MEASUREMENT OF MECHANICAL STRENGTH, THERMAL CONDUCTIVITY AND MOISTURE OF EARTH SAMPLES FROM CRETE, GREECE, CONTAINING CLAY AND STRAW FOR ARCHITECTURAL APPLICATIONS

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Abstract: In this interdiciplinary research effort, three important properties, which determine the behaviour of various building materials for earth architecture, are studied, in the context of the mediterranean natural conditions in Greece. In particular a) mechanical and b) thermal properties are studied and c) the moisture content of the samples. The samples are all made from local materials found on Crete and fall into two categories, namely i) unfired earth bricks and ii) light clay-straw infills. It is further attempted to relate the findings and hence the suitability of these materials not only to issues of sustainable ecological building and energy conservation, but also to issues relating to a seismically active area such as Greece.

1.EARTH ARCHITECTURE

1.1. General

Economic and environmental conditions in many countries worldwide have increased awareness of the need for planning sustainable buildings in rural and urban areas alike. Issues like safeguarding energy resources and reducing carbon dioxide emissions has led to a resurgence of interest at governmental level for natural building techniques that use earth-based materials (Little and Morton 2001; Thornton 2004). Clay when compared to other widely used construction materials such as reinforced concrete or metal, displays significant advantages mainly related to environmental criteria, such as life cycle assessment, enhancing of local natural and human resources etc. The evaluation of earth-based materials requires the knowledge of a diverse range of properties like mineralogy, mechanical strength, thermal insulation and moisture retention. This, due to its complexity, calls for an interdisciplinary approach. In this context we are investigating, for the first time, unfired Cretan earth and related construction materials containing straw, with the aim to determine some important properties applicable to restoration of monuments and to new constructions alike.

In particular we have conducted experiments and present here our first results for compressive strength, thermal conductivity and moisture, for samples of four different earth compositions. Each earth type is subdivided further to four categories each containing a different fraction of straw.

1.2. Greek earth architecture

It is known that earth has been widely used as construction material since the prehistoric era, such as the settlements of Dimini and of Sesklo (Mastoraki 2005), although specialized research is very limited on the application of clay to Greek architecture and city planning. Up to the middle of last century, earth has been used as construction material in many Greek areas, mostly in the form of unfired bricks for external masonry, or in a mixed technique, with timber, for both external and internal walls. The application of raw earth in building and fortress constructions has been documented for important archaeological places (ancient Smyrna, Athens, Pafos, Elefsina) (Müller-Wiener 1995). In traditional Greek architecture numerous evidences, of varied typological form and usage, have been identifed in urban, semi urban and agricultural areas (Papaioannou, 2003; Filippidis, 1991). In the recent past a significant degree of maturity of the adobe techniques is evident (Mousourakis 2008) in entire settlements (Korestia, Kranionas), in small centres of neoclassical architectural style (Amfissa, Galaxidi, Chrisso) and in areas of emigrant reception (Kokkinia, N.Pefki, Magico of Xanthi). Most applications of clay nowadays are found in small restoration works (Tambakika in Amfissa), new interventions in historical buildings-museums (“Chani”, ie travelling Inn, of Gravia) and in small private constructions of experimental nature.

1.3. Technical requirements in Greek legislative framework

The fact that Greece is the most tectonically and seismically active region within the Mediterranean Basin (Vannucci 2004) is a significant parameter to consider. The current regulations divide Greece in 3 areas where the design acceleration for buildings ranges between 0,16 g – 0,36 g. As recent research shows the well suited combination of timber framed structures with earth based materials displays a satisfactory

antiseismic behavior (Karakostas et al 2005).
For the structural requirements of constructions in Greece which may be applied to earth based architecture, the Greek Seismic Code (EAK 2000) (FEK 2184B/20-12-1999) is applied, combined to Eurocode No 5 "Design of Timber Structures". For earthen buildings there are no specific regulations. This means that, currently, earthen constructions, such as earth bricks and light clay-straw infills, can only be allowed as non-load bearing elements.
In Greece, the effort to reduce the energy consumption in buildings has been effected through the inplementation of a legislative framework first drawn up in 1979. The so called Thermal Insulation Regulation (FEK 362/4-7-79) divides the country in 3 basic zones, A, B and C, according to the climate characteristics and specifies a limit of maximum value for the heat transmission rate (U-value, [kcal/m^2h °C]). This value is directly related to the coefficient of thermal conductivity k of the building materials and to the thickness of the building element. For external masonry the Greek regulations put an upper limit of U ≤ 0,6 kcal/m^2h °C (U ≤ 0,69 W/m^2K). This legislation is already subject to harmonization with the European Directive 2002/91/EC for the Energy Performance of Buildings and the new framework awaits approval.

2. EXPERIMENTAL

2.1. Sample preparation and characteristics

Soils occur on Crete mainly within the Neogene basins. Soil samples of different colouring from Western Crete, in an area of 10 to 20 km from the city of Chania have been collected and investigated, for their suitability as raw materials for architectural applications. In particular, 4 types of soils were studied, taken from the local sites of Agia (AG), Alikianos (AL), Gerani (GE), and Souda (SO), in order to evaluate their properties as building materials. The samples were taken from ground rungs at half a meter depth below ground level so as to avoid any organic content.
The investigated soil samples show a variety of colours, red, yellow, brown. Their natural moisture content reached 10-15% (Markopoulos et al 2008). Their mineralogical characteristics were identified by using X-ray diffraction (XRD) analysis and a quantitative mineral phase analysis was performed using the Siroquant V2.5 Quantitative XRD software.
In order to determine their physical technical characteristics, laboratory measurements of soil particle size distribution and plasticity were undertaken, for each soil. Also a number of cube specimens 5x5x5 cm were produced, compacted, and cured for 28 days under laboratory conditions for the necessary compressive strength measurements following ASTM standards. Their ability to absorb environmental moisture was also investigated experimentally by placing the samples into a closed

dessicator containing water in order to achieve a 100% RH environment. In particular, a 28-day old earth-only sample was weighted and placed on a porcelain disc into a glass dessicator containing enough water to cover its base, thus avoiding direct contact of the samples with water. A weighting procedure was carried out every 5 days under a practically constant laboratory temperature. Furthermore, a number of cube specimens were produced from each soil type by adding straw in 3 different straw to earth ratios (1/3, 1, 3) in order to measure their mechanical strength and investigate their thermal behaviour by measuring their coefficient of thermal conductivity.
The raw materials are mainly composed of quartz, illite, muscovite, chlorite and calcite, with some Fe-minerals, feldspars and traces of gypsum, halite and anhydrite. The amount of clay minerals varies from 13 to 45%. The high percentage of quartz and mica is due to the presence of the Phyllite-Quartzite Unit in the surrounding area (Frydas and Keupp, 1996; Frydas et al., 1999; Markopoulos et al, 2008).
The granulometry of the samples was investigated in the soil fraction <2 mm using a sedimentation test, the Bouyoucous soil particle size analysis (Day 1960).
Both the results of XRD and particle size analyses are shown in Table 1.

Samples	**Sand %**	**Silt %**	**Clay %**	**Main Minerals %**
AGIA (AG)	79	8	13	ill 31.5%, qz 50%, mu 5.2%, Goe 3%
ALIKIANOS (AL)	23	32	45	ill 34%, qz 33.3%, mu 25.4%, Fd 7.4%
GERANI (GE)	21	42	37	ill 11.2%, qz 15.5%, mu 9.5%, cc 63.8%
SOUDA (SO)	57	26	17	ill 34.7%, qz 32.2%, mu 1.4%, chl+sm 8.8%

ill: illite, qz: quartz, mu: muscovite, fd: feldspar, cc: calcite, goe: goethite, chl: chlorite, sm: smectite

Table 1. Classification (weight) and mineralogy of the soils (table by authors).

The investigated samples could be classified: as silty clays (AL and GE), as silty sand (AG) and as silty to clay sand (SO) (Markopoulos et al, 2008). The slight shrinkage or swelling of the soil cube specimens, observed after removing the mould, can be associated with the minerals they contain and their swelling potential (Bain 2007; Markopoulos et al. 2008). All earth samples contain illite and muscovite. These clay minerals are of non expanding type and have a very low swelling potential and a specific surface area with values between 10 – 200 [m^2/g] (Bain 2007).
The Atterberg limits (liquid limit LL, plastic limit PL) as well as the plasticity index (PI= LL-PL) were determined using both the Casagrande method in comparison with the Cone Penetration Test (ASTM D2487-00).They were found to be: LL22.6 PL18.1 PI4.5 for AG, LL 26.9 PL15.4 PI 11.5 for AL, LL44.7 PL18.1 PI 26 for GE, LL25.5 PL13.6 PI 11.9 for SO. Particularly, acording to the IETcc recommendations (Delgado-Jiménez et al, 2006) for soil selection for rammed earth, the main important properties for the suitability of a soil are soil grading and plasticity.

2.2. Measurement of compression strength

The mechanical strength of a soil is very much dependent on the voids ratio of the soil after ramming, cohesive strength of fines content, aggregate strength and moisture condition during testing. Thus density of the soil influenses its mechanical strength. However the mechanical strength can only be determined accurately by measurement (MOPT 1992).

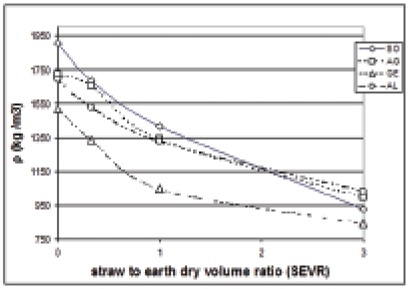

Figure 1. The specific weight, ρ, of four earth types (SO, AG, GE, AL), as a function of their straw content, expressed as Straw to Earth dry Volume Ratio (SEVR). For each earth, samples are prepared at four values of SEVR: 0 (*no straw – all earth*), 0.333=1/3 (*1 straw – 3 earth*), 1 (*1 straw – 1 earth*) and 3 (*3 straw – 1 earth*). The lines simply join the data points (graphic by authors).

The addition of straw lowers the specific weight values in all samples as shown in Fig. 1.

The results of our mechanical compression strength tests are shown in Table 2. As can be seen the compressive crushing strengths of unstabilized soil vary from 1.7 to 3.5 MPa thus covering the needed strength ranges for rammed earth and adobe production (Markopoulos *at al.,* 2008, MOPT, 2006). The soil SO exhibits high natural compressive strength of 3.5 MPa. The presence of straw increases the strain each sample can sustain without fracturing and reduces the maximum stress. The AL type of earth with straw exhibits the same stress to strain curve for all straw to earth dry volume ratios which could be explained by its high clay content that reaches 60%.

2.3. Measurement of coefficient of thermal conductivity

he coefficient of thermal conductivity, k, characterises the rate of heat propagation through a material by conduction (Zemansky 1957). Thus for unidirectional heat propagation, in a slab, k is the proportionality constant in the equation
$(dQ/dt)=k\Delta\theta A/x$, which expresses analytically the rate (dQ/dt) of heat Q flowing between two points having a temperature difference $(\Delta\theta)$ and distanced a small length (x), through an area (A) perpendicular to the direction of propagation. The units of k are $Watts\ m^{-1}\ K^{-1}$, often written W/mK.

In the present work the method used for the measurement of k is based on resistively heating the sample with constant power and allowing it to attain thermal equilibrium with its suroundings. It was developed specifically and will be described in detail elsewhere. The temperature is recorded as a function of time, at several points in the sample, suitably chosen to average out the inhomogeneities of the clay-straw material. In this, first impementation of our method, the modeling of the experiment is restricted to analytical solutions, based on symmetry assumptions. The analysis proceeds by transforming the data points (position, temperature) in order to least square fit (LSF) to a straight line. The coefficient of thermal conductivity *k* is obtained from the slope of the best line. The uncertainty of *k* is also obtained from the LSF. The

Sample	Straw to earth dry volume ratio - SEVR	Stress $\sigma \pm \delta\sigma$ (2*sd) (MPa)
AG 0	0	1.69 ±0.37
AG 1/3	1/3	1.27 ±0.21
AG 1	1	0.86 ±0.31
AG 3	3	0.46 ±0.27
AL 0	0	1.79 ±0.63
AL 1/3	1/3	0.89 ±0.51
AL 1	1	0.85 ±0.55
AL 3	3	0.77 ±0.37
GE 0	0	1.9 ±0.2
GE 1/3	1/3	1.17 ±0.55
GE 1	1	0.77 ±0.16
GE 3	3	0.75 ±0.24
SO 0	0	3.45 ±0.51
SO 1/3	1/3	2.38 ±0.23
SO 1	1	1.35 ±0.28
SO 1/3	3	0.87 ±0.24

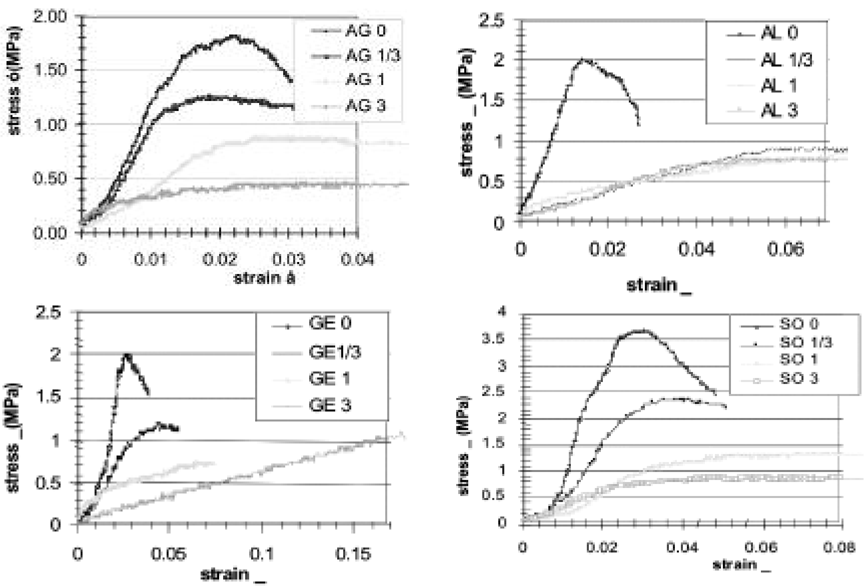

Table 2. Compression strength of the samples. In each graph taller trace refers to SEVR=0 (table by authors).

apparatus was tested for calibration purposes by using a sample of commercially available extruded polystyrene insulation board (styrofoam) of known *k* value. The k values for our samples are plotted in Fig. 2 below as a function of the specific weight. The error bars shown represent 1 standard deviation. The modelling of the experiment attempts to reduce systematic errors or take them into account as corrections whenever possible (eg loss mechanisms that reduce sample heating, geometrical position of data points, etc).

2.4. Measurement of moisture storage

The tendency of the earth-only samples to absorb moisture is shown in Fig. 3 where their normalized weight is depicted as a function of time at 5 day-intervals. During the first 5 days all samples absorb roughly the same amount of environmental moisture. During the next 5-10 days all of them exhibit a weight loss. Afterwards they absorb at a similar rate and they tend to saturate after 35 days.

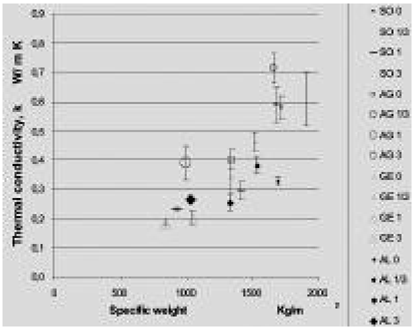

Figure 2. The coefficient of thermal conductivity, k, for four earth types: (SO, AG, GE, AL), each divided into four categories marked by the straw to earth dry volume ratio (SEVR: 0– 1/3–1–3). The size of the symbol of the earth-type increases with increasing SEVR (graphic by authors).

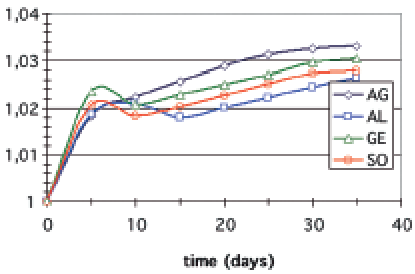

Figure 3. The normalized weight of the four types of earth-only samples in a 100% RH (relative humidity) environment, as a function of time. The lines simply join the data points (graphic by authors).

3. DISCUSSION

The investigated samples show an appropriate soil grading and satisfactory plasticity, due to the presence of adequate amounts of clays in all samples, with PI-values between 9-20, which are within the IETcc recommendations. From the earth types studied here, AG and SO types are suitable for adobe production, and AL and GE are suitable for both plaster and adobe applications.

The earth type SO has the highest compressive strength value which is attributed to an appropriate soil particle grading as well as to an adequate silt to clay ratio in its mineralogical components.

The coefficient of thermal conductivity for building materials containing clay and/or straw has been the subject of many efforts in the past, over a wide range of sample specific weights (Minke 2000; Goodhew and Griffiths 2004; Thornton 2004; Goodhew and Griffiths 2005). The four types of earth used in this study have specific weights which range from 1700 kg/m^3 to 1900 kg/m^3 for samples that contain earth only and from 850 kg/m^3 to 1700 kg/m^3 for samples containing both earth and straw. Each *k* value is derived from measurements involving a single sample, by using the standard least square fitting technique where it is assumed that all errors lie in one variable. Our results show, see Table 3, the well established trend, which appears in the litterature, of k values increasing with specific weight (Thornton 2004; Goodhew and Griffiths 2005).

The earth types AG and AL have similar specific weights but quite different k values, of 0.59 W/m K and 0.33 W/m K, respectively, It is seen that their k values are inversely proportional to their clay content of 36% and 60% respectively. It is worth noting that the addition of straw does not affect this relation between k values and clay content. It is also seen that the increase in clay content reduces the k–values which is desireable.

Thus we find that *k* may differ significantly for samples of quite similar specific weight but made from different earth types (clay, silt and sand) and/or having different SEVR (straw to earth dry volume ratio). It is therefore concluded that grouping such materials according to their specific weight alone, as is the case in the litterature, may not be sufficient to characterize their thermal properties.

In conclusion there exist in Western Crete a variety of earth materials well suited to sustainable architectural applications.

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Earth type	Straw to earth dry volume ratio (SEVR)	Coefficient of thermal conductivity k W/mK	Specific weight (Kg/m^3)	δk (1sd) W/mK
SO	0	0,61	1907,0	0,09
SO	1/3	0,59	1683,0	0,06
SO	1	0,29	1414,3	0,03
SO	3	0,23	927,3	0,01
AG	0	0,58	1720,9	0,04
AG	1/3	0,71	1656,8	0,05
AG	1	0,40	1338,6	0,03
AG	3	0,39	996,8	0,03
GE	0	0,46	1517,8	0,03
GE	1/3	0,34	1335,0	0,06
GE	1	0,20	1045,5	0,02
GE	3	0,19	842,8	0,01
Al	0	0,33	1692,4	0,01
Al	1/3	0,38	1529,2	0,03
Al	1	0,25	1327,8	0,03
Al	3	0,27	1028,6	0,01
Styrofoam	callibration	0,030	32,5	0,002

Table 3. Measured thermal conductivity values (table by authors).

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Curriculum

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