



## **The role of adobes in the thermal performance of vernacular dwellings**

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## SUMMARY

Adobe walls are considered to be high thermal mass structures, as they have the ability to store thermal energy. In order to evaluate the thermal inertia of adobes, the delay of the thermal heat wave propagation and the ratio of the reduced temperature of the external to the internal surface are normally investigated; these are expressed by the dynamic indicators of time lag and decrement factor respectively. The present study employs in situ temperature monitoring of a 50 cm thick adobe wall with probes installed at various locations along its thickness. The results are analysed in terms of existing standards and numerical equations. The measured time lag for a period of 24 hours is thus estimated at approximately 5 hours. However, the discussion brings light to the discrepancy between calculated and measured time lag data and raises the issue of evaluating the time lag for massive adobe walls in a longer time range.

## 1. INTRODUCTION

Passive solar systems are among the most widespread environmental design strategies adopted in vernacular architecture. The thermal inertia of adobe walls, in particular, contributes to a delay of heat transmission (Asan 2006) and to a restriction of temperature deviations between the external and internal surfaces of the building envelope, thus establishing more stable indoor thermal conditions.

The effectiveness of thermal mass as an environmental design strategy depends on a series of parameters, such as the orientation of the building, the type of ventilation, the location and distribution of the thermal mass in the building envelope and the solar absorptivity of the wall surface (Kontoleon and Eumorfopoulou 2008, Santamouris and Asimakopoulos 2013). In order to evaluate the thermal inertia effect, two dynamic indicators are widely used: the time lag and the decrement factor. The time lag depicts the heat transmission delay, i.e. the time needed for the heat wave of a specific period to propagate from the outdoor to the indoor surface of a wall. The decrement factor evaluates the heat storage capacity of a wall and represents the ratio of the decrease of the amplitude of the thermal wave during heat transmission. A series of research studies focused on the estimation of the time lag and the decrement factor for adobes with the use of numerical methods (e.g. Asan 2006, Saldivar and Batty, 2006). The present paper focuses on the in situ monitoring of the temperature along the thickness of an adobe wall, thus offering a real-time evaluation of the aforementioned dynamic indicators.

## 2. METHODOLOGY

For the purposes of this research, a 50 cm thick adobe wall, which constitutes part of the south façade of a vernacular building in the village of Kapedes, Cyprus, was monitored. This wall is considered to be representative of the vernacular earthen architecture of Cyprus. Temperature probes were installed sideways at various locations along the thickness of the aforementioned adobe wall (Fig. 1). The temperature sensors were nickel alloy type K thermocouples connected to a multi-channel data logger (PicoLog TC-08). Good adhesion of the sensors to the wall was ensured through the use of re-usable adhesive, preventing thermal bridging.

The properties of thermal conductivity ( $\lambda$ ) and specific heat capacity ( $C_p$ ) of the wall adobes were also measured using ISOMET 2104 (Applied Precision Ltd.). Thermal diffusivity ( $\alpha$ ) was further calculated as a function of the above properties and density ( $\rho$ ), according to the following equation:

$$\alpha = \lambda / \rho C_p \quad (1)$$

The time lag ( $\varphi$ ) and decrement factor ( $f$ ), were calculated using the following numerical equations proposed by Asan (2006):

$$\varphi = \begin{cases} \tau(T_{si\_max}) - \tau(T_{se\_max}) & \text{for } \tau(T_{si\_max}) > \tau(T_{se\_max}) \\ \tau(T_{si\_max}) - \tau(T_{se\_max}) + P & \text{for } \tau(T_{si\_max}) < \tau(T_{se\_max}) \\ P & \text{for } \tau(T_{si\_max}) = \tau(T_{se\_max}) \end{cases} \quad (2)$$

$$f = \frac{A_{si}}{A_{se}} = \frac{T_{si\_max} - T_{si\_min}}{T_{se\_max} - T_{se\_min}} \quad (3)$$

Where  $\tau(T_{si\_max})$  and  $\tau(T_{se\_max})$  represent the time when the interior and exterior surface temperatures respectively reach their peak value, within a period  $P$  of 24 hours.

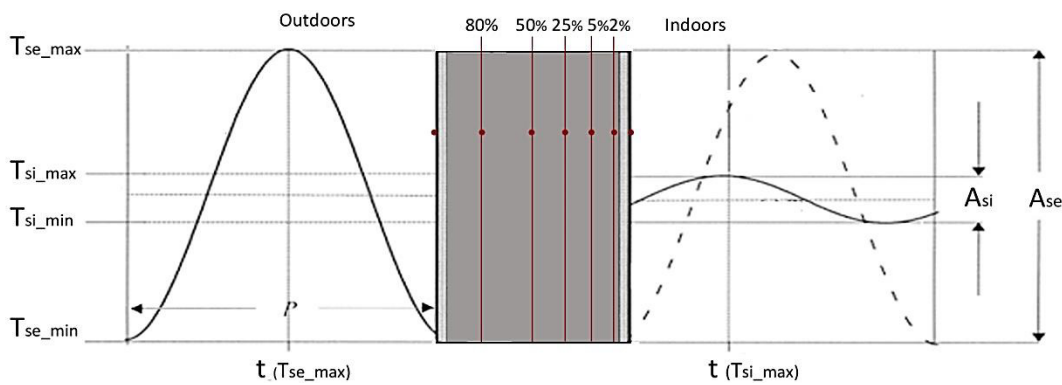


Fig. 1: Heat flux phenomenon and points of temperature recording on the adobe wall.

For comparative reasons, the aforementioned dynamic indicators (i.e. time lag and decrement factor), were also calculated according to EN ISO 13786, following the thermal admittance framework. Moreover, the numerical equation of time lag, in relation to the specific heat capacity ( $C_p$ ), density ( $\rho$ ) and material thickness ( $L$ ), used by Rafidiarison et. al. (2012) was also used.

For recording the external environmental conditions, a weather station was installed on the roof of the building under investigation. Interior air temperature and humidity levels were also recorded. Selected results from the summer period of 2013 (July and August) and the winter period of 2014 (February) are hereby presented and discussed. The building was not occupied during the experimental period and thus the air exchange rate was limited. During the period of July 2013, night ventilation was applied with windows remaining open between 19.30-06.30 (a period during which the outdoor temperature was lower than the indoor temperature).

### 3. RESULTS AND DISCUSSION

The average values and standard deviation of the dynamic indicators obtained during the aforementioned selected periods, calculated according to Asan (2006), are summarised in Table 1. Asan (2006) states that, for wall thickness beyond 50 cm, the decrement factor remains stable and close to zero. This is in line with the results

reported in Table 1; the decrement factor is below 0.05 for both summer and winter periods, indicating high thermal stability in the interior environment.

Periodic swings of the environmental temperature during a period of 24h generate a heat wave that flows through the thickness of a wall, from the outside to the inside. The depth of penetration of the diurnal heat wave depends mainly on the thermal diffusivity of the wall material. The heat flux through the adobe wall under investigation in this study was examined through a detailed representation of the temperature fluctuation within the wall (Fig. 2) for a period of 24 hours. From the results, great thermal stability is noticed at all monitoring positions from 50% onwards. In the contrary, the monitoring position of 80% presents a wider fluctuation of temperature, as it is affected directly from the temperature levels on the exterior surface. The south orientation of the wall under investigation, and consequently the high solar radiation imposed on it, explains the wide temperature fluctuations observed on the external wall surface, despite the fact that the temperature fluctuation of the external environment is much smaller (ca. 8°C) (Table 2).

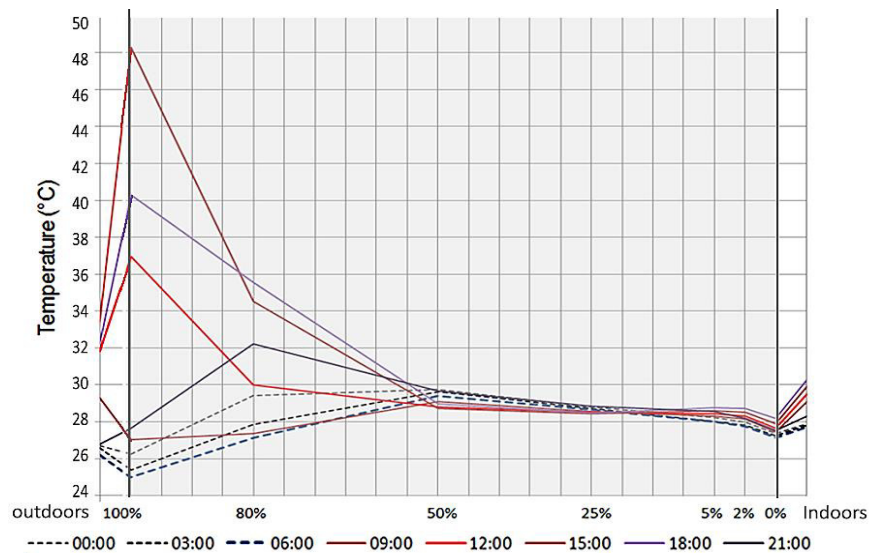


Fig. 2: Section of the wall with corresponding hourly temperature values recorded on 24/07/2013.

Table 2 presents the time and corresponding values of minimum and maximum temperature recorded during the summer period of July 2013, when night ventilation was applied. As observed, maximum internal surface temperatures ( $T_{si\_max}$ ) occurred around 20.00h, while maximum external surface temperatures ( $T_{se\_max}$ ) occurred around 15.00h. This indicates a time lag of approximately 5 hours within a period of 24 hours and it is in line with the results calculated according to Asan (2006) (Table 1). It is worth noting that, results for specific days present higher or lower time lag values, depending on particular weather conditions i.e. wind velocity, solar radiation, air humidity, rapid temperature change etc.

Table 1: Average and standard deviation of experimental time lag and decrement factor.

Period	Time lag $\phi$ (h)	SD	Decrement factor $f$ (-)	SD
24/07/2013 - 30/07/2013	05:09	00:17	0.040	0.007
26/08/2013 - 31/08/2013	05:40	01:40	0.015	0.004
04/02/2014 - 13/02/2014	05:28	01:14	0.008	0.002

Table 2: Time and value of maximum and minimum temperature levels recorded.

Time and value of maximum temperature levels																		
Date	80%		50%		25%		5%		2%		Int. Surface		Ext. Surface		Indoor Air		Outdoor Air	
2013	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.
24-Jul	17:05	35.8	00:05	29.8	20:35	28.9	19:40	28.9	19:40	28.9	19:40	28.3	14:35	49.3	18:30	30.4	13:15	33.8
25-Jul	17:20	36.4	23:30	29.8	23:30	28.9	19:35	28.9	19:45	28.8	19:50	28.4	15:00	51.4	19:40	30.5	12:50	33.3
26-Jul	17:15	36.3	23:55	30.1	23:55	29.1	20:05	29.2	19:45	29.1	19:50	28.7	14:35	51.4	12:55	30.8	17:00	34.3
27-Jul	17:15	36.2	01:00	30.1	00:00	29.2	19:40	29.2	19:40	29.2	19:50	28.7	14:45	51.3	18:50	30.8	14:35	34.1
28-Jul	17:00	35.7	00:50	30.1	00:50	29.2	19:45	29.1	19:40	29.0	19:40	28.5	14:40	50.7	19:30	30.7	15:00	32.8
29-Jul	17:10	35.8	00:25	29.9	00:25	29.0	22:45	28.9	19:40	28.9	20:15	28.3	14:35	51.2	17:55	30.4	15:40	31.8

Time and value of minimum temperature levels																		
Date	80%		50%		25%		5%		2%		Int. Surface		Ext. Surface		Indoor Air		Outdoor Air	
2013	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.	Time	Temp.
24-Jul	06:55	27.01	14:20	28.71	14:55	28.4	06:15	28.0	05:55	27.7	05:50	27.1	06:20	24.9	01:55	27.7	01:05	25.8
25-Jul	07:05	27.06	14:40	28.73	15:15	28.5	02:20	28.0	01:35	27.8	02:05	27.2	06:25	24.9	01:05	27.4	20:50	25.2
26-Jul	07:25	27.28	14:10	28.98	16:00	28.8	00:55	28.4	00:00	28.2	00:00	27.7	06:15	25.2	00:00	28.4	00:55	26.4
27-Jul	07:00	26.83	14:35	29.01	16:15	28.8	01:45	28.7	02:00	28.5	05:40	27.9	05:40	24.1	01:35	28.7	23:55	26.8
28-Jul	07:40	26.59	14:50	28.88	17:35	28.7	06:20	28.5	06:15	28.2	06:00	27.5	06:15	24.3	06:05	28.1	01:30	26.4
29-Jul	07:30	26.42	14:40	28.65	16:05	28.5	06:15	28.2	06:10	27.9	06:00	27.3	06:10	24.3	04:05	27.9	22:00	24.3

The in situ time lag results are, nevertheless, not consistent with the values given by calculations under sinusoidal boundary conditions (Table 3); these results are significantly higher and reach approximately 19 hours within a period of one day. Simple calculation methods describe the response of adobes to a periodic (sinusoidal) thermal 'forcing' of a heat flow by radiative, conductive heat transfer processes and internal convection within the pores of the wall material. These calculations are therefore based on the properties of the specific adobe material found on the wall under investigation (Table 4) and use the conventional heat transfer coefficients for the surface resistance according to EN ISO 6946, neglecting the effect of air humidity or heat transport by air flow. Cole and Sturrock (1977) provided one of the earliest reviews on the number of parameters affecting convective heat exchange coefficients in the exterior surfaces, pointing out the difficulty and importance of their estimation when in situ measurements are taken into account. Other researchers also point out the discrepancy between theoretical thermal inertia indicators and experimental values, because of the non-sinusoidal boundary conditions of the in situ values and the effects of wetting due to rain and of adsorption-desorption of water vapour due to changes in relative humidity (e.g. Gasparella et.al. 2011, Rees et. al. 2001).

Table 3: Calculation of time lag and decrement factor under sinusoidal boundary conditions

Method of calculation	Period P (hours)	Time lag $\phi$ (hours)	Decrement factor f (-)
ISO 13786	24	19.62	0.04
	72	30.60	0.30
$\frac{24L\sqrt{\rho\pi C_p}}{2\pi\sqrt{24\lambda 3600}}$	24	18.4	
	72	31.9	

Table 4: Thermal properties of adobe material

Density $\rho_b(\text{kg/m}^3)$	1405
Thermal conductivity $\lambda$ (W/mK)	0.50
Specific heat capacity $C_p[\text{J}/(\text{kg}\cdot\text{K})]$	996
Thermal diffusivity $a$ ( $\text{m}^2/\text{s}$ )	$3.57 \times 10^{-7}$

It is worth noting that, the time period for the thermal forcing is usually considered to be 24 hours. However, for high mass structures, larger periods can be considered. The diagram of hourly distribution of temperature in Fig.3 depicts the temperature flux through the wall under investigation, at all monitoring locations, for a period of 3 days in July 2013. During that period, a radical fall of the indoor air temperature is noticed every day at 19.30h, when ventilation is applied; this also affects the sensors located at 2% and 5% of the wall depth. The temperature at 25% and 50% monitoring locations remains rather stable. Yet, a closer observation of the diagram in Fig. 3 can raise an interesting discussion on the value of time lag. If we keep track of the time when the maximum temperature occurs, starting from the external surface towards the interior, the following is observed:  $\tau(T_{se\_max}) \approx 15.00$ ,  $\tau(T_{s80\%\_max}) \approx 17.00$ ,  $\tau(T_{s50\%\_max}) \approx 00.00$ ,  $\tau(T_{s25\%\_max}) \approx 00.00$ ; however  $\tau(T_{s5\%\_max})$  and  $\tau(T_{s2\%\_max})$  occur at around 20.00. The correspondence of the time when the heat wave hits every position during the 3-day period under investigation can lead to the argument that  $\tau(T_{si\_max})$  corresponds to the peak observed on the following day (i.e. time lag ca. 29 hours). This observation is in line with the results reported in Table 3. Baggs and Mortensen (2006) suggest that a 25 cm thick adobe wall presents a time lag of 9.2 hours. Andreadaki (2006) mentions a time lag of 8.1 hours for a 30 cm thick adobe wall, while for the same wall thickness Asan (2006) mentions a time lag of 8.84 hours. Houben and Guilaud (1994) refer to a range of 12.3 to 13.7 hours of time lag for a 40 cm thick adobe wall. Considering the linear correlation of wall thickness and time lag values, the in homogeneity of adobes per se and the in situ measurement conditions (e.g. presence of moisture), the literature review reveals adequate correspondence with the research findings reported here.

#### 4. CONCLUSIONS

The high time lag ( $\geq 5$  hours) and low decrement factor ( $< 0.05$ ) values recorded in this paper confirm the thermal stability in the indoor environment of adobe structures. The time lag values calculated according to the equations introduced by Asan (2006) for a period of 24 hours are significantly lower than respective values calculated according to numerical methods under sinusoidal boundary conditions. Furthermore, the in situ data for a 3-day monitoring period also suggest time lag values exceeding 5 hours. This is in line with other studies mentioned in the literature and points towards the need for the evaluation of the time lag of massive adobe walls taking into account longer periods of time.

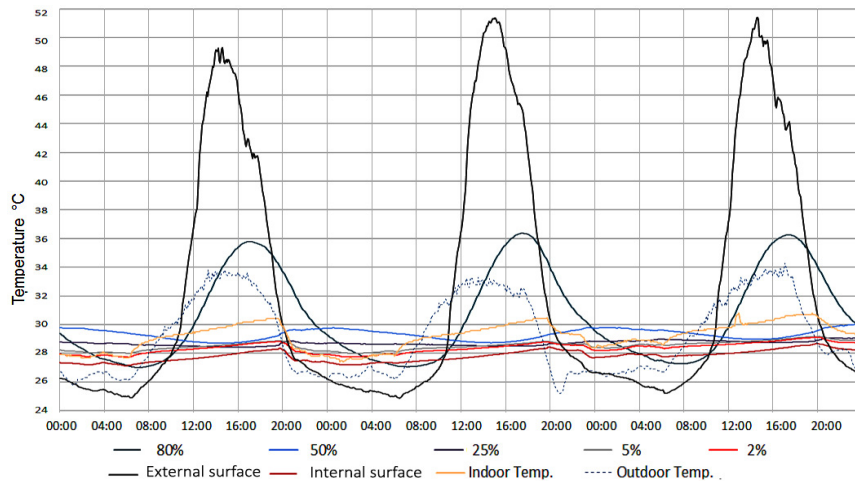


Fig. 3: Hourly temperature distribution in all sensor locations during 3 days in July 2013.



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