EVALUATION OF AUTOCLAVED AERATED CONCRETE (AAC) AS A REPAIR MATERIAL FOR TIMBER FRAMED HISTORICAL STRUCTURES

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Abstract: In the recent repair works of historical structures, autoclaved aerated concrete (AAC) started to be used, especially in timber framed historical structures as an alternative material to the original mudbrick, brick or stone infill. For its proper use in maintenance and repairs of historical structures, the material properties of AAC, its compatibility with the historical materials and within the structure should be discussed. This study was conducted to understand the material properties of AAC fabricated in Turkey in order to discuss its compatibility as a repair material in historic structures. Analyses were done to determine its basic physical, mechanical, durability and compositional properties. The properties of AAC were compared with those of historical mudbrick, brick, timber, mortar and plaster samples and its compatibility with the historic fabric was discussed. It was concluded that further studies are needed to allow its use in repairs of historic structures.

Keywords: autoclaved aerated concrete (aac), compatibility, infill material, material properties, timber framed historical structures.

1. INTRODUCTION

Autoclaved Aerated Concrete(AAC) is being preferred as a building material due to its several advantages such as its light weight, low thermal conductivity, high fire resistivity and soundproofing properties (Taşdemir & Ertokat, 2002; Grutzeck, Kwan & Di Cola, 2004; Narayanan & Ramamurthy, 2000a; 2000b). It is also observed that AAC has recently started to be used as a repair material alternative to original mudbrick, brick and stone infill, especially in Turkey.

Even though there are some studies on AAC (Taşdemir et al., 2002; Grutzeck et al., 2004; Narayanan et. al., 2000a; 2000b), there is need for more extensive and comprehensive studies both on its material properties and its compatibility with the neighbouring materials in historic structures, which is vital for their long term survival (Sasse & Snethlage, 1997).

This study was conducted to better understand the material properties of AAC and its compatibility as a repair material for timber-framed historical structures with the emphasis on its basic physical properties as total porosity, bulk density, drying behaviour and water vapour permeability in terms of water diffusion resistance coefficient(μ), mechanical properties as dynamic modulus of elasticity (Emod) and uniaxial compressive strength (UCS), wet-to-dry strength ratio (UCSwet/UCSdry) as a durability parameter and its pozzolanicity. It is suggested that μ, Emod and UCS were

among the most important parameters of compatibility (Sasse et al., 1997). Any material introduced into the historical structure should not have lower μ and higher Emod or UCS. Water vapour permeability is an important physical property that has to be taken into account in order to prevent condensation problems in the structure after repairs. Other important issues of compatibility between the repair material and the original materials of the building are the bonding properties and the dilatation properties under variable atmospheric conditions such as temperature and humidity changes (Mertz, 2004). Pozzolanic activity is a property which is closely related with the bonding capability of AAC with lime mortars which are more suitable repair materials than cement containing mixtures (Sasse et al., 2004). The compatibility of AAC with the historic materials and the structure was discussed by comparing its determined physical, mechanical and bonding properties with those of historic materials such as , mudbrick, brick, timber, lime mortars and plasters.

2. MATERIALS AND METHODS

The properties of repair materials should be similar to those of original ones within a certain range so that their compatibility with the neighbouring materials is achieved (Sasse et al., 2004). Therefore, the selected material properties of AAC were determined by laboratory analyses, then, the data obtained were used to compare its properties with those of historical materials.

Two types of AAC, one produced as infill material (G2) the other produced as load-bearing unit (G4) were examined . The samples were produced from the AAC blocks of 25 x 30 x 60 cm according to the TS EN 678 (1995) and TS EN 453 (1988) standards. Additional samples were also prepared from core and exposed(wire-cut) surfaces to clarify the differences between those parts.

The physical properties bulk density (D), porosity (P), water absorption capacity (WAC), saturation coefficient (S), water vapour permeability, drying behaviour and evaporation rate were determined according to ASTM (1993), RILEM (1980) and Turkish Standards (TSE, 1995; TSE, 1988). In addition, examination of thick sections by optical microscopy were done. Water diffusion resistance coefficient, μ value was determined for the samples with varying thickness from the wire-cut surface, such as 1.25, 2.5 cm (TSE, 1990).

Modulus of elasticity value (E_{mod}) of AAC samples were determined indirectly by ultrasonic pulse velocity measurements (UV) since it is an important mechanical property which shows the deformation ability of a material under external forces. (RILEM, 1980; ASTM 1990; ASTM, 2003a; 2003b). For this purpose, a pulse generating test equipment, PUNDIT Plus, with its probes, transmitter and receiver of 220 kHz and 50 kHz, was used. E_{mod} values of the samples were then calculated with certain equations including both their D and UV.

Uniaxial compressive strength values(UCS) of the samples were determined by using ELE International Compact-1500 UCS Instrument as direct measurement. In addition, point load strength index (Is) was also determined by using Point Load Testing method using appropriate equations as indirect measurement (Topal, 1995; Topal, 1999/2000, ISRM, 1985). The correction factor, k (UCS/Is) was then determined by using UCS

measurements and the Is values. (Broch and Franklin, 1972; Anon, 1972; Bieniawski, 1975; Anon, 1977; Beavis et al., 1982; Foster, 1983; I.S.R.M., 1985; Topal, 1995; Norbury, 1986).

Durability properties were examined in terms of saturation coefficient (S), and wet-to-dry strength ratio based on UCS (R_{UCS})(Winkler, 1986, 1997; Topal, 1995; Topal and Doyuran, 1997). UCS values of wet samples were determined to clarify the reductions on the saturated samples after soaking in water for 5 days. The changes in E_{mod} values in relation to water were also followed. For this, E_{mod} values were measured on the dry samples during 2 cycles of wetting and drying. E_{mod} values were also measured on the dry samples which were left in water for 20 days after being saturated under vacuum.

Mineral composition of the samples were determined by the analyses of pozzolanic activity and X-Ray Diffraction (XRD). Pozzolanic activity indicated the reaction ability of AAC with calcium hydroxide by producing the calcium–silicate-hydrate (C-S-H) network, in fact the bonding capacity with lime mortar. The pozzolanic activity of AAC were examined by using the Luxan method (Luxan et al., 1989) for its fine grains lower than 125μ diameter using the powder produced during cutting of the samples. The pozzolanic activity of the aggregates lower than 125μ used in the production of AAC was also examined. They were provided by the manufacturer of AAC. In the analysis, 1.25 gr sample in powder was mixed with 50 ml saturated $Ca(OH)_2$ solution and the change in the electrical conductivity of the mixture was measured by using Metrohm AG Herisau, Konduktometer E382. The decrease in the electrical conductivity within 2 minutes were used for the evaluation of pozzolanic activity. For the XRD analysis, the powder samples were analysed by using Phillips Model PV 3710 X-Ray Diffractometer with Cu K α X-Rays.

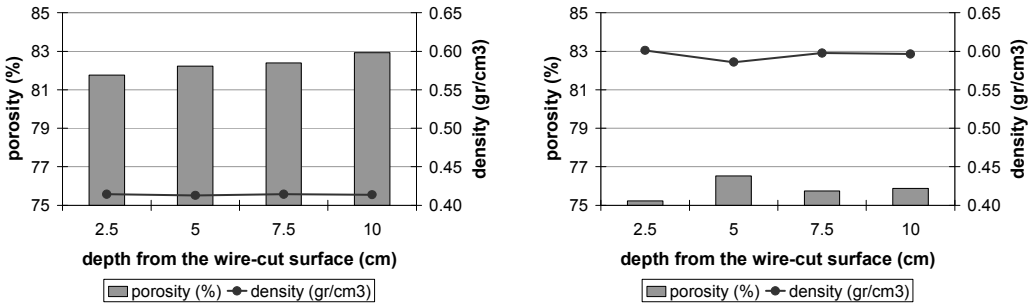
3. RESULTS AND DISCUSSIONS

The combined interpretation of the results obtained from the laboratory analyses were done to define the material properties for AAC and to discuss whether it is a proper material for repairs of historic timber framed structures.

The bulk density and porosity of G2 and G4 samples were found to be 0.4 g/cm^3 and 78%, and 0.6 gr/cm^3 and 68%, respectively. Water absorption capacity (WAC) for both G2 and G4 was found to be extremely high with values of 193% and 114%, respectively (see Table 1). AAC, used as an infill, G2, and load bearing purposes, G4, were found to be very porous and lightweight materials while G4 was, expectedly, denser and less porous than G2. The samples taken from the wire-cut (exposed) surfaces of AAC blocks within the 2.5 cm thickness were found to have slightly less porosity (see Figure 1).

Table 1: Basic Physical and Mechanical Properties of G2 and G4 samples

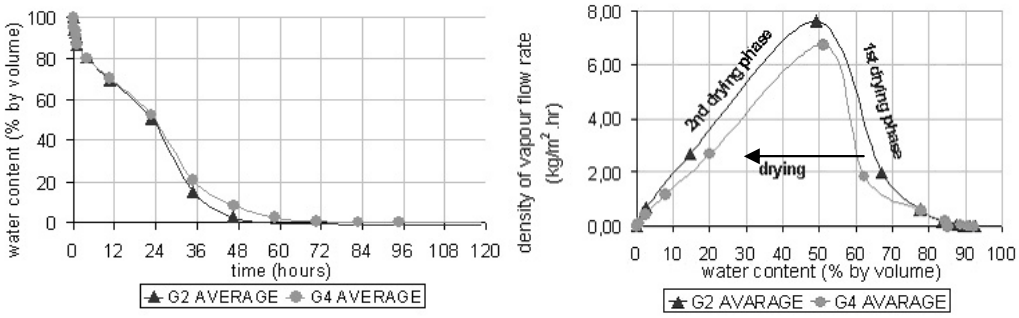
Properties	**G2**	**G4**	**Properties**	**G2**	**G4**
D (gr/cm^3)	0.4	0.6	UCS (MPa)	1.88	2.76
UV (m/s)	1965	1962	WAC (% by weight)	193	114
E_{mod} (Gpa)	1.4	2.1	P (%)	78	69
S (0-1)	0.46	0.62	R_{UCS} (%)for the samples which were left in water for 5 days after being saturated	58.5	54.4



(a) (b)

Figure 1: bulk density and porosity values for the (a) G2 samples and (b) G4 samples of 2.5 cm, 5 cm., 7.5 cm and 10 cm depth from the wire-cut surfaces. The samples taken from the wire-cut surfaces until 2.5 cm depth have the lowest porosity.

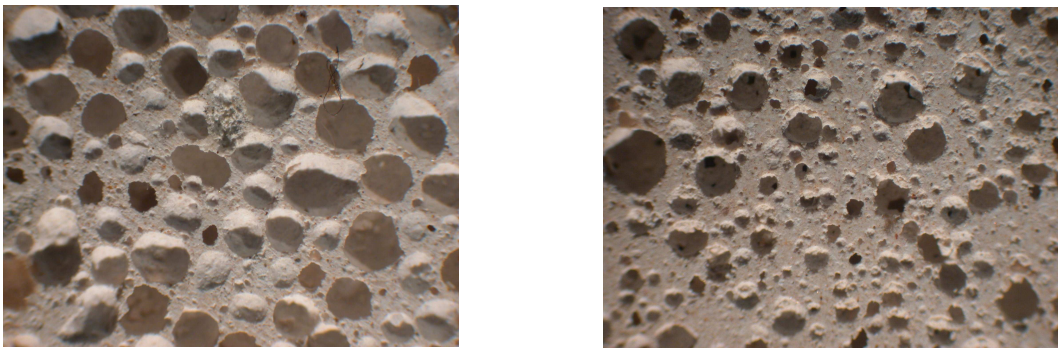
The laboratory analyses on evaporation rate(kg/m2.hr), drying curve (water loss as % by volume) and saturation coefficient(S) defined as the ratio of free sorption to the sorption under vacuum gave some information on pore size distribution characteristics of AAC. The saturation coefficient of G2 was found to be lower than that of G4, with the values of 0.46 and 0.62, respectively (Table 1). This indicated that G4 should have higher proportion of fine pores when compared to G2 since a high value of saturation coefficient indicates presence of high proportion of fine pores allowing water to be absorbed by capillary action (BRE, 1997; RILEM, 1980; Winkler, 1997). At 20oC and 40% RH conditions, the curve of evaporation rate showed two different drying phases. At the first drying phase the evaporation had an increasing rate and after at a critical point, the second drying phase had a decreasing rate (Figure 2b). Evaporation during the first drying phase depends solely on the exposed climatic conditions while during the second drying phase it depends on the material properties (Massari and Massari, 1993; Torraca, 1982). The critical point, corresponding to the critical moisture content level, was found to be about 50% by volume for both G2 and G4 samples. 50% critical moisture content was a high value when compared to porous historic materials (Massari and Massari, 1993; Tuncoku, 2001; Tuncoku et al., 1993). This showed that AAC retains water more than historic brick, brick mortar and stone mortar. The evaporation rates of G4 and G2 samples were found to be in the range of 0.03 – 6.73 kg/m2h and 0.03 – 7.61 kg/m2h respectively (Figure 2b). G4 samples, with 3 days of drying period, dried out slower than G2 samples with 2 days of drying period (Figure 2a). G4 samples that dried out slower had higher saturation coefficient than G2. Both drying experiment and saturation coefficient determinations support each other and indicate that G4 has higher proportion of finest pores than G2.



(a) (b)

Figure 2. (a) Drying curve by decrease in volume versus time at 20°C and 40% RH conditions; **(b)** Variation of evaporation rate as a function of moisture content by volume; showing that G4 dries out slower than G2.

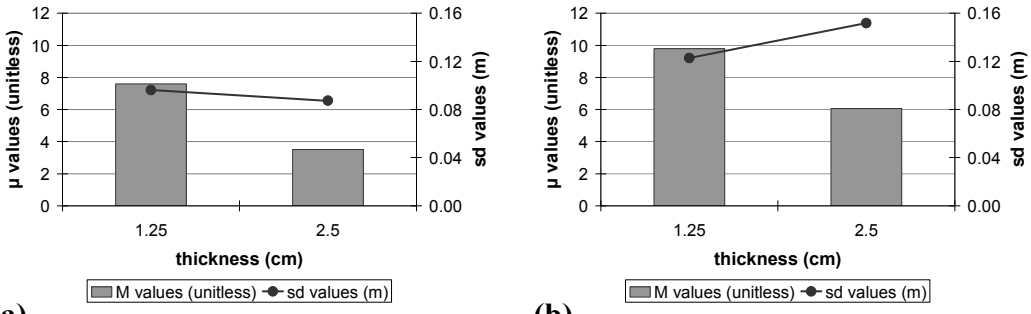
Microscopic examination of thick sections supported those conclusions. G2 appeared to have higher proportion of large pores than G4, therefore dried out quicker (see Figure 3)



(a)G2 **(b)**G4

Figure 3. Thick sections showing large pore size distribution of AAC. Longer side of the micrograph: 1 cm.

µ values of G2 for 1.25 cm and 2.5 cm thickness were found to be 7.59, 3.52 and and µ values of G4 were 9.78, 6.06 respectively. It was observed that there is a reduction in µ values with the increasing thickness from the exposed(wire-cut) surfaces. This reduction is more recognisable for G2 when compared to G4 (see Figure 4). Considering the thickness of the walls in timber framed structures as 10 cm, by using the obtained µ values for 2.5 cm thickness, the SD values of G2 and G4 blocks were calculated to be 0.35 and 0.61 respectively. However, the real SD of the blocks should be lower than those.

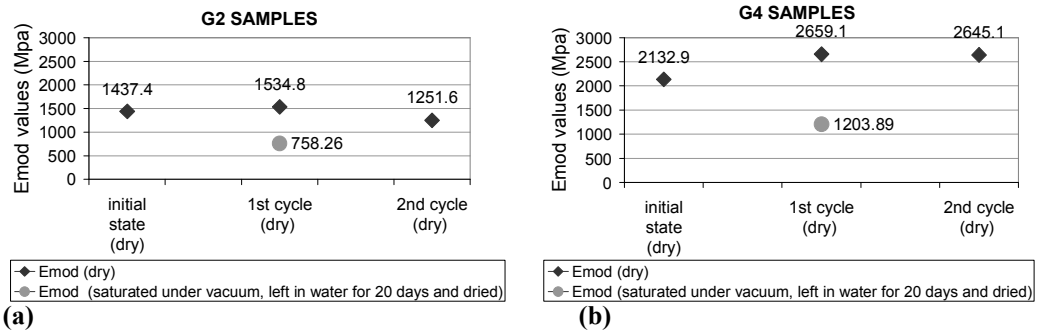


(a) **(b)**

Figure 4. The equivalent air thickness of water vapour permeability ***(SD)*** and water diffusion resistance coefficient**(µ)** values for G2(a) and G4(b) samples with 1.25 and 2.5 cm thickness.

Ultrasonic velocity values(UV), E_{mod},and UCS were found to be 1965 m/s, 1.4 GPa and 1.88 MPa for G2 while 1962 m/s, 2.1 GPa and 2.76 MPa for G4, respectively (see Table 1). UCS values of AAC material was found to be within the acceptable range defined for AAC products by RILEM (1993). According to prEN 12602 standards (1999), G2 was in the class of AAC 2 while G4 was in the class of AAC3. k value, UCS/ Is , was found to be 4.7 and 3.9 for G2 and G4, respectively. Those values were observed to be close to those for the weak rocks (Topal, 1999/2000; Topal, 1995).

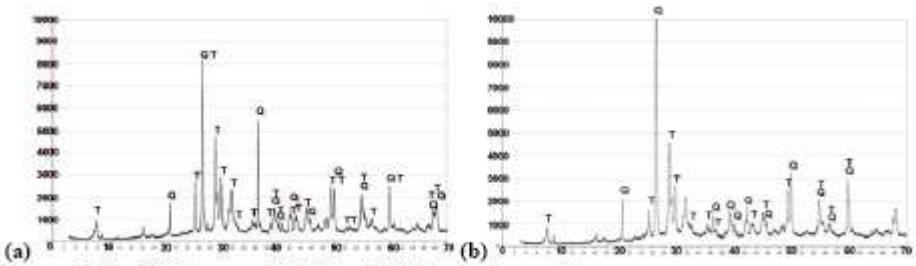
Considerable changes in mechanical properties were determined on saturated AAC samples. Wet-to-dry strength ratio based on UCS for the G2 and G4 samples which were left in water for 5 days after being saturated were found to be 58.5% and 54.4 % respectively. According to Winkler's classification (Winkler, 1993), both G2 and G4 samples seemed to be unsafe materials for frost and hygric forces. The E_{mod} values of both G2 and G4 started to fall after the first wetting drying cycle. In addition, a significant reduction was observed on the E_{mod} values of the dry samples which were previously left in water for 20 days after being saturated under vacuum (see Figure 5).



(a) **(b)**

Figure 5. Modulus of Elasticity values, E_{mod}, as a function of wetting-drying cycles for G2 (a) and G4(b) samples.

Mineral composition of the samples were determined by the pozzolanic activity and XRD analyses. The pozzolanic activity values of G2 and G4 samples were found to be 0.85 to 0.95 mS/cm, respectively, and of aggregate used in the production of AAC as the raw material was found to be 0.27 mS/cm. According to the classification defined by Luxan *et.al* (1989), the powdered AAC samples were determined as variable pozzolanic while its aggregate was non-pozzolanic material. Examination of XRD traces showed that the main minerals detected were 11 A^o Tobermorite and quartz, and the rest were muscovite and biotite (Figure 6).



(a) (b)

Figure 6. The XRD traces of G2 (a) and G4(b) powder samples

3.1. Comparison of AAC with Historic Building Materials

The properties of AAC and historic building materials were given in Table 2. In comparison to historic brick, mudbrick, mortar and plaster, AAC was found to be less dense and more porous with very high water absorption capacity, however its bulk density was close to that of timber (Tuncoku, 2001; Tuncoku et al., 1993; Akkuzugil, 1997; Güdücü, 2003; Eriç, 1980; Richardson, 1976). AAC seemed to absorb and retain water. Therefore, it should be well protected from water in any repair work to prevent deteriorations. It was understood that AAC samples dry much faster than some historic bricks and some historic mortars (Tuncoku 2001, Tuncoku, 1993; Tuncoku et al., 1993). Both G2 and G4 blocks with a thickness of 10 cm were found to have similar water vapour permeability characteristics with the historic mudbrick, brick, brick mortar, some plasters and timber. In addition, G2 seemed to be more suitable for repairs of these historic materials with its higher water vapour permeability (Akkuzugil, 1997; Güdücü, 2003; Akyazı, 1998; Kumaran et al, 1994:6; Yıldırım Esen, 2004). The UCS and Emod values of AAC samples were found to be within the range for those of historic mudbrick, brick, stone mortars, brick mortars and some plasters, however, they were a bit lower than those of historic bricks (METU MCL Studies, 2004; Eriç, 1980; Olivier et al., 1993; Eriç et al, 1980; Güdücü, 2003; Yıldırım Esen 2004; Tuncoku 2001; Tuncoku et al., 1993; Kahya, 1991). A significant reduction in the mechanical properties of AAC in relation to the presence of water was observed. This clearly indicated that AAC material should be avoided from direct water exposure to maintain its inherent mechanical properties. In addition, AAC seemed to be less pozzolanic than some of those historic stone and brick masonry mortars. This may lead to bonding problems at the interface of AAC with repair materials such as pozzolanic lime mortars and plasters within the historical structure. The pozzolanic activity of fine aggregates of AAC was found to be non pozzolanic while the aggregates of historic mortars and plasters were good pozzolans. Such a result showed the necessity for further studies to examine its bonding with the historic fabric.

4. CONCLUSIONS

Results of this study showed that AAC was found to be less dense, more porous than historic materials and it has very high water absorption capacity, however its density is close to timber. The water vapour permeability is also within the range of those for historic materials. AAC dried much faster which seemed as an advantage. In terms of mechanical properties such as E_{mod} and UCS, AAC is similar to historic materials within an acceptable range. However, it loses its inherent mechanical properties considerably in the presence of water. In addition, its aggregates are far less pozzolanic which may lead weak or no bonding with the historic fabric when used with lime mortars.

Consequently, it is clear that further studies are necessary in order to permit the use of AAC as a repair material in timber framed historic structures as an alternative to mudbrick or brick infill.

Table 2. The Comparison Of Material Properties Of AAC With Those Of Historical Materials

MATERIAL PROPERTIES	AAC	HISTORIC MUDBRICK	HISTORIC BRICKS	HISTORIC MORTARS,	PLASTERS and TIMBER SAMPLES
Density (gr/cm^3)	0.4-0.6	1.2-1.6 (Eriç, 1980) 1.17-1.63 for burnt mudbrick (Güdücü, 2003)	1.3-1.8 (Tuncoku et al, 1993; Tuncoku, 1993), 1.16- 1.64 (Tuncoku, 2001)	1.29 for burnt mud-plaster and 1.51 for burnt mud-mortar (Güdücü, 2003) 1.39-1.85 for stone mortars (Tuncoku, 1993), 1.25-1.74 for brick mortar (Tuncoku, 1993)	0.97 – 1.84 for lime plasters (Yıldırım Esen et al., 2004) 1.28-1.78 for lime plasters, 1.33-1.73 for gypsum plasters (Akkuzugil, 1997), 0.3-0.8 for wood(Richardson, 1976),
Porosity (%volume)	68.0-78.0	31.6-54.62 (Güdücü, 2003)	28.1-49.6 (Tuncoku, 1993) 33.9-57.4 (Tuncoku, 2001)	29- 59for mortars (Yıldırım Esen et al., 2004), 40.1 for mud-mortar (Güdücü, 2003), 27.36-45.88 for stone mortars (Tuncoku, 1993) 27.81-52.26 for brick mortars (Tuncoku, 1993)	23.52-41.38 for gypsum plasters, 32.05-47.82 for lime plasters (Akkuzugil, 1997)
WAC (%weight)	192 for G2 114 for G4	33.5-76.34 for burnt mudbrick (Güdücü, 2003)	12-37 (Tuncoku, 1993; Tuncoku et .al. 1993)	63.08-78.82 for burnt mortars(Güdücü, 2003)	19.75-38.54 for lime plasters, 11.39-31.43 for gypsum plasters (Akkuzugil, 1997)
(*SD*) for 10 cm thickness (m)	<0.35 for G2 <0.61 for G4	0.28-0.32 (Akkuzugil, 1997) 0.06 for burnt mudbrick (Güdücü, 2003)	0.9- 1.29		0.23-1.62 for lime plasters 0.21-0.37 for mud plasters 0.68 for horasan plasters 0.8 for timber
μ	<3.52 for 2.5 cm G2 <6.06 for 2.5 cm G4	2.75- 3.23 (Akkuzugil, 1997) 0.57 for burnt mudbrick (Güdücü, 2003)	9.06- 12.85 (Akyazı, 1998)		2.3-16.2 for lime plasters (Yıldırım Esen et al., 2004), 9.84 for lime plasters and 2.09 for mud plasters(Akkuzugil, 1997), 11.9 for lime plasters and 3.69 for mud plasters and 6.77 for horasan plasters (Akyazı, 1998) 8 for timbers (Kumaran et. al., 1994)
Duration of drying at 20^{o}C an 40% RH (days)	2 for G2 3 for G4		~10 for historic bricks (Tuncoku et .al. 1993)	5 or 6 for some stone and brick mortars (Tuncoku, 2001)	
Drying rate (kg/m^2.hr)	0.03 – 6.73 for G4 0.03 – 7.61 for G2		1.08 (at max)(Tuncoku, 1993)	~1.87 (at max)(Tuncoku, 2001)	
Emod (GPa)	1.4 for G2 2.1 for G4	0.7 (METU-MCL studies Fall 04'-REST 556), 1.2- 2.1 (Güdücü, 2003)	3.1 - 5.2 for bricks (Yıldırım Esen et al., 2004)	2.3-3.6 for brick mortars (Yıldırım Esen et al., 2004), 0.6-10.2 for stone mortars (Tuncoku, 2001), 0.6-3 for brick mortars (Tuncoku, 2001)	0.7-6.6 for lime plasters (Yıldırım Esen et al., 2004)
UCS (Mpa)	1.88 for G2 (UCS) 2.76 for G4 (UCS)	5.69 Mpa (METU-MCL studies Fall 04'-REST 556), 0.3-2Mpa (Eriç, 1980), 0.5-2 Mpa for non stabilized earth (Olivier, et. al. 1993), 1Mpa for normal mudbrick according toT.S. 2514 (Eriç et. al, 1980)	17 (Kahya, 1991)		
$I_{s(50)}$(Mpa)	0.4 for G2 0.7 for G4	0.1- 2.8 for burnt mudbrick (Güdücü, 2003)	2.96- 3.34 (Yıldırım Esen et al., 2004)	0.06- 1.83 for stone mortars 0.09- 0.72 for brick mortars (Tuncoku, 2001)	0.02-0.15 for plasters (Güdücü, 2003)
R_{Emod} (%)	63.5 for G2 and 100 for G4 23.5 for G2 and 36 for G4 for the samples left in water for 20 days after being saturated				
R_{UCS} (%)	58.5 for G2 and 54.4 for G4 for the samples left in water for 5 days after being saturated	50-60 for burnt mudbrick (Güdücü, 2003)			
pozzolanic activity (mS/cm)	0.85 for G2 and 0.95 for G4 0.27 for the aggregate	3-5.7 for burnt mudbrick (Güdücü, 2003)		9 for the aggregates of mortars (Yıldırım Esen et al., 2004), 0.4-1.5 for brick mortars (Tuncoku, 2001) 1.7- 3.3 for stone mortars (Tuncoku, 2001)	7 for the aggregates of plasters(Yıldırım Esen et al., 2004) 1.8- 6.4 for burnt plasters (Güdücü, 2003)

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