From traditional construction towards sustainable construction: Thermophysical properties of exterior walls

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Abstract— **Nowadays, the regenerative and sustainable construction constitutes a research subject which presents strong opportunities within the framework of sustainable development. This article aims to present a review of previous researches on the thermophysical properties of exterior walls, from traditional construction to regenerative and sustainable construction. The methodology aims to a cross analysis of the previous works undertaken on the thermophysical properties of exterior walls, to know the time lag and the decrement factor, for three types of construction. From the standpoint the building materials and the wall thickness, in hot and dry climate, such as Laghouat city, south of Algeria. The exterior walls of traditional exterior are built with eco-materials (adobes or stones). The single walls of current construction are built with hollow bricks or cinder blocks. The proposed walls for regenerative and sustainable construction built with the proposed regenerative eco-materials, recently developed following an environmental and sustainable approach. The latter are the sand concrete without and with lignocellulosic materials (wood shavings and/or barley straws). The wall thickness varies from 10 to 52 cm, in order to target the optimal wall thickness buit with the stones, the adobes and the proposed regenerative eco-materials. The objective is to study the effect of wall thickness and the thermophysical properties for different building materials, on the time lag and decrement factor, from traditional construction towards regenerative and sustainable construction, in order to assess the thermophysical behavior of the different exterior walls and target the best regenerative eco-material. Finally, the approach of regenerative and sustainable construction of new buildings are focused on the search for development of regenerative eco-materials with low thermal diffusivity, which characterizes the concept of thermophysical properties or thermal inertia of the building material scale, intended for the opaque building envelopes.**

Keywords— **Regenerative and sustainable construction, traditional construction, current construction, building envelope, thermophysical properties of walls.**

I. Introduction

Nowadays, the regenerative and sustainable construction constitutes a research subject which presents strong opportunities within the framework of sustainable development. It should be noted that the thermophysical properties of exterior walls (time lag and decrement factor) of exterior wall depend on the thermophysical properties of building materials, the wall thickness [1]. The thermal behavior analysis in a building is very important, as designers tend to decrease the heat transmission across walls as much as possible [2]. The time lag is the difference in time between the exterior and interior heat wave peaks, compared to the 24 h of a day. The main challenge of time lag is to limit the discomfort caused by significant temperature variations in buildings and to reduce energy consumption in winter and summer. Building envelopes with higher time lag is an appropriate strategy to reduce energy consumption and improve indoor thermal comfort [3].

In this context, thermal inertia is one of the main characteristics of traditional construction, and one of the basic principles of bioclimatic architecture. Several studies have shown that the design of traditional houses in hot and dry climate are adapt to climatic conditions of the site, and is more comfortable than modern houses of current architecture [4]. For example, south of Algeria, during the warm days, the traditional house was comfortable without the need for an active air-conditioning system, allowing for a demand reduction. In contrast, the current houses, which required air conditioning and sophisticated equipment to suit the occupants' thermal comfort demands, resulted in a significant increase in energy demand [5]. Traditional construction has always endeavored to use local building materials adapted to climatic conditions, in order benefits from a long time lag, in the transfer of heat between outside and inside with a high storage capacity opaque envelope [4].

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This article aims to a cross analysis of the previous works undertaken on the thermophysical properties (time lag and decrement factor) of exterior wall for three types of construction. From the standpoint the building materials and the wall thickness, in hot and dry climate, such as Laghouat city, south of Algeria. The exterior walls of traditional construction are built with eco-materials (adobes or stones). The single walls of current construction are built with hollow bricks or cinder blocks. The proposed walls for regenerative and sustainable construction built with the proposed regenerative eco-materials, recently developed following an environmental and sustainable approach. The wall thickness varies from 10 to 52 cm, in order to target the optimal wall thickness buit with the stones, the adobes and the proposed regenerative eco-materials. The wall thickness of hollow bricks or cinder blocks is 20 cm.

In this work, the proposed regenerative eco-materials are the sand concrete without and with lignocellulosic materials (wood shavings and/or barley straws), which are considered as new lightweight composites based on the valorization of local materials and waste in construction is an environmental and sustainable approach. These new lightweight concretes have light densities and therefore improved thermal properties (thermal conductivity, specific heat and thermal diffusivity). This approach contributes to improving the thermophysical properties of exterior walls (time lag and decrement factor).

The objective is to study the effect of wall thickness and the thermophysical properties for different building materials, on the time lag and decrement factor, from traditional construction towards regenerative and sustainable construction, in order to assess the thermophysical behavior of the different exterior walls, and target the best regenerative eco-material. On the other hand, is to target the best constructive technique of exterior walls.

II. Thermophysical Properties of Exterior Wall

In this work, the heat flux through the wall was assumed in one direction (x) and depends on the time (t). The equation of heat transfer by conduction is, therefore, a function of (T, t, x), it is written as follows [3]:

$$k\frac{\partial^2 T}{\partial x^2} = \rho c_P \frac{\partial T}{\partial t}, \quad (1)$$

When (k) is the thermal conductivity, (ρ) is the density and (cp) is the specific heat of the material constituting the wall. To solve this problem, two boundary conditions and an initial condition are required [3]:

$$\begin{aligned} k\left(\frac{\partial T}{\partial x}\right)_{x=0} &= h_i[T_{x=0}(t) - T_i], \\ k\left(\frac{\partial T}{\partial x}\right)_{x=L} &= h_o[T_{sa}(t) - T_{x=L}(t)]. \end{aligned} \quad (2)$$

When h_i is the coefficient of heat transfer by convection to the interior wall surface, ho is the coefficient of heat transfer by convection from the exterior wall surface, $T_x = 0$ is the temperature of the interior wall surface, $T_x = L$ is the temperature of the exterior wall surface, T_i is the temperature of the "test room" and T_{sa} (t) is the sol-air temperature.

Time lag (***TL***) or ‘‘thermal dephasing” and the decrement factor (***DF***) are the thermophysical properties of exterior walls. The time lag (***Tl***) determines the capacity thermal storage for building materials. The time it takes for the temperature to propagate from the exterior surface to the interior surface is called the “time lag”, as shown in Fig. 1. The time lags are calculated by the following equation [3]:

$$\boldsymbol{TL = t.T_e^{max} - t.T_i^{max}\ (h)} \quad (3)$$

t.Temax = Time of the maximum temperature of exterior wall surface.

t.Timax = Time of the minimum temperature of interior wall surface.

During the propagation of the temperature from the exterior wall surface to the interior wall surface for a period (P = 24 hours), its amplitude will decrease according to the thermophysical properties of building materials. This means that when the temperature reaches the interior surface of the wall, it will have considerably lower amplitude than the amplitude of the exterior surface of the wall [6], as shown in Fig. 1. The decrement factor (***DF***) is determined by the following equation [3]:

$$\boldsymbol{DF = \frac{A_{int}}{A_{ext}} = \frac{T_i^{max} - T_i^{min}}{T_o^{max} - T_o^{min}}} \quad (4)$$

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$A_{interior}$: Temperature difference of the amplitude of the interior surface of the wall.
$A_{exterior}$: Temperature difference of the amplitude of the exterior surface of the wall.
Where are the amplitudes of the temperature in the interior and exterior surface of the wall. It should be noted that the temperature on the exterior wall surface, includes the temperature of the exterior air combined periodically with solar radiation and convection between the air of the exterior wall surface and the exterior air.

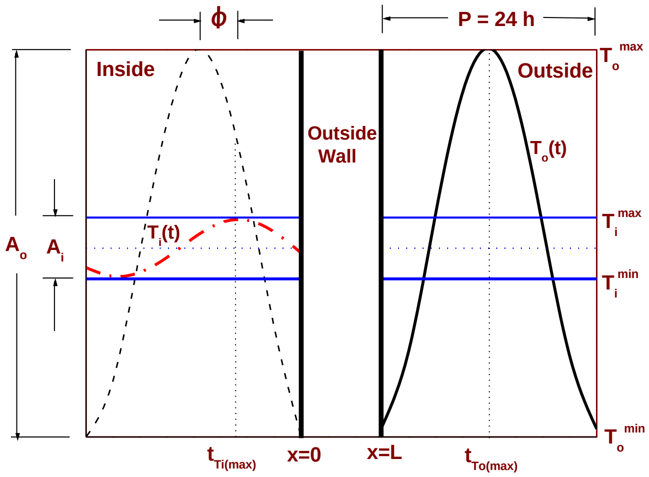

Fig. 1 Schematic representation of thermophysical properties of wall (Time lag (***TL***) and decrement factor (***DF***)) [6]

III. Methods

The time lag and decrement factor are obtained by numerical simulation with EnergyPlus softoire. The main data of the numerical simulation are the geographical coordinates of the Laghouat city, the climatic data of the summer day, and the thermophysical properties of the building materials of the built exterior walls. Laghouat city is located 400 km south of Algiers: Longitude = 2.87°E, Latitude = 33.80°N and Altitude = 765 m. Laghouat city is located in the north climatic zone (D), which is characterized by both seasons, hot-dry climate in summer and cold in winter.

The numerical simulation was made by the EnergyPlus software and applied to the studied walls supposed to be located in Laghouat city. The weather data for the summer day are: the maximum outside temperature = 42.2°C and minimum outside temperature = 24.9°C. The cell dimensions ‘‘test room” (2 x 2 x 2.5 m), are inspired of the literature [7]. The thermophysical properties of the building materials used in the studied walls are shown in Table I.

By using the EnergyPlus software (Version 1.2.2.030), we can get through time, in hours of the day, the temperature of the outside wall surface, the temperature of the inside wall surface and the temperature of the indoor air of cell "test room" whose dimensions are (2 x 2 x 2.5 m). The envelope of the cell has a door (0.60 x 1.70 m) in the wall oriented to the south.

TABLE I
Thermophysical Properties of Building Materials

Building materials	**Thermal conductivity (W/mK)**	**Specific heat (J/kgK)**	**Density (kg/m^3)**
Adobes [8]	0.75	900	1500
Stones [9]	1.1	1043	2000
Cinderblocks [10]	1.10	1080	1300
Hollow bricks [10]	0.48	936	900
SC [1]	1.40	1209	2003
SC-BS-15 [1]	1.32	1560	1895
SC-LM-35 [6]	1.00	1821	1470
SC-WS-60 [11]	0.80	1876	1368
Cement mortar [12]	1.4	1200	2100
Plaster [12]	0.5	1000	1300
Lime mortar [12]	0.87	1079	1800

IV. Results and Analysis

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A. Analysis of previous works for south walls

It should be noted, that the south orientation constitutes a compromise between summer and winter, which will contribute favorably to improve the thermal comfort level in summer. Knowing that the recommended time lag is ≥ 8 hours in accordance with the recommendation of the climatic zone of Laghouat city [7]. The objective is to target the houses typology with low thermophysical properties of exterior walls (low thermal inertia) and the houses typology with thermophysical properties of exterior walls (high thermal inertia).

The results of the numerical simulation as well as the equations (3 and 4) allow us to calculate the different time lags (***TL***) and the decrement factors ***(DF)***. According to Table II, we can conclude that: The outside walls of traditional houses are built during (1852-1970) with eco-materials, such as the adobes (wall thickness 42 cm) or the stones (wall thickness 32 cm), which are considered as exterior walls with high time lag [13]. The exterior walls of current houses are built during (1970-2024) with hollow bricks or cinderblocks (wall thickness 22 cm), which are considered as exterior walls with low time lag [13].

Furthermore, towards a regenerative and sustainable approach to houses are considered as exterior walls with high thermal inertia. The advantage is in favor of lightweight regenerative eco-materials with improved thermophysical properties, such as (SC-LM-35) and (SC-WS-60), with the optimal wall thickness is 20 cm. This is explained by the low thermal diffusivity [14], such as for the (SC-LM-35 = 0.373 m^2/s ($x10^{-6}$)) and (SC-WS-60 = 0.311 m^2/s ($x10^{-6}$)) compared to (SC = 0.578 m^2/s ($x10^{-6}$)) and (SC-BS-15 = 0.592 m^2/s ($x10^{-6}$)).

TABLE III
RELATIONSHIP BETWEEN WALL THICKNESS AND TIME LAG FOR SOUTH WALLS

House typologys	Traditional houses		Current houses		Towards a regenerative and sustainable approach to houses			
Building materials	Used eco-materials		Used building materials		Proposed regenerative eco-materials			
Wall thicknesses	Adobes [8]	Stones [9]	Cinder blocks [10]	Hollow bricks [10]	SC [1]	SC-BS-15 [1]	SC-LM-35 [6]	SC-WS-60 [11]
10 cm	-	-	-	-	3 h	4 h	4 h	4 h
12 cm	4 h	4 h	-	-	-	-	-	-
15 cm	-	-	-	-	4 h	5 h	6 h	6 h
20 cm	-	-	-	-	6 h	7 h	**8 h**	**8 h**
22 cm	7 h	7 h	**6 h**	**7 h**	-	-	-	-
25 cm	-	-	-	-	**8 h**	**9 h**	9 h	10 h
32 cm	10 h	**10 h**	-	-	-	-	-	-
42 cm	**12 h**	9 h	-	-	-	-	-	-
52 cm	9 h	9 h	-	-	-	-	-	-

- **SC**: Sand concrete (density **(ρ)** = 2042 kg/m^3**)**;
- **SC-BS-15**: Sand concrete lightened by 15 kg/m^3 of barley straws (density **(ρ)** = 1895 kg/m^3**)**;
- **SC-LM-35**: Sand concrete lightened by 35 kg/m^3 of barley straws and wood shavings (density **(ρ)** = 1470 kg/m^3**)**;
- **SC-WS-60**: Sand concrete lightened by 60 kg/m^3 of wood shavings (density **(ρ)** = 1368 kg/m^3**)**.

When the wall thickness increases, the time lag increases following linear equation having a positive trend whose correlation coefficients approximate 1 (R = 0.99591) as shown in (Fig. 2) for different building materials, these linear trends are similar to literature results [15]. It should be noted that the advantage of the results is in favor proposed regenerative eco-materials with low density. In general, when the lignocellulosic materials content increases, the density decreases; which contributes to decreasing the thermal diffusivity which is a function of thermal conductivity (**k**), specific heat (**c**) and density (**ρ**). The thermal diffusivity (***a***) is determined by the following equation:

$$\mathbf{a = k / \rho . c} \qquad (5)$$

However, when the wall thickness increases, the ***(DF)*** decreases (Fig. 3), following polynomial equation having a negative trend strong, whose correlation coefficients approximates 1 (R^2 = 0.98241). Moreover, when the (***TL***) increases, the (***DF***) decreases following polynomial regression, with a correlation coefficient (R^2 = 0.9977) as shown in (Fig. 4) for different building materials. These correlation trends are similar to literature [15].

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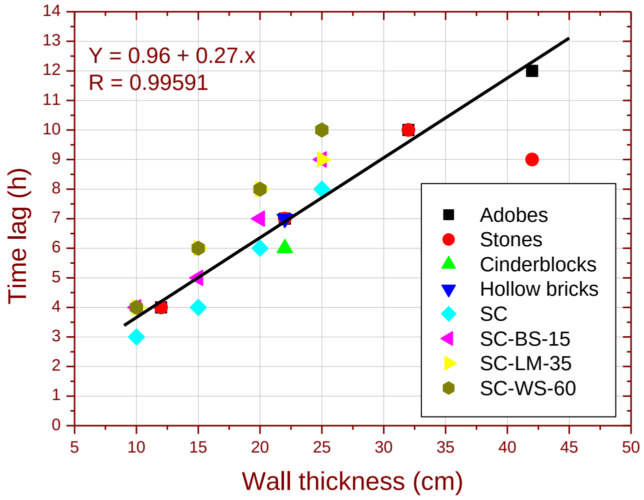

Fig. 2 Relationships between wall thickness and thermophysical properties of wall for different building materials

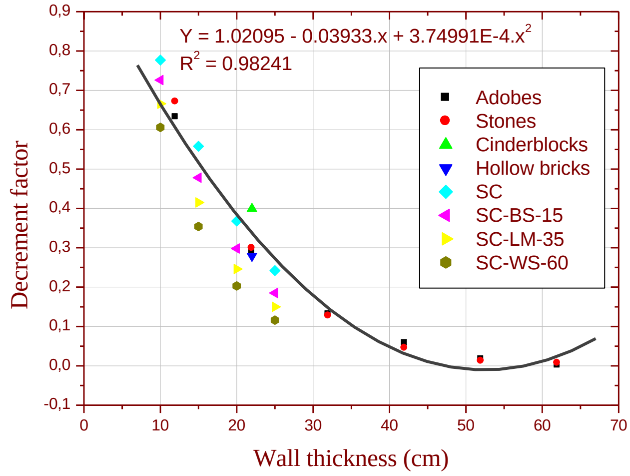

Fig. 3 Relationships between wall thickness and thermophysical properties of wall for different building materials

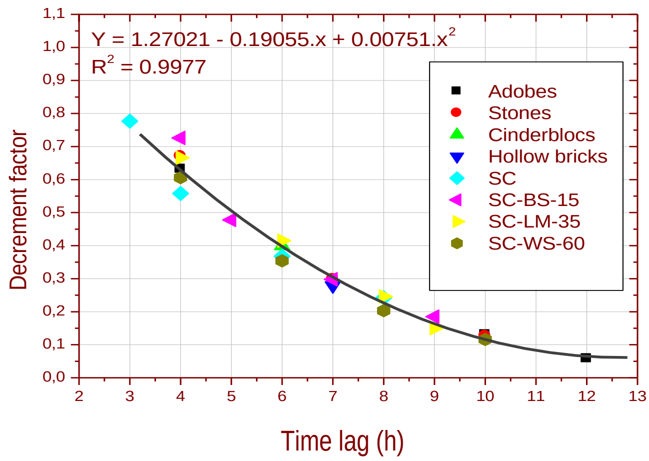

Fig. 4 Relationships between wall thickness and thermophysical properties of wall properties for different building materials

B. Walls built with proposed regenerative eco-materials for south walls

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Fig. 5 shows the existence of a positive linear trend between wall thickness and (***TL***) for the regenerative eco-material. When the wall thickness increases, the (***TL***) increases with a correlation coefficient (R = 1) for (SC-WS-60) and very close to 1 for the other regenerative eco-materials. These linear trends are similar to the literature [15]. The advantage is in favor of regenerative eco-material with improved thermal diffusivity [14].

Fig. 6 when the wall thickness increases, the decrement factor decreases, which is similar to the literature [15]. It should be noted the existence of a strong relationship between the (***TL***) and the (***DF***) for the different wall thicknesses, as shown in Fig. 7. When the (***TL***) increases, the (***DF***) decreases, following polynomial equations, with correlation coefficients very close to 1 for the different regenerative eco-materials. The advantage is always in favor of lightweight regenerative eco-materials (low thermal diffusivity).

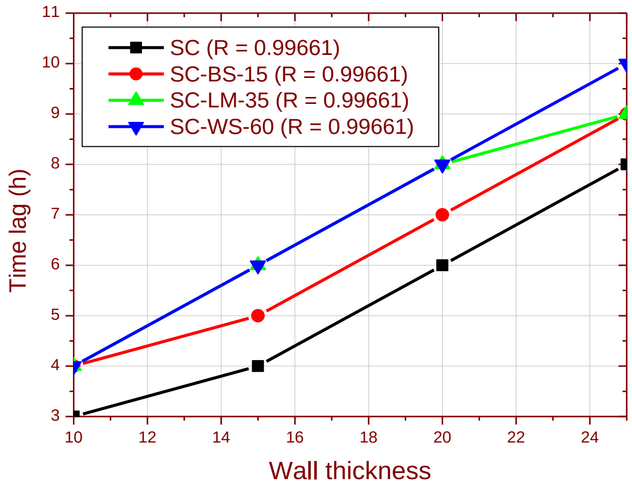

Fig. 5 Relationship between wall thickness and thermophysical properties of wall for proposed regenerative eco-materials

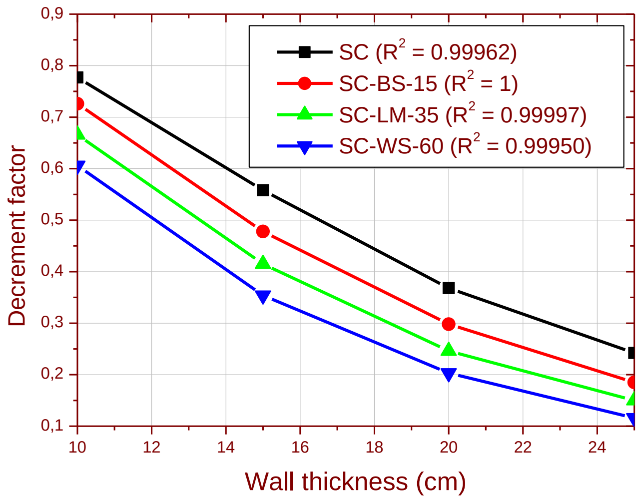

Fig. 6 Relationship between wall thickness and thermophysical properties of wall for proposed regenerative eco-materials

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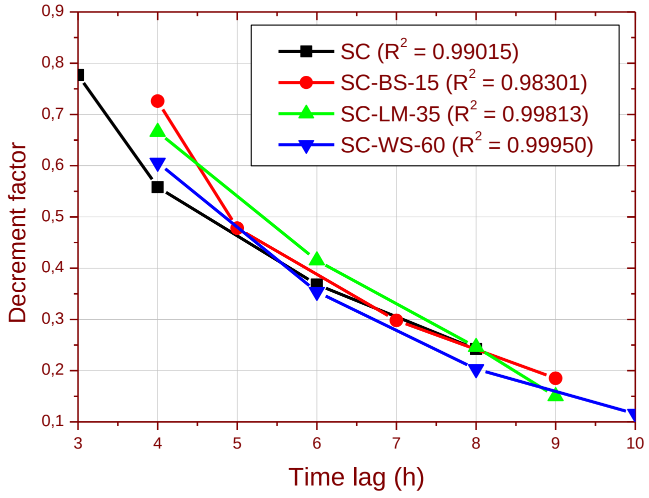

Fig. 7 Relationship between wall thickness and thermophysical properties of wall for proposed regenerative eco-materials

C. Effect of orientations of double walls

Summary the results of the simulation are reported in (Fig. 8 and Fig. 9) and equations (3 and 4) are used to calculate the time lag (***TL***) and the decrement factor (***DF***) of the four walls of the proposed regenerative eco-materials.

To further improve the thermophysical performance of the wall made from proposed regenerative eco-materials in the cases of double-walls (10 + 5 + 10 cm) with coatings for interior and exterior wall surfaces of 1 cm thick was led. Fig. 8 and Fig. 9 show the advantageous effect of double wall with a thickness of 27 cm. It was found that the best regenerative eco-material is (SC-WS-60) because all the orientations of the wall gave a (***TL***) ≥ 8 hours. Moreover, the (SC-LM-35) presents the best compromise between the properties of thermophysical properties of wall, with a (***TL***) ≥ 8 h for all orientations, except the 'west' orientation with (***TL***) = 7 hours, but the time lag remains, nevertheless, acceptable, because it is very close to the recommended time.

For example, of the simulation results shown in Fig. 10 and equations (3 and 4) are used to calculate the time lag (***TL***) and the decrement factor (***DF***) of the various orientations of double walls (SC-WS).

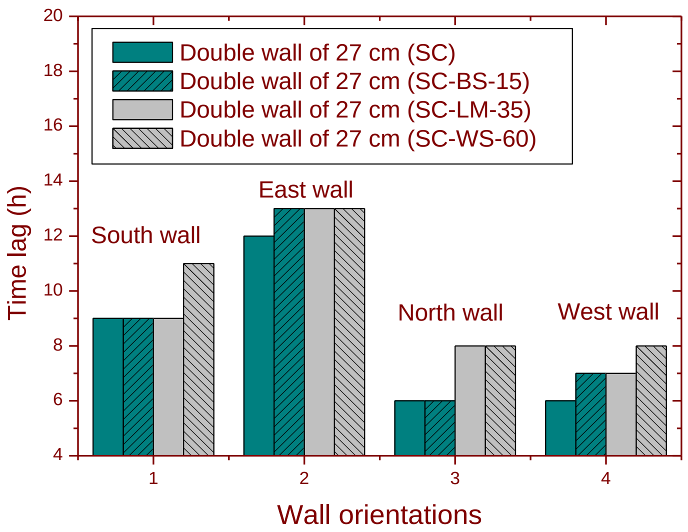

Fig. 8 Effect of wall orientation on time lag and decrement factor – Case of double wall –

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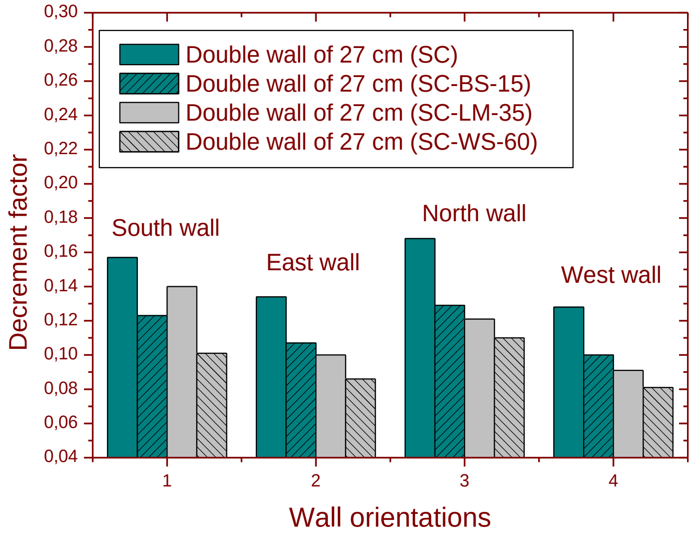
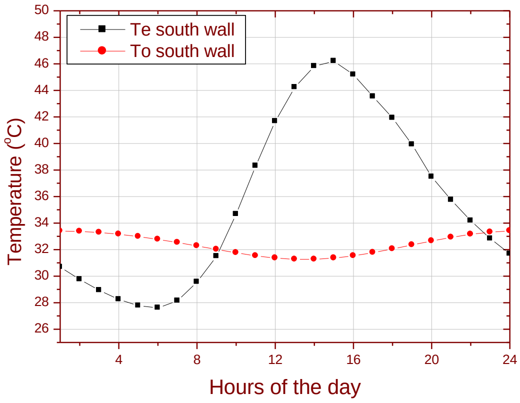
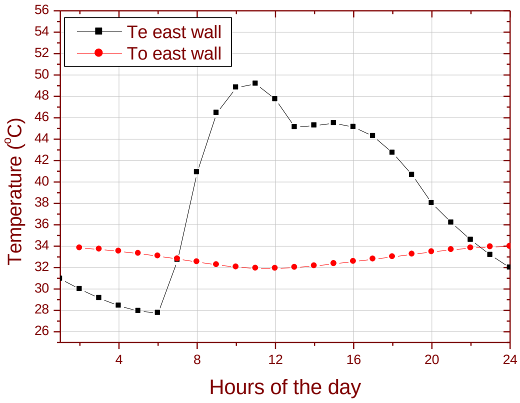


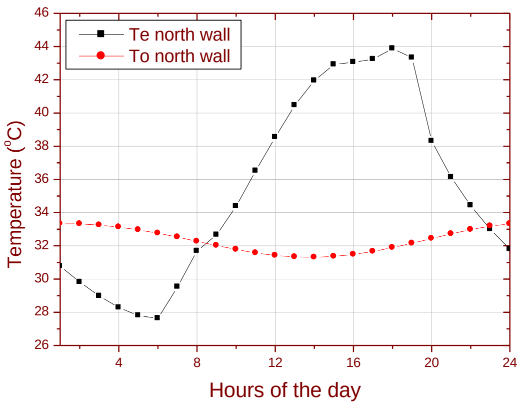
Fig. 9 Effect of wall orientation on time lag and decrement factor – Case of double wall –



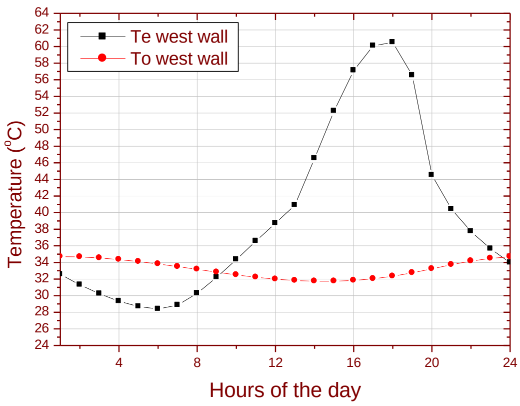
a) Temperature of exterior and interior wall surface by (SC-WS-60) of south orientation



b) Temperature of exterior and interior wall surface by (SC-WS-60) of east orientation



c) Temperature of exterior and interior wall surface by (SC-WS-60) of north orientation



d) Temperature of exterior and interior wall surface by (SC-WS-60) of west orientation

Fig. 10 Effect of wall orientation on time lag and decrement factor – Case of double wall built with (SC-WS-60) –

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In the region hot and dry climates, the daily temperature amplitude, the difference in temperature between day and night, is significant. It is necessary to resort to one of the strategies of hot and dry climates, such as using the principle of thermal inertia (thermophysical properties of the wall) and the orientation of the walls, which are among the basic principles of bioclimatic architecture or eco-architecture.

The calculation of the time lag and the decrement factor provide an indirect index of the thermal comfort conditions interior, while offering the possibility to design strategies on the reduction of the requested energy load and consequently to reduce the energy consumption of buildings [16].

One of the strategies of bioclimatic or sustainable architecture is the climate zoning approach, which contributes to better thermal comfort with reduced energy consumption, so you have the spaces according to their energy needs, that is to say, the need to develop a "climate zoning" by combining the habitable spaces following the south orientation and the east, and the service areas (buffer zones) of the north orientation and west. Moreover, this finding on the preferred orientation is consistent with the recommendation of the literature [1,17]. This recommendation from the literature is consistent with sand concrete without wood shavings. Nevertheless, the sand concrete lightened by the wood shavings all the orientations are right.

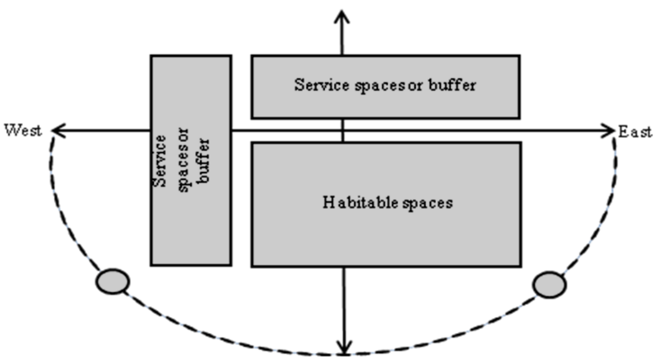

Fig. Climate zoning [16]

V. Conclusions

The development of a new eco-sand concrete based on wood shavings, which is considered as an insulating-bearer lightweight sand concrete, may led to many benefits, such as the use of local materials that are available in large quantities and at low cost, reuse of industrial waste, reduction of CO_2 emissions, durability of building materials and finally reducing the energy consumption during the production phase and operating through the development of a material constituting the exterior wall of a building possessing a long time lag and a low decrement factor.

Indeed, in arid environments, this type of lightweight concrete allows to minimize the impact of exterior climate factors and thus contribute to improve the level of thermal comfort with reduced energy consumption. Note that the materials developed are interesting by their thermal behavior. Their mechanical characteristics also allow a compatible design with modern constructions.

The thermophysical properties of wall (time lag and decrement factor) is among the most important characteristics of traditional construction to achieve thermal comfort following a passive strategy of bioclimatic architecture. Traditional construction has always endeavored to use local building materials adapted to climatic conditions.

For the current construction, it is necessary to move towards a thermal retrofit strategy for the existing opaque building envelopes (case of outside walls and roofs) with low thermophysical properties of wall (Time lag < 8 hours). One approach is to add a proposed regenerative eco-materials, for example with phase change materials, in order to improve the building energy efficiency, and to improve the level of thermal comfort with reduced energy consumption.

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The approach of regenerative and sustainable construction of new buildings are focused on the search for development of regenerative eco-materials with low thermal diffusivity, which characterizes the concept of thermophysical properties of the building material scale, intended for the opaque building envelopes. Moreover, these regenerative eco-materials must have a compromise between thermal diffusivity and compressive strength.

However, the requirements of a sustainable construction is to minimize the exterior climatic effects and therefore minimize energy consumption, it is therefore necessary to provide eco-materials having reduced thermal conductivity and high specific heat in order to have a high thermophysical properties .

Finally, it should be noted that the obtained results are encouraging, promising in the eco-design option and are widely incentives to promote this type of wood sand concrete, as it is possible to design passive houses using the two basic principles of bioclimatic architecture in arid environment thermophysical properties of wall and wall orientation. This approach that we can qualify as eco-architectural or regenerative and sustainable architecture, contributes favorably to improve the level of thermal comfort and the reduction of energy consumption in houses in the south of Algeria.

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