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Study of the dynamic thermal behavior of the walls of standard constructions in Madagascar

RABEMANANTSOA Herimamy N.[1] – RAHELIARILALAO Bienvenue[2]

1 : Dr. Ing., Centre National de Recherches Industrielle et Technologique (CNRIT) – 101 Antananarivo, Madagascar.
2 : Professor, Ecole Doctorale Ingénierie et Géoscience (INGE) – Université d'Antananarivo, 101 Antananarivo, Madagascar.

Corresponding author: RABEMANANTSOA Herimamy N.
Address: Centre National de Recherches Industrielle et Technologique (CNRIT), BP 2694, 101 Antananarivo, Madagascar.
E-mail: rabemanantsoaherimamy@gmail.com
Phone number: +261 34 13 877 38 / +261 33 46 053 02.

ABSTRACT

Passive housing guarantees a comfortable indoor climate in all seasons without having to resort to expensive systems in terms of energy consumption. Building materials, thanks to their thermal inertia, the ability on the one hand to slow down and attenuate the propagation of thermal wave fluctuations and on the other hand to absorb and store energy, play a major role in this sense. The object of this article is to determine the thermal inertia of earth-based walls, shaped in brick or not, typical envelopes of dwelling houses in Madagascar. The study is based on the dynamic thermal characteristics defined by the international standard ISO 13786. This also specifies the methodological for their calculations. The results are intended to guide the choice integrating thermal comfort with low energy consumption in future constructions. They show that the thickness of the wall has a significant effect on the time lag as well as the decrement factor of the daily variations of the temperature. It follows that, compared to brick walls, rammed earth walls present a greater capacity to absorb, store and release heat. It can be deduced that building designed with such an envelope provide better thermal comfort during hot seasons in the highlands where tropical climate is tempered by altitude and throughout the year in other regions. These encouraging results prove that traditional earth constructions have their place in sustainable building today.

Key words: Thermal inertia – Time lag – Decrement – Rammed raw earth – ISO 13786 - Heat transfer matrix

1. INTRODUCTION

The international standard ISO 13786 was developed to provide an assessment instrument capable to quantify the characteristics describing the dynamic thermal behavior of building components under the influence of thermal stresses (temperatures and heat flows) varying on their faces **[1] [2]**. The thermal lag and the decrement factor are generally the two characteristics taken into account **[3] [4]**. They describe the thermal inertia of the entire building envelope or part of it. This is a concept that covers both the accumulation of heat and its progressive restitution, with a time lag and amplitude damping **[5]**. According to *Jean Louis I.* **[6]**, it reflects the ability of the wall to oppose temperature variations. Many authors have shown the link between inertia and the thermal comfort and energy efficiency of buildings, defined as an imposing combination of minimized energy needs and consumption in both hot and cold seasons. *Norén* **[7]**, *Aste* **[8]** and *Medjelekh* **[9]** have shown its influence on the reduction of heating energy consumption for houses located respectively in Sweden, Algeria and Italy. Studies conducted in France have taken into account energy expenditure in air conditioning **[10] [11]**. The works of *Elangovan R.* **[12]** in India and *Carlos J.* **[13]** in the United Kingdom claim that thermal inertia reduces heat flux gains in summer and heat losses in winter. Investigative work undertaken in Spain has led to *De Gracia A.* **[14]** to the conclusion that the evaluation of thermal inertia leads to a better estimate of thermal comfort and the reduction of energy needs and consumption.

Due to their thermal inertia, certain constituent materials of the components favor better than others the natural regulation of the interior climate of the habitat, and this in the absence of a heating and air conditioning system. In the case of Madagascar, the household survey carried out by the National Institute of Statistics in 2010 **[15]** shows that most of the construction materials used for walls and partitions are designed with raw materials that are little transformed, whose earth, shaped brick or not. The purpose of this article is therefore to determine the parameters for evaluating the thermal inertia of earthen walls of standard constructions in Madagascar. Our main objective is to identify the structures that provide the best thermal comfort without resorting to a conventional heating or cooling system.

2. METHODS AND IMPLEMENTATION

2.1. Synoptic presentation of ISO 13786

We have opted for an analytical approach following the procedures of ISO 13786, a standard designed to quantify the characteristics describing the inertia of building components. It is dedicated to single-layer planar components or made up of several homogeneous layers subjected to unidirectional heat flows. The theoretical development of this method is based on the analogy between transient heat transfer and quadrupoles where the voltages, current intensities and electrical resistances are expressed respectively in temperatures, heat fluxes and thermal resistances. The conduction within each homogeneous planar layer, as well as the heat transfer by radiation combined with the convective exchanges between the walls in contact with the moving fluids, are represented by transfer matrices. The assembly constitutes an association of cascaded quadrupoles characterized by a transfer matrix denoted Z linking the complex amplitudes of the temperature and of the heat flow of the inlet -external face exposed to solar radiation and atmospheric conditions- and of the outlet. -face in contact with the internal ambient air- of the thermal quadrupole **[2]**.

2.2. Implementation on walls

Our investigative work focuses on four types of walls widely used in the construction of residential houses in Madagascar. We distinguish monolayers, walls erected with rammed earth called wall n°1 or with fired bricks, wall n°2. Cement mortar coatings are commonly used in cases of fired brick walls. Two-layer walls are thus obtained when the coating is applied only on the interior surface (wall n°3) and three-layer walls when both sides are covered (wall n°4).

2.3. Heat transfer matrices

Whether for monolayer or multilayer walls, the interior walls are in contact with the internal ambient air. The exterior ones are in contact with atmospheric air and directly exposed to solar radiation. For monolayer walls (n°1 and 2), the heat transfer matrix Z results from the product of the transfer matrix of the layer itself with the transfer matrices of the outer and inner boundary layers. We have:

$$Z = \begin{pmatrix} Z_{ii} & Z_{ie} \\ Z_{ei} & Z_{ee} \end{pmatrix} = \begin{pmatrix} 1 & -{}^{1}/_{h_e} \\ 0 & 1 \end{pmatrix}_{ext} \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} 1 & -{}^{1}/_{h_i} \\ 0 & 1 \end{pmatrix}_{int} \qquad (1)$$

For multilayer walls, the heat transfer matrices of the coatings must also be taken into account. So we have :

- For wall n°3 :

$$Z = \begin{pmatrix} Z_{ii} & Z_{ie} \\ Z_{ei} & Z_{ee} \end{pmatrix} = \begin{pmatrix} 1 & -{}^{1}/_{h_e} \\ 0 & 1 \end{pmatrix}_{ext} \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}_b \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}_m \begin{pmatrix} 1 & -{}^{1}/_{h_i} \\ 0 & 1 \end{pmatrix}_{int} \qquad (2)$$

- For wall n°4 :

$$Z = \begin{pmatrix} Z_{ii} & Z_{ie} \\ Z_{ei} & Z_{ee} \end{pmatrix} = \begin{pmatrix} 1 & -{}^{1}/_{h_e} \\ 0 & 1 \end{pmatrix}_{ext} \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}_m \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}_b \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}_m \begin{pmatrix} 1 & -{}^{1}/_{h_i} \\ 0 & 1 \end{pmatrix}_{int}$$

(3)

The indices *m* and *b* correspond respectively to the 1cm coating layer of cement mortar and to the layer of fired clay brick.

We can discover in the ISO 13786 standard **[2]** the expressions of the elements of the heat transfer matrix of each layer of the wall and of the exterior and interior boundary layers.

2.4. Determination of the thermal lag Δt_f and the decrement factor *f*

The thermal lag represents the thermal delay with which a temperature cycle from the exterior side reaches the interior side while passing through the wall. It is related to the element argument Z_{ie} evaluated in the range from -2π to 0 according to the formula below:

$$\Delta t_f = \frac{P}{2\pi} arg(Z_{ie}) \qquad (4)$$

The decrement factor *f* represents the amount of heat produced at the inner surface by a temperature oscillation on the outer side. It is expressed by the following relation:

$$f = \frac{R_{th}}{|Z_{ie}|} \qquad (5)$$

Or R_{th} is the steady state thermal resistance of the component calculated according to ISO 6946 **[22]** without considering thermal bridges for consistency with calculations in ISO 13786. We expand their expressions below:

- Walls n°1 and 2: $$R_{th} = \frac{1}{h_i} + \frac{d}{\lambda_{éq}} + \frac{1}{h_e} \quad (6)$$
- Wall n°3: $$R_{th} = \frac{1}{h_i} + \frac{d_m}{\lambda_m} + \frac{d}{\lambda_{éq}} + \frac{1}{h_e} \quad (7)$$
- Wall n°4: $$R_{th} = \frac{1}{h_i} + \frac{d_m}{\lambda_m} + \frac{d}{\lambda_{éq}} + \frac{d_m}{\lambda_m} + \frac{1}{h_e} \quad (8)$$

d_m and λ_m are respectively the thickness and the thermal conductivity of the cement mortar.

2.5. Data required for calculations

The data required to run all the calculations fall into two groups. First of all, there are the dimensions and the thermophysical properties of each material used, recorded in table 1.

The thicknesses used in this table are those currently adopted in full-scale constructions in Madagascar **[15]**. The characteristic length H of the walls is equal to $1m^2$.

Secondly, there is microclimatic data which includes temperature data. The temperature data used are those obtained after experimental measurements on both sides of the walls of two types of measurement cells. The first cell is built with fired clay bricks and the other with rammed earth. They are carried out on an open-air site and subjected to identical, real climatic conditions.

We have designed an appropriate calculation tool, developed in an Excel environment to carry out all the calculations in order to avoid calculation errors.

3. RESULTS

All calculations have been carried out in accordance with the calculation procedures stipulated by the international standard ISO 13786.

3.1. The elements of the heat transfer matrix Z

The modules as well as the arguments of the elements of the transfer matrix Z for the four types of walls are grouped in table 2. The values of the thermal lag and the decrement factor are deduced therefrom.

3.2. Thermal lag and decrement factor

They are represented in figures 1 and 2. During the measurement campaign days, we have:

- A thermal lag Δt_f between 12.62 and 12.67 hours and a decrement factor varying around 15% for the rammed earth wall (wall n°1).
- For the simply fired clay brick wall (wall n°2), its thermal lag varies from 7.66 to 7.68 hours. With an *f* factor between 23.54% to 23.68%.
- The fired clay brick wall with a cement mortar coating on the interior side has a thermal lag of 9.04 to 9.06 hours and a decrement factor *f* of 21.37% to 21.88%.
- Finally, a thermal delay of 10.88 to 11 hours and a decrement factor of 18.93% to 19.31% were noted for the fired clay brick wall with a cement mortar coating on both sides (wall n°4).

The values of Δt_f and *f* are not constant during the measurement campaigns. However, they don't make a big difference. This can be explained by the fact that these are intrinsic parameters of the envelope. On average, the thermal lag and the decrement factor of the walls studied are:

- Δt_f =12.65h and f = 15.44% for the rammed earth wall ;
- Δt_f = 7.66h and f = 23.68% for the fired clay brick wall ;
- Δt_f = 9.05h and f = 21.62% for the fired clay brick wall with interior coating ;
- Δt_f = 10.94h and f = 19.14% for brick wall with interior and exterior coating.

4. DISCUSSION

First of all, we notice that the wall having a high thermal lag has a low decrement factor. And conversely, a small phase shift is associated with a large decrement factor *f*. Our results, like all those reported in the literature, agree well with the direct correlation between the two parameters, a correlation recognized universally **[8] [17] [18]**.

After, the rammed earth wall 40cm thick has a thermal lag of 12.65h and a daily decrement factor equal to 15.44%. This means that the temperature of the inner surface is at its maximum 12.5 hours after the temperature peaks of the outer face have been reached. At these instants, the amplitude of the temperature of the internal face represents only about 15% of that of the external face. We can say that there is a significant reduction.

Walls made of 33cm thick fired clay bricks are characterized by significantly lower delays and, therefore, higher decrement factors. Only that coated on both sides (wall n°4°) has values close to those of the rammed earth wall. The thickness and density of the materials used are probably the cause of this difference. Indeed, these two quantities are very strongly linked to the thermal inertia of a wall and several authors have attested to this **[11] [19] [20] [21]**. It has been proven that the thickness is more decisive than the nature of the component material itself. The most probative is a linear correlation, that is to say that the degree of thermal inertia increases linearly with thickness and density. The combined effect of less thickness and less mass explains why fired brick wall no. 2 without any coating has the lowest thermal inertia compared to the other two. This means that temperature peaks from the outside will be quickly transmitted inside this wall, and will be weakly damped.

It is therefore clear that the rammed earth wall with a thickness of 40cm has good abilities to delay and reduce the amplitudes of interior surface temperature and attenuate the internal temperature of the building, according to the ISO 13786 standard. This is followed by clay brick walls with interior and exterior cladding. Without coating, the latter have a very low thermal inertia given the values of its dynamic thermal characteristics.

5. CONCLUSION

The study of the dynamic thermal behavior of a building component comes down to determining its thermal inertia. This is described by the thermal lag and the decrement factor between the temperature fluctuations of the external walls exposed to atmospheric conditions and the internal walls of the building envelope, the two parameters generally taken into account in construction. Several methods can be used to carry out the study, including the international standard ISO 13786. Calculation procedures are required by this standard to arrive at the characteristics relating to the thermal behavior of a building component which allow its inertia to be interpreted. The interest of this study lies in the fact that the implementation of the calculation procedures required by the ISO 13786 standard on the walls of vernacular constructions in Madagascar made it possible to compare their dynamic thermal behavior. The results obtained allowed us to confirm the correlation between the phase shift and the decrement factor. Compared to our main objective, we were able to identify the most efficient structures among those currently implemented in standard constructions in Madagascar. Thus, the results showed that rammed earth walls have an indisputable superiority compared to other walls of the same function in terms of their ability to resist fluctuations in heat flow or external temperatures. And that the application of a layer of cement mortar on the walls of the fired clay brick wall contributes significantly to the improvement of its inertia. We deduce that a building constructed with raw earth promotes the natural regulation of the indoor climate without having to resort to a conventional heating or cooling system, by offering an almost stable indoor temperature. The rammed earth wall is therefore classified among the best passive systems for regulating the interior temperature of the building. In the context of the climatic diversity of the Big Island in particular, it provides better comfort during the hot season on the highlands benefiting from a tropical climate at altitude, and all year round in the coastal regions. These encouraging results prove that traditional rammed earth constructions have their place in the design of sustainable building, to cope with climate change.

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7. TABLES

Table 1: Thicknesses and thermophysical properties of materials.

Materials	Fired clay brick	Rammed earth	Cement mortar
Thicknesses d [cm]	33	40	1
Volumic mass ρ [kg.m^{-3}]	1400	1700	1860
Thermal conductivity $\lambda_{éq}$ [W.m^{-1}.K^{-1}]	0.54	0.80	0.98
Specific heat C_p [J.kg^{-1}.K^{-1}]	900	900	840

Table 2: Modules and Arguments of the Four Transfer Matrix Elements.

Walls	Date	Elements of the heat transfer matrix Z							
		Z_{ii}		Z_{ie}		Z_{ei}		Z_{ee}	
		Mod	Arg	Mod	Arg	Mod	Arg	Mod	Arg
Wall n°1	05/13/2019	21.15	-2.65	5.51	0.20	132.24	0.98	34.46	-2.46
	05/14/2019	21.18	-2.65	5.51	0.20	132.24	0.98	34.42	-2.46
	05/15/2019	21.22	-2.65	5.71	0.21	132.24	0.98	35.57	-2.45
	05/16/2019	21.26	-2.65	5.75	0.21	132.24	0.98	35.78	-2.44
	05/17/2019	21.21	-2.65	5.62	0.20	132.24	0.98	35.07	-2.45
	05/18/2019	21.21	-2.65	5.63	0.21	132.24	0.98	35.15	-2.45
	05/19/2019	21.23	-2.65	5.71	0.21	132.24	0.98	35.57	-2.45
Wall n°2	05/05/2019	11.64	3.14	3.59	-0.34	73.26	0.68	22.66	-2.79
	05/06/2019	11.64	3.14	3.59	-0.34	73.26	0.68	22.70	-2.79
	05/07/2019	11.64	3.14	3.58	-0.34	73.26	0.68	22.60	-2.79
	05/08/2019	11.64	3.14	3.62	-0.33	73.26	0.68	22.87	-2.79
	05/09/2019	11.64	3.14	3.64	-0.33	73.26	0.68	23.01	-2.79
	05/10/2019	11.64	3.14	3.64	-0.33	73.26	0.68	22.98	-2.79
	05/11/2019	11.64	3.14	3.54	-0.34	73.26	0.68	22.36	-2.80
Wall n°3	05/05/2019	13.78	-2.99	4.02	-0.20	82.12	0.79	24.06	-2.70
	05/06/2019	13.78	-2.99	3.95	-0.21	82.12	0.79	23.62	-2.71
	05/07/2019	13.78	-2.99	3.94	-0.21	82.12	0.79	23.55	-2.71
	05/08/2019	13.78	-2.99	3.94	-0.21	82.12	0.79	23.59	-2.71
	05/09/2019	13.78	-2.99	4.00	-0.20	82.12	0.79	23.87	-2.70
	05/10/2019	13.78	-2.99	4.02	-0.20	82.12	0.79	23.98	-2.70
	05/11/2019	13.78	-2.99	4.00	-0.20	82.12	0.79	23.86	-2.70
Wall n°4	05/05/2019	14.53	-2.93	4.02	-0.15	92.04	0.90	25.53	-2.61
	05/06/2019	14.52	-2.93	3.88	-0.17	92.04	0.90	24.65	-2.62
	05/07/2019	14.52	-2.93	3.74	-0.18	92.04	0.90	23.73	-2.64

	05/08/2019	14.53	-2.93	3.72	-0.18	92.04	0.90	23.58	-2.64
	05/09/2019	14.54	-2.93	3.83	-0.17	92.04	0.90	24.28	-2.63
	05/10/2019	14.54	-2.93	3.99	-0.15	92.04	0.90	25.32	-2.61
	05/11/2019	14.53	-2.93	3.85	-0.17	92.04	0.90	25.46	-2.63

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10. FIGURES

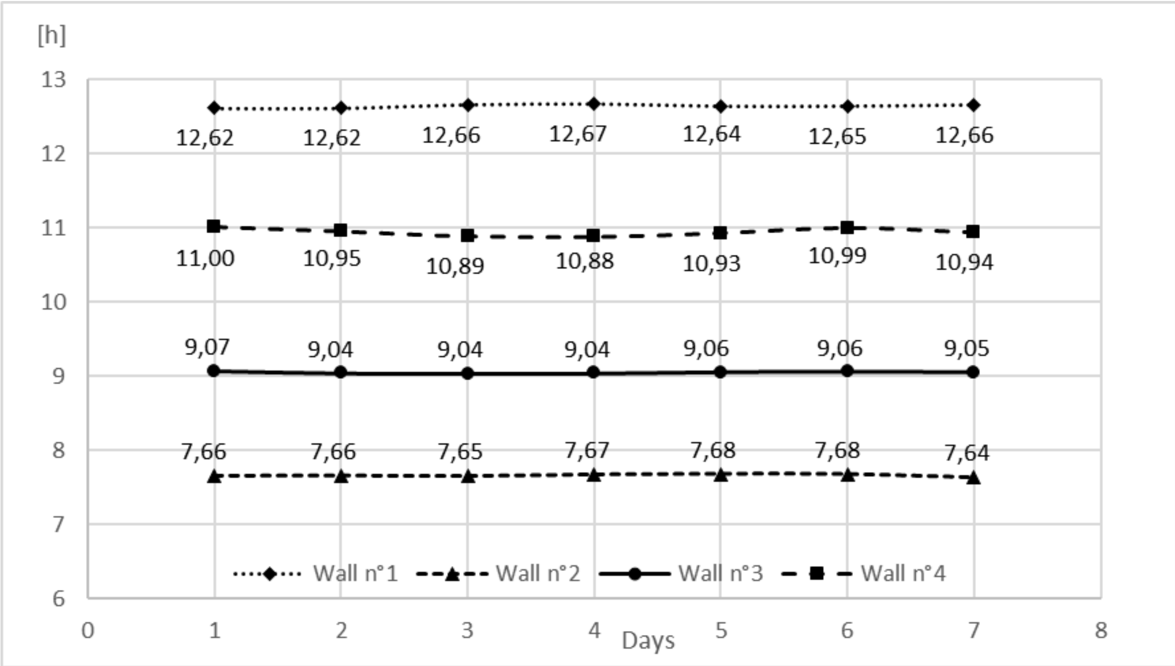

Figure 1: Daily thermal lag of the walls.

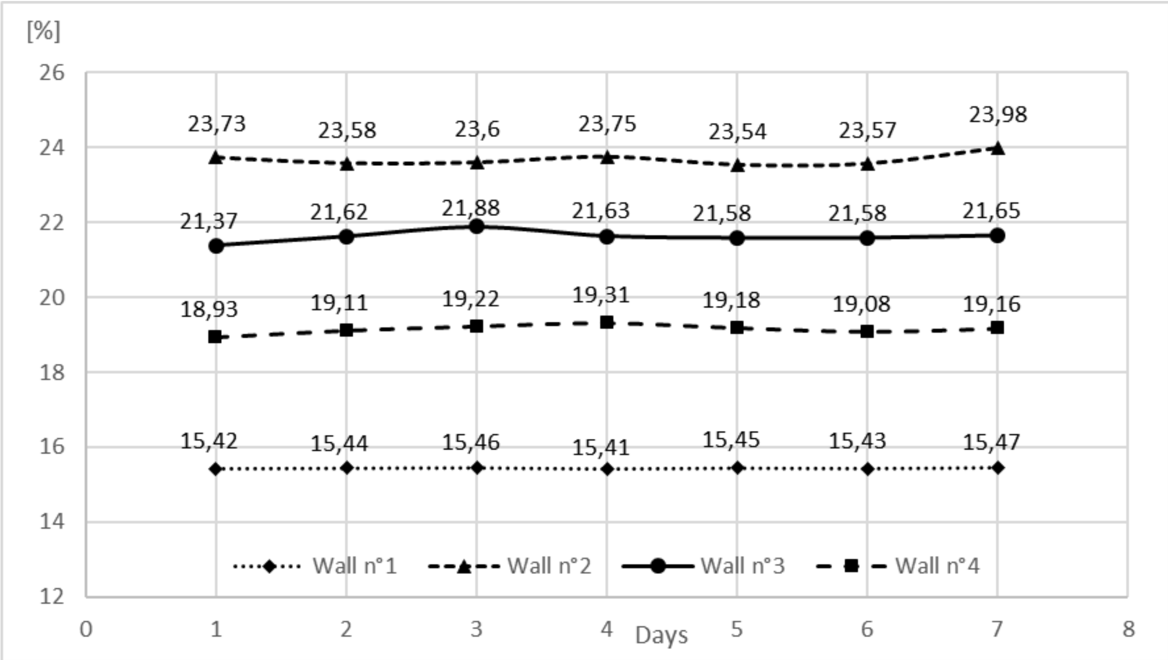

Figure 2: Daily Wall Decrement Factors.

These figures show us the thermal lag and the decrement factor of each wall recorded during the seven days of the measurement campaign.