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Mechanical investigation on adobe samples belonging to the archaeological site of Arslantepe (Malatya, Turkey)

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Abstract
Arslantepe is located in the Malatya plain, in eastern Anatolia, an oasis surrounded by the Anti-Taurus Mountains, 15 km south-west of the Euphrates River, with the sub-elliptic eruptive rock mass of GelincikTepe to the northeast, from which building materials are still extracted today. It is built on lacustrine soils, formed by layers of sand and marly clays. The site is an artificial settlement mound, approximately 30 m in height and 4 ha in size. It was occupied without major interruptions from at least the fifth millennium B.C. to the Middle Age. This paper presents the results of an experimental analysis carried out in order to evaluate the mechanical properties of different types of adobe bricks extracted both from residential and monumental buildings. The tested adobe samples belong to a chronological period that ranges from the beginning of the fourth millennium and the end of the third millennium B.C. and they provide an initial understanding on the characterization of a constructive culture at the beginning of human civilization. The investigation permitted to establish a relationship among the mechanical and physical properties of the samples, the type of building that they belong and the raw material used.

Keywords: Adobe, Near Eastern archaeology, Mechanical analysis

1. Introduction
Since ancient times, people all over the world have used earth as their main building material. Earthen architecture is characterized by a very rich and varied architectural production, ranging from archaeological sites to living monuments and from groups of buildings to historic towns and cultural landscapes. Nevertheless, there is little information on the wealth of expertise that allowed the ancient builders to achieve such magnificence in the design of earthen architecture(Avrami and Guillaud, 2008).
Up to date, there is a distinct lack of formal technical guidance concerning the laboratory testing of adobes. Unfired earth is excludedfrom the clauses of internationally used standards referring to masonry materials. Standardized testing methods for evaluatingthe unconfined compressive strength of cohesive soils do exist but they examine earthen materials from the scope ofgeomechanics, rather than in the context of common building applications(ASTM International, 2006). Useful guidelines can be found in national directive documents developed by certain individual countries and states(Standards Australia Handbook 194, 2002; New Zealand Standard 4298, 1998; Houben, 2005; Morel, 2002; Briccoli, et al., 2008; Illampas et al., 2014). Nonethelessdue to the heterogeneity of earthen materials, the variations in shape and form that occur between different areas worldwide and the different production techniques encountered in each region, their broader applicability is arguable.
This study deals with thecharacterization of the mechanical behaviour of adobe bricksat the archaeological site of Arslantepe-Malatya (Turkey). In recent years, chemical and physical analyses were carried out on Arslantepe's building materials (Liberotti et al., 2011; Liberotti and Quaresima, 2012). The interdisciplinary approach integrating archaeological investigation with laboratory tests on adobe bricks aims at opening a new perspective into the dynamic analysis of ancient architecture. Some experimental analyses were performed at the Structures

and Materials TestingLaboratory of the University of Florence (Department of Architecture)[1]to evaluate the mechanical properties of different types of adobe. These experimental analyses are part of a wider research focused on traditional construction materials based on the experience acquired and validated in various constructive contexts (Briccoli et al., 2008; Rovero et al., 2009; Rovero and Fratini, 2013; Sani et al., 2012; Rovero and Tonietti, 2012; Fratini et al., 2011; Gamrani et al., 2012; Rovero and Tonietti, 2014).
The extensive excavation carried out since 1961 by the Italian Archaeological Excavation in Eastern Anatolia[2] allowed identifying, by means of diachronic reading, the changes occurring in the localization, type, function and use of internal and external spaces (Frangipane, 2004). Thus, it was possible to perform a diachronicanalysis on earthen walls, taking into consideration buildings dated from the beginning of the fourth millennium to the end of the third millennium B.C.The accuracyandthe large amount ofdataprovidedby thearchaeologicalexcavationfor such a long sequence allowed havinga detailed ontextin which to placethe results of laboratory analysis.

1.1. Historical and geomorphological context
Arslantepe is located at the south-eastern edge of the plain of Malatya, in eastern Turkey, about 15 km south of the Euphrates River (Figure 1). The plain is bordered to the east by the Euphrates valley and to the south by the Taurus Mountains. Its altitude varies between 700 m and 1100 m above the sea level. Lying in a vast tectonic depression (60 km in length and 30 km in width) with southwest-northeast direction, annual temperatures are lower than those of its surroundings are. Given the lack of local rainfall and high summer temperatures, the vegetation is steppe-like, but the water from the mountains allows the formation of a fertile oasis.

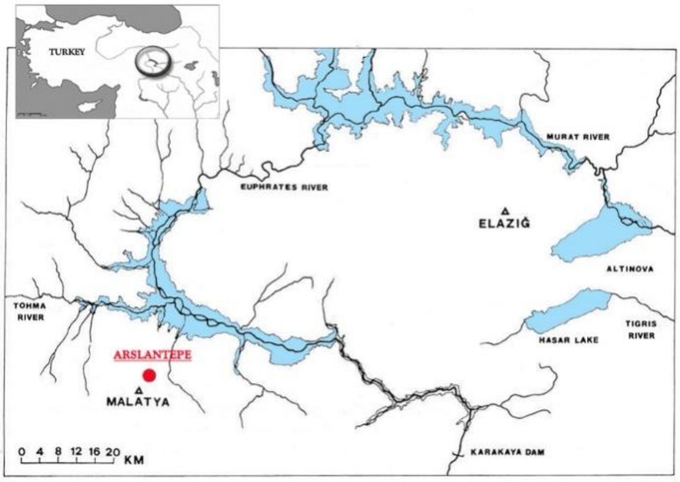

Figure 1: Location of Arslantepe in Eastern Anatolia (after Conti and Persiani, 1993)

The region of Malatya is rich in rivers, some of considerable length, all converging into the Euphrates. A hydrogeological study conducted by a team of geologists in collaboration with the Italian Expedition of Eastern Anatolia (Palmieri and Marcolongo, 1983) has highlighted numerous natural springs, which exploit the conspicuous karst spring waters of the tributaries of the Euphrates river about 200 metersaway from Arslantepe (fig.2).
According to this study, the easternmost area of the plain of Malatya is crossed by an underground stream flowing mainly in the northwest, which would explain the high moisture content of the soil and the numerous water sources. These exceptional hydrogeological characteristics create favourable conditions for spontaneous irrigation even in dry periods, making the area an ideal agricultural region. Northwest of Malatya is a mountainous area, made of marbled limestone and basalt. To the south and south-west a large area consisting of Palaeozoic soils constitutes the Malatya Daglari, marbled limestone, gneissic rocks, schistand volcanic rocks, all affected by severe erosion. Immediately south of Malatya and for a long stretch to the east and northeast is the Eocene flyschoid facies with limestone and clay. The Malatya plain, triangular in shape, sets in a Sarmatian depression.

[1] Henceforth, the laboratory will be named as LPMS.
[2] Prof. Marcella Frangipane is directing the Italian Archaeological Expedition in Eastern Anatolia on behalf of the Sapienza University of Rome, Italy: www.uniroma1.it/arslantepe/

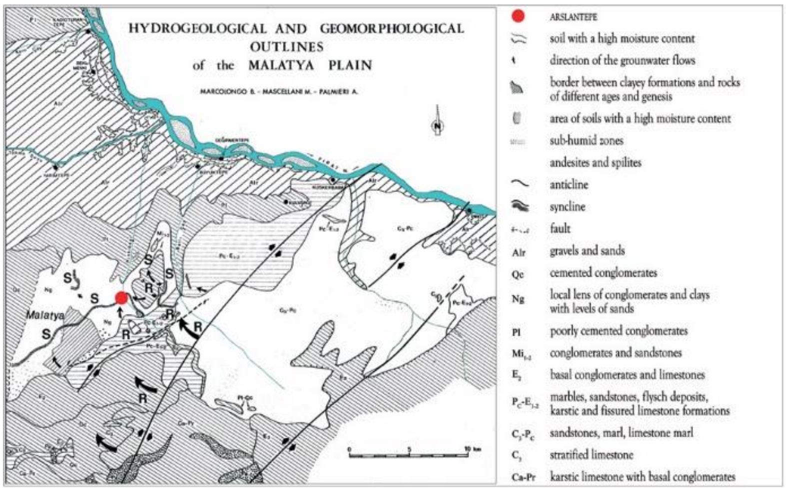

Figure 2: Hydrogeological and geomorphological features of Malatya plain (after Marcolongo et al., 1978)

Arslantepe rests on lacustrine soils, constituted by layers of sand and marly clays (Figure 3). To the northeast the sub-elliptic shaped Gelincik Tepe emerges, an eruptive rockmass (andesite, spilite and trachyte) fromwhich building materials have been extracted (Palmieri, 1978). The earliestsettlement levels reached so-far date tothe Late Chalcolithic, periods VIII (4200-3800 B.C.), VII (3800-3350 B.C.) and VI A (3350-3000 B.C.) of the site sequence.Finds from these periods have shed newlight on the origin of cities and on theprocess of State formation, as monumental mud-brick buildings become known on the western side of the mound. In particular, the ones dated to period VI Ahave demonstrated the key role of Arslantepe in the early state organizations. Arslantepe was in fact one of the main proto-state centres at the end of the fourth millennium B.C., and one of the poles of “urbanization” in the north-Mesopotamian region (Frangipane, 1993). At the beginning of the Early Bronze I (period VI B, 3000-2800 B.C.) the palatial organization system was violently interrupted by nomadic groups who established permanently on the territory by building wooden huts and small rectangular rooms (Frangipane et al., 2005). During the Early Bronze II (period VI C, 2800-2500 B.C.), archaeologists unearthed a series of wooden structures and mud brick houses surrounded by several storage pits and round activity areas, the positions of which shifted repeatedly with time (Persiani, 2008).In the subsequent period VI D (Early Bronze III, 2500-2000 B.C.), the settlement got larger, including separated buildings consisting of rectangular rooms with open courtyards.


Figure 3: Arslantepe as seen from above. Google © 2009

1.2. Outlines of seismicity in the Malatya plain
The Malatya plain is located in the Anatolian Plate, near the east edge delineated by seismically-active fault system EAFZ (East Anatolian Fault Zone) and a few kilometres to the west of the union between the EAFZ and the seismically-active fault system NAFZ (North Anatolian Fault Zone).

The EAFZ is an active left-lateral strike slip fault forming the boundary between the Anatolian Block to the northwest and the Arabian - African plates to the southeast. The EAFZ is approximately 650 km long in the NE-SW direction and 1-30 km wide. Major recent earthquakes on the EAFZ are: 1905 Malatya (M = 6.8), 1971 Bingöl (M = 5.9) and 1975 Lice (M = 6.6). Historical data suggest that this area was very active during the past 2000 years and certainly also in the previous millennia (Bulut et al 2012; Barka 1988).

2. Adobe samples

Adobe bricks were sampled from walls pertaining to different chronological periods (Table 1).

Table 1: List of samples. Identification, collocation, chronology, reference building.

Sample	*Adobe*	*Location*	*Absolute chronology*	*Site sequence*	*Typology of building*
1	A9	A950	3800-3350 B.C.	Period VII	temple C
2	A5	A950	3800-3350 B.C.	Period VII	temple C
3	A7	A582	3800-3350 B.C.	Period VII	elitist residence
4a	A4	A946	3350-3000 B.C.	Period VI A	palace complex
4b	A4	A946	3350-3000 B.C.	Period VI A	palace complex
4c	A4	A946	3350-3000 B.C.	Period VI A	palace complex
5	A3	A209	3350-3000 B.C.	Period VI A	palace complex
6	A8	A1369	3000-2900 B.C.	Period VI B1	domestic context
7a	A2	A937	2900-2800 B.C.	Period VI B2	fortification wall
7b	A2	A937	2900-2800 B.C.	Period VI B2	fortification wall
8	A1	A529	2500-2000 B.C.	Period VI D	domestic context
9a	A6	A278	2500-2000 B.C.	Period VI D	round house
9b	A6	A278	2500-2000 B.C.	Period VI D	round house

The first three samples belong to period VII of the site sequence. Samples 1 and 2were extracted respectively at 1.30 m and 0.80 m from the floor level and come from A950, a small room of a large tripartite ceremonial buildingcalled 'Temple C' (Figure 4A). This structure measures 22 by 20 m and stands on a platform of huge stone slabs with wooden poles (Alvaro, 2010: p. 94-102). External walls of room A950 are 1.40-1.50 m thick and 1.80 m high (preserved). The mud bricks are laid with mortar on horizontal layers and are heterogeneous in size. While the width (20 cm) and height (6-7 cm) are roughly unvarying, the length does not seem to be regular, ranging between a minimum of 12 cm and a maximum of 80 cm.
Sample 3, extracted at 0.65 m from the floor level, comes from a 1.30 m thick wall in room A582made by a number of irregular rows of mud bricks (Figure 4B). These mud bricks are very irregular in morphology and size (from a minimum of 6x20x25 cm to a maximum of 8x25x97 cm), almost never blocks, and often take a sketched and deformed shape. As walls and columns are plastered and painted, this room belongs to a complex of buildings thatprobably had an important function, be it the dwelling of chiefs or high rank families (Frangipane, 1996).
Samples 4a, 4b, 4c and 5 are from the palatial complex of period VI A, whose walls range in thickness between 0.85 and 1.30 m. The layers of these walls are composed of two or more rows of mud bricks ranging in dimensions between 30x60 cm and 40x50 cm, with a thickness of 7-8 cm. Samples 4a-b-c come from A946, one of the rooms of the residential buildings excavated north of the palatial complex (Figure 4C) in a topographicallyelevatedareacompared to the restof the settlement (Alvaro, 2010:p. 45-71). Sample 5 comes from room A209 (Figure 4D), a long corridor that, at a certain time, was strongly impacted by the fire, as the dark color of the enrichment testifies. The sampled wall leans to another wall previously erected, of equal thickness.
Sample 6 belongs to a 13x15 cm (8 cm high) mud brick that was used as andiron and was found close to the heart of room A1369 (Figure 4E). This room is part of a monumental building with thick mud brick walls dating back to period VI B1. Due to large number of ceramic vessels that were found on the floor, A1369 probably served as a storage room (Frangipane, 2014).

Samples 7a and 7b come from one of the collapsed mud bricks of the only imposing construction executed in period VI B2, a5.75 m thick fortification wallwith internal buttresses, with a maximum preserved height of 2,50 m, including the stone foundations (Figure 4F). The mud bricks size of this massive wall ranges from 25-30 to 35-65 cm, with a thickness between 7 and 8 cm. Apart from its articulated structure, made by plastered niches, recesses and steps carved within the wall, it is interesting to note how the laying of the mud bricks fitted into the shape of the wall. Later on, small plastered rooms were huddled on the external sides of the wall.
Sample 8 was belongs to period VI D, which encompasses a very complex stratigraphic sequence with several building levels. However, no public or religious structures have been found so far during excavations (Persiani, 2008). Sample 8 was extracted at a height of40cmfrom the floor levelfrom the southern wall of A529, a squared room whose walls have only one row of 35x22 cm mud bricks (8 cm high), laid as stretchers with their long, narrow side exposed (Figure 4G).
Sample 9a and 9b come from A278, one of some peculiar sub-circular and semi-subterranean structures that appeared during period VI D, among the other rectangular shaped buildings (fig.4H). It is very difficult to interpret the functionof these so-called round houses, as no material was found *in situ* (Conti and Persiani, 1993). The wall is 22 cm thick and the sample was extracted at a height of50cmfrom the floor level.

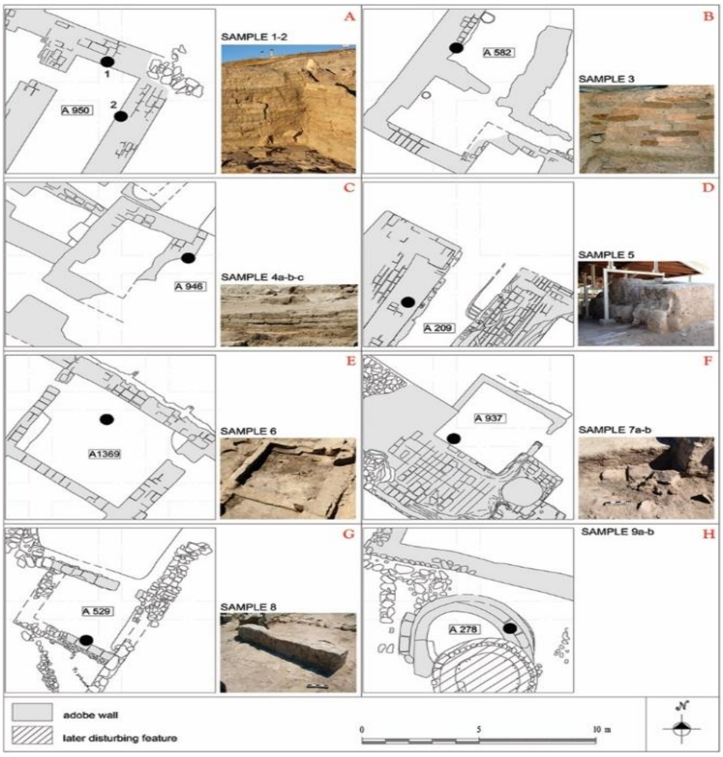

Figure4: Identification of the provenanceof the samples.

3. Mechanical investigation

For the mechanical investigation, a set of specimens representative of different existing adobe construction typologies was selected from eight different areas of Arslantepe. Within the site, it was impossible to perform destructive tests on original portion of masonry to evaluate the most significant mechanical parameters of material (compressive strength, elastic modulus, kinematic ductility and available kinematic ductility). Thus, the adobe bricks extracted from Arslantepe by the archaeologists were brought at the LPMS of Florence and they were cut to obtain cubic specimens to be subjected to compression tests (Fratini et al., 2011).

3.1. Preparation of test specimens

We decided to test samples in the laying direction of the original adobe bricks. The specimens were cut from adobe bricks in dry conditions, with an electric saw circular disc, but it was very difficult to obtain rectified cubic specimens because the most part of the adobes had a tendency to break. In fact, because of the material characteristics and the invasiveness of the procedure of cutting, a weakening of the specimens may have occurred (Figure 5).

Figure5: Some specimens after cutting

Due to the irregularity of the specimens, the effective resistant surface of cross section was obtained by the intersection between the top area and the bottom area (Figure 6).

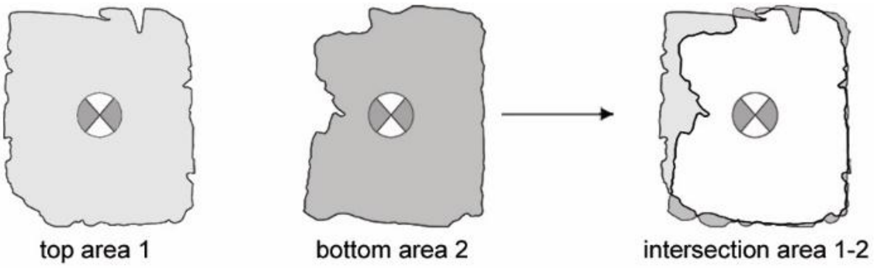

Figure6: Identification of the actual effective resistant surface in the 9a specimens.

To improve the irregularity of the surface and to allow a uniform distribution of the load during the tests, the top and bottom faces of all the specimens were levelled using abrasive sheet.

3.2. Test setup and procedure

Each specimen was placed under a hydraulic press with 50 kN loading cell able to induce graded deformation and, on the upper surface of the loading steel plate, four displacement transductors, type CE Cantilever, were positioned (Figure7-8).

Figure7: Compression test apparatus

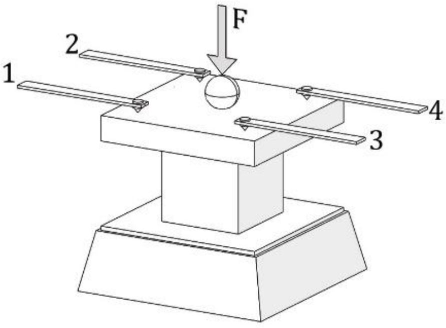

Figure8: Compression test apparatus, schema

Tests were performed in displacements control in order to record the diagram load-displacement also in the post peak phase. The results obtained during the tests were processed and for each stress-strain diagram were identified characteristics points (Figure 9): Li, starting point of the linear segment; L, end of the linear segment; M, stress peak; L', intersection between the linear branch and the ordinate corresponding to the stress peak M; U, ultimate stress conventionally equal to 60% of M.

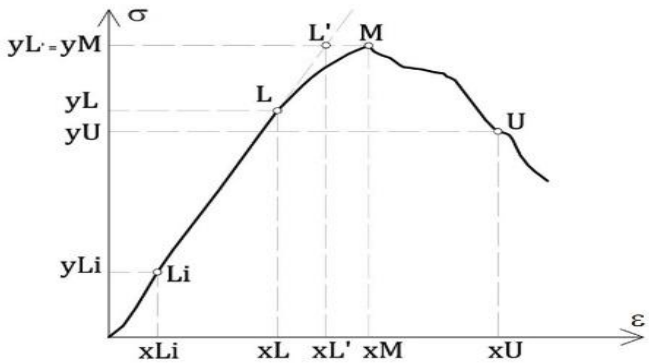

Figure9: Identification of the characteristics points in stress-strain diagram

The valuesof the following mechanical parameters were calculated by using the values of the characteristic points recorded during the tests: compressive strength σc=(ym), elastic modulus (tangent stiffness) E=(yl−yli)/(xl−xli), kinematic ductility μc=(xm/xl') and available kinematic ductility μcd=(xu/xm).
Figure10 shows the diagrams of alltested specimens, while in Figure11the diagrams of all specimens (except for 9a and 9b specimens that exhibited much greater mechanical properties) were represented.Figure 12 shows diagrams comprising specimens from period VII and VI A. The values of compression and elastic modulus were represented through histograms for an immediate comparison (Figures 13, 14).

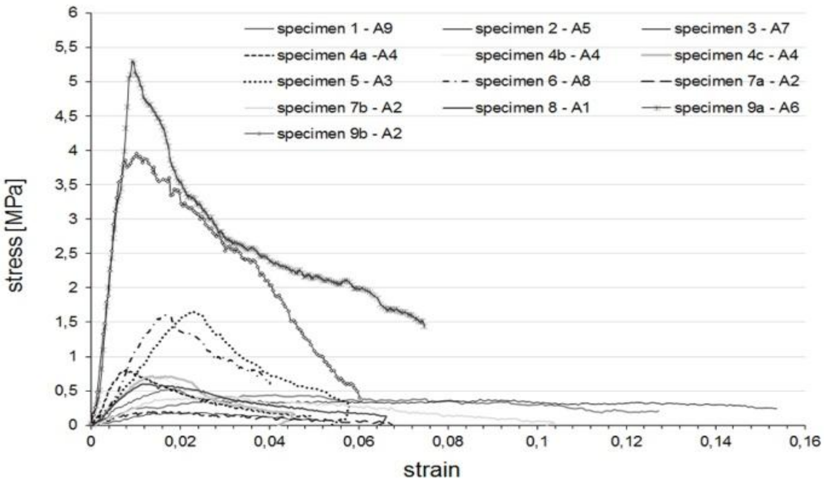

Figure10: Stress-Strain diagrams for all the tested specimens

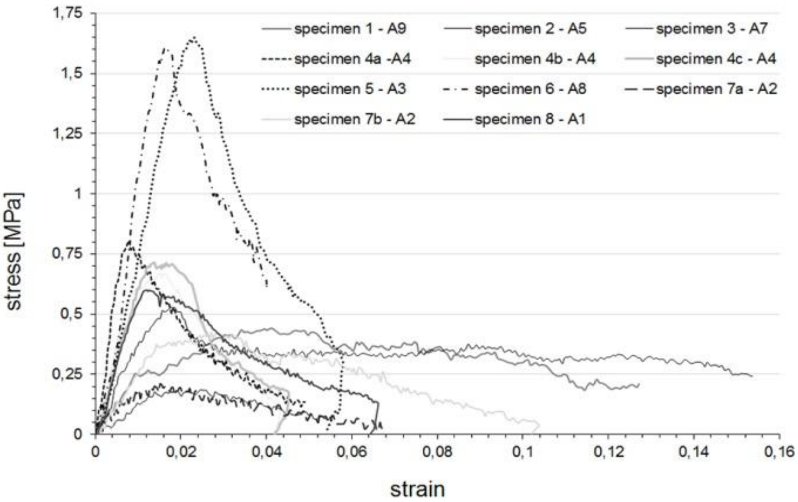

Figure 11: Stress-strain diagrams for all specimens without 9a and 9b specimens that exhibited much greater mechanical properties.

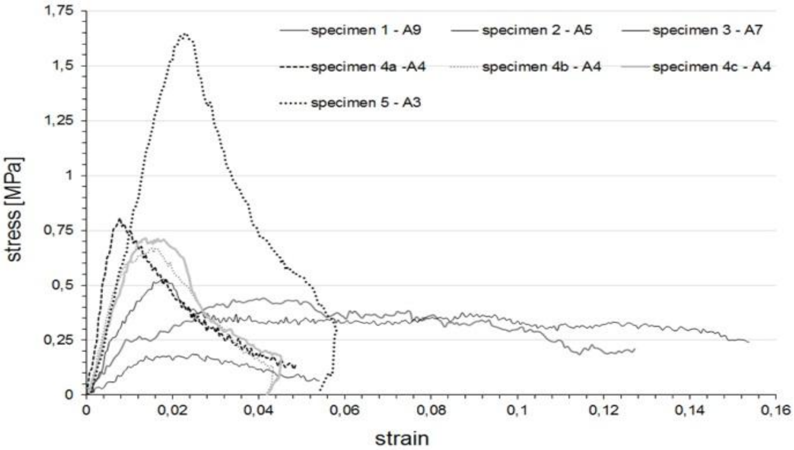

Figure 12: Stress-strain diagram of specimens ofperiod VII and VI A

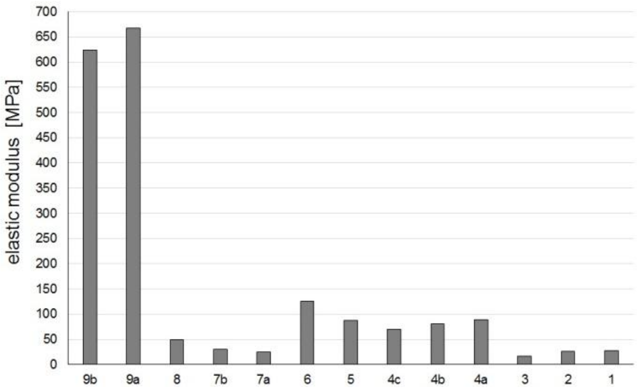

Figure 13: Elastic modulus of all specimens

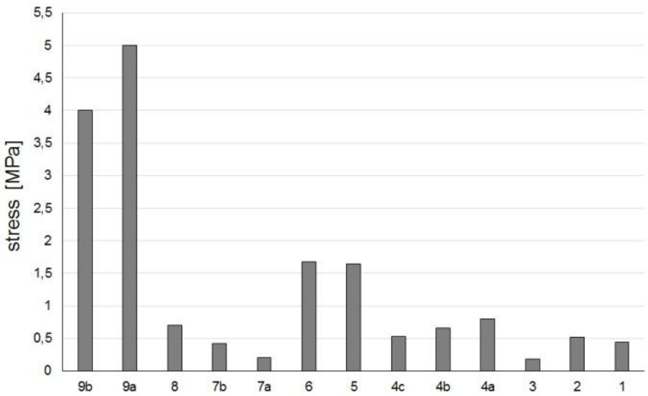

Figure 14: Compressive stress of all specimens

3.3. Mechanical analyses

For all testedspecimens, compressive failure occurredby acracking parallel to the direction of loading. Specimens exhibited a significant deformation already at maximum compressive stress, before reaching the complete rupture. The values of compressive strength ranged between 0.18 to 5 MPa. The variability of the obtained results depends on the origin and on the implementation period of the samples but it reflects anywaytheusual inherent heterogeneity of the material and the randomness of natural earth materials that can lead to an uncertain mechanical behaviour.The results are summarized in Table 2.

4. Results and discussion

As stated before, samples 1 (A9) and 2 (A5) come from a monumental building, Temple C (period VII),that shows a complexity in the building materials chosen as well as in the construction techniques adopted. The excellent deformation capacity detected by the mechanical test, as well as the high value of compressive strength, could suggest that the manufacturing process of the adobe bricks, laid in coherent layers, involved aspecial care over the anti-seismic aspect of the building system.

Sample 3 (A7) is part of the same context of technological and constructive experimentation above described. Given the irregular shape of the sampled adobe bricks, despite the supposed elitist use of this room, the production process does not seem to be very accurate. From a mechanical point of view, the low elastic modulus and strength values show poor resistance to compression, although the good deformation capacity may indicate the intention to support the anti-seismic properties of the earthen construction system.

Samples 4a-b-c (A4) and 5 (A3) are from the palatial complex of period VI A. The former exhibits inferior mechanical characteristics compared to the latter, but the quality of the load-displacement diagram is perfectly comparable. They all showed a coherent response to compression and gave no dispersion. The difference in the mechanical behaviour may be due to the function of the rooms from where they were extracted: samples 4a, 4b and 4c come from a house; sample 5 comes from the hallway of a monumental complex, with greater load bearing capacity.

Table 2: Physical and mechanical properties of the tested specimens

Specimen	*Adobe*	*Cross section [mm²]*	*Compressive strength [MPa]*	*Elastic modulus [MPa]*	*Kinematic ductility [μc]*	*Available kinematic ductility [μcd]*	*Weight [g]*	*Density [Kg/m³]*
1	A9	2133	0.44	27.46	2.55	6.62	292.64	2208
2	A5	2094	0.52	26.47	1.88	10.94	184.52	1757
3	A7	1854	0.18	16.65	1.88	3.24	265.84	2464
4a	A4	1970	0,80	88.44	0.87	2.17	175.01	1615
4b	A4	2741	0.66	80.65	1.84	3.08	357.10	2101
4c	A4	2479	0.53	69.58	1.34	2.90	308.20	1750
5	A3	1933	1.64	87.31	1.15	1.69	209.80	2040
6	A8	1655	1.68	125.53	0.65	1.13	233.06	2235
7a	A2	1746	0.21	24.40	1.69	3.20	193.35	1579
7b	A2	1409	0.42	30.62	1.79	4.15	204.08	2896
8	A1	2084	0.7	50.01	0.98	2.66	275.60	2128
9a	A6	2100	5.0	666.78	1.02	2.72	194.70	1490
9b	A6	1776	4.0	623.44	1.46	5.17	186.47	1499

Sample 6 (A8) is very similar to sample 5 from the mechanical point of view: they show both high strength and stiffness. However, sample 5 belongs to a palatial complex where the construction technique is refined; sample 6 may have been reused as andiron. Both were exposed to fire, although they are not fired.
Samples 7a and 7b (A2) were extracted from a massive masonry that does not require highstructural performance, and then the adobe bricks did not need a very accurate manufacturing. The load-bearing diagram shows low resistance, low stiffness and weak reserve of resistanceafter the peak of strength.
Sample 8 (A1) shows good resistance values. It was taken from a domestic structure of period VI D, when the architectural clusters of the settlement become compact and well-defined, with streets, squares and drainage systems. Research on period VI D distribution and function of spaces is still in progress, but it is appropriate to state here that, as the architectural typologies and the material culture are now strongly consolidating, the mechanical values detected by sample 8 should be taken as reference value.
Samples 9a and 9b (A6) come from the same settlement of period VI D, but they show unexpectedvalues of compressive strength and elastic modulus, something different from any other construction of that period, exceeding even the average of the contemporary adobe bricks. It is noteworthy that a clear archaeological interpretation concerning the function of the round structure from which the samples were extracted still lacks. This opens an even more interesting perspective about future investigations.

Conclusion

The work shows the results of an interdisciplinary research where archeologists and architects cooperated. The aim of the investigation deals with the possibility to carry out an initial understanding of the constructive culture at the beginning of human civilization. In such perspective, the synergy between different research fields may offer great opportunities through the integration and strengthening of viewpoints and methods of analysis.The characterization of materials, connected to the conditions of arrangements in constantly changing settlements, sheds light on the first steps of a technical culture by which the evolution of human thinking can be easily approached. The occurrence of sedentary completely changes the way of living on the planet: throughout the archeological activity of excavation – extensive and scientifically conducted – together with constructive investigations and Laboratory analysis, technical and distributive choices can be described and gradually understood. Theycan explain and highlight the first fundamental passages of a relationship with both anthropic and natural environment that will affect our subsequent history.

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