry grass was used in the mortar. Water content in the soil used for mortar was slightly increased relative to that for mudbrick construction (24%).

Once mortar dried to constant conditions as verified by the suction and volumetric water content sensors installed inside it in each mudbrick wall (in practically the same time as the mudbricks) the walls were loaded to failure. Load was increased slowly and the stress-strain curves obtained are shown in Fig. 8 along with the tangents corresponding to the modulus of deformation in the elastic region. Both compressive strength and modulus of elasticity decreased with increasing dry grass content, the former in agreement with compressive strength obtained from small-size samples (Fig. 6). Comparison between the compressive strength values from the small mudbrick walls and the compressive strength from load-rate controlled compression of cubes

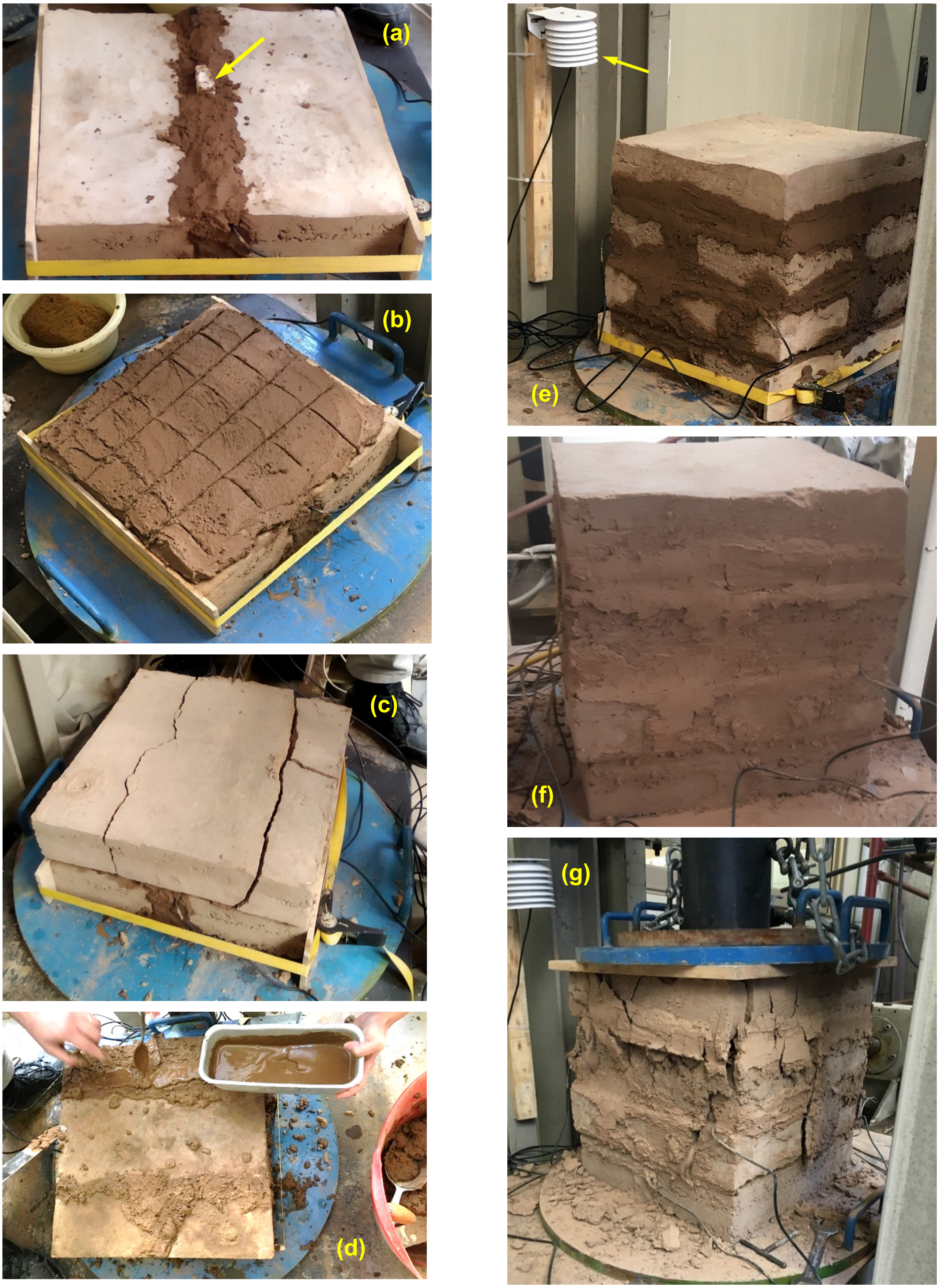

Fig. 7. a) Bottom row of half-size mudbricks for the 0% content of dry grass (arrow indicating TEROS12 sensor installed in fresh soil mixture used as mortar), b) first horizontal layer just applied, c) first whole mudbrick with sensors heavily cracked, d) finer fraction slurry prepared to fill cracks, e) small mudbrick wall just built (arrow indicating relative humidity sensor), f) the same wall after drying to constant conditions, and g) the same wall during loading close to peak strength (severe cracking already developed).

trimmed from the mudbricks is shown in Fig. 9. 20-30% smaller compressive strength of the walls compared to compressive strength from load-rate controlled compression of cubes should be expected.

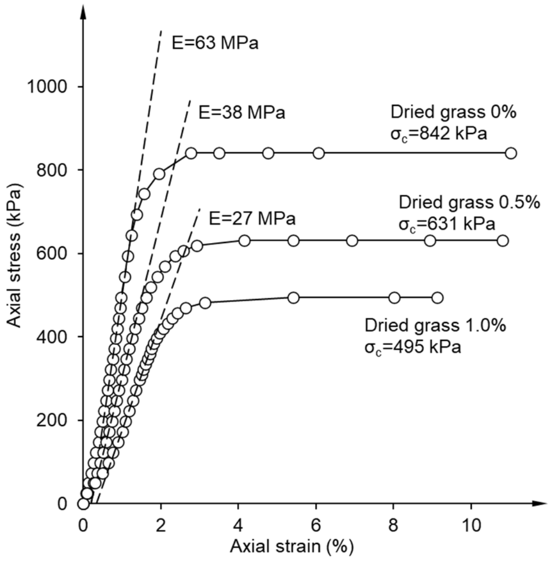

Fig. 8. Stress-strain curves obtained from load-rate controlled compression of the three mudbrick walls prepared along with the tangents corresponding to the modulus of deformation in the elastic region.

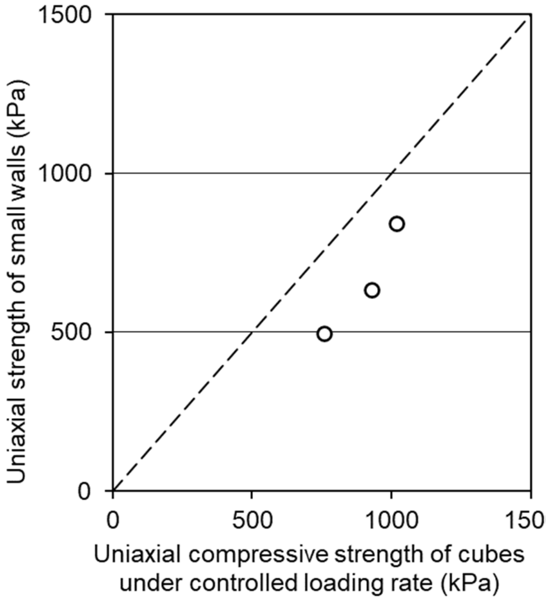

Fig. 9. Comparison between the compressive strength values from the small mudbrick walls and the compressive strength from load-rate controlled compression of cubes trimmed from the mudbricks.

6 Conclusions

Mudbricks were prepared using the compaction energy per volume and initial moisture content found in a separate experimental investigation to lead to a final dry unit weight equal to that of actual ancient mudbricks used in the Eleusis ancient mudbrick walls [3]. Three different dry grass contents were tested. One mudbrick for each dry grass content was instrumented with sensors monitoring both suction and volumetric water content. Drying to constant conditions was achieved within 5 weeks for all dry grass content but with a higher initial drying rate observed for mudbricks with dry grass and a higher final suction developed in the mudbricks. Lack of dry grass led to cracking of the mudbricks indicating that dry grass increases tensile strength at the early stages of drying. Specimens of various geometries were trimmed from one mudbrick for each dry grass content and tested under various loading methods revealing relations between the compressive strength for each loading method and sample geometry. Three small mudbrick walls were built, each with mudbricks of different dry grass content but mortar from the same soil of the mudbricks without dry grass inside it. These were also instrumented and monitored until the soil in the mortar dried to constant conditions and were then loaded to failure in compression. All compressive strengths obtained, both from specimens and the small mudbrick walls indicate that the compressive strength after drying to constant conditions decreases with increasing dry grass content. 20-30% smaller compressive strength of the walls compared to compressive strength from load-rate controlled compression of cubes should be expected.

7 Acknowledgements

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