Effect of the integration of hemp wool as an insulation material for the construction of the roof and external walls of a typical Moroccan building

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Abstract. This paper deals with the integration of thermal insulation in Moroccan buildings roofs and external walls in order to reduce energy consumption due to the use of air conditioning systems. The insulation material under investigation is the hemp wool, an eco-friendly material whose use allows the storage of the Carbone and help reducing greenhouse gas emissions. In order to assess the dynamic thermal performance of the typical Moroccan insulated building, a life cycle cost analysis is conducted based on annual cooling transmission loads specific to the climate of Meknes, Morocco. Optimum insulation thicknesses, energy savings and payback periods are determined for a building life-span of 20 years. Investigations are carried out based on an implicit finite difference method using a home-made code developed in Matlab.

Keywords: energy consumption; energy savings; hemp wool; optimum insulation thickness; payback period.

1. Introduction
In the context of sustainable development, the new thermal regulations in the building sector are orienting consumers towards the use of bio-based insulation materials. Contributing to the reduction of greenhouse gas emissions and temporary carbon storage, these renewable materials are derived from either plant biomass or animal biomass.

Thanks to its porous structure and its thermal insulating properties, hemp is increasingly used in eco-construction. It can be used as hemp concrete inside a wood frame structure, or as hemp wool for insulation, or even as hemp-lime mortar for coating. Colinart et al. [1] conducted an experimental study to assess the hygrothermal behavior of three hemp concrete walls. The first one was uncoated, and the others were coated with lime-sand and hemp-lime plasters. Results showed that, when the wall is coated, the levels of vapour pressure are more dampened compared to the uncoated wall, and the moisture transfers are modified thanks to the low permeability of hemp-lime and sand-lime plasters.

Costantine et al. [2] investigated experimentally the thermal behavior of hemp concrete for external building wall insulation. Results obtained for indoor temperature and relative humidity underlined the
ability of hemp concrete to dampen the outdoor climatic conditions. Then, the SPARK environment was used to validate the experimental approach. Good agreement was shown between experimental measurements and numerical values. The thermal performance of insulation materials was assessed by Gori et al [3]. The authors studied the effect of thermal insulation position on the thermal performance of a bi-layered wall. Obtained results showed that the most effective position of the insulating layer is when it is located on the outside of the building structure. Furthermore, in order to decrease the energy consumption and to realize maximum energy savings, insulation materials must be used with optimum insulation thickness. Indeed, Nematoucha et al. [4] calculated the required insulation thickness with the corresponding energy savings for buildings in two different cities with two different climates. Two wall structures were considered: compressed stabilized earth wall and concrete block wall. The insulation material used was the extruded polystyrene. Results showed that in the city of Yaounde which is characterized by an equatorial climate, optimum insulation thickness and energy savings for the south facing wall were equal to 0.08 m and 51.69 $/m², respectively. For the city of Garoua which is characterized by a tropical climate, optimum insulation thickness calculated for a north orientation wall was obtained as 0.11 m and energy savings as 97.82 $/m². Furthermore, Based on the isotropic model of Duffie and Beckman [5], Ibrahim et al. [6] determined the optimum insulation thickness according to cooling requirements in buildings located in the city of Beirut, Lebanon. The insulation material chosen was extruded polystyrene, and the optimum insulation thicknesses obtained are 4.9, 4.8, 4.1 and 4.1 for the west, east, north and south orientations, respectively.

In this study, hemp wool is used as bio-based insulation material. Afterwards, considering only cooling requirements specific to the Moroccan city of Meknes, a life cycle cost analysis is applied in order to calculate optimum insulation thicknesses for roof and external walls of a Moroccan typical building.

2. Analysis and modelling

2.1. Studied configurations

![Roof configuration](image1)

![External wall configuration](image2)

**Figure 1.** (a): Roof configuration, (b): External wall configuration
Two composite wall structures are considered: the first one concerns a Moroccan typical roof configuration and the second one describes a typical external wall configuration. In the two wall structures, an insulation layer varying from 1 to 10 cm is introduced and located on the external side of the multilayer walls.

The insulation material chosen in our study is the hemp wool, a bio-based insulation material with thermo-physical properties close to those of the expanded polystyrene, the most classical insulation material [7].

The materials used in the wall structure and their thermal properties are given in Table 1.

| Material          | \( k \) (W/m.K) | \( \rho \) (kg/m\(^3\)) | \( C_p \) (J/kg.K) |
|-------------------|-----------------|-----------------|-----------------|
| Brick block       | 0.62            | 1800            | 840             |
| Concrete block    | 0.51            | 1400            | 1000            |
| Cellular Concrete | 0.22            | 600             | 880             |
| Hemp wool         | 0.04            | 35              | 1200            |
| Tile              | 1.704           | 2300            | 700             |
| Cement plaster    | 0.72            | 1865            | 840             |

### 2.2. Mathematical model

Considering constant thermophysical properties and no heat generation, the heat transfer through each layer of the external wall is governed by the transient 1D heat equation expressed as:

\[
-k_j \frac{\partial T_j}{\partial x} = \rho_j c_j \frac{\partial T_j}{\partial t}, \quad j = 1,2,\ldots,M
\]

where \( k_j \), \( \rho_j \) and \( c_j \) are the thermal conductivity, the density and the specific heat of the \( j \)th layer, respectively. \( T_j \) is the temperature, \( x \) and \( t \) are spatial and temporal coordinates.

Eq.1 is solved with the specification of an initial and two boundary conditions. As initial condition, an arbitrary uniform temperature field is assumed. The outdoor and indoor boundary conditions are given as follows, respectively [11]:

\[
-k_i \left( \frac{\partial T_i}{\partial x} \right)_{x=0} = h_o (T_o(t) - T_{x=0})
\]

(2)

\[
-k_m \left( \frac{\partial T_m}{\partial x} \right)_{x=L} = h_i (T_{x=L} - T_i)
\]

(3)

where \( h_i = 9W/m^2\cdot K \) and \( h_o = 22W/m^2\cdot K \) are the combined inner and outer heat transfer coefficients. \( T_i \) is the indoor air temperature maintained constant at a fixed design temperature \( T_i = 26^\circ C \) according to Moroccan Standard NM ISO 7730 RTCM [12]. The outside surface of the wall is exposed to the sol-air temperature \( T_o(t) \) which includes solar radiation effects on the outdoor temperature and is expressed as follows [11]:

\[
T_o = T_a + \frac{a_l T_o - \Delta R}{h_o} \frac{\varepsilon \Delta R}{h_o}
\]

(4)
where $T_a$ is the outdoor air temperature. $a$ and $I_T$ are the external wall surface solar absorptivity and the total solar radiation, respectively. $\frac{\varepsilon \Delta R}{h_v}$ express the correction factor and is assumed to be 4°C for horizontal surfaces and 0 for vertical ones [13].

The outdoor air temperature $T_a$ and the hourly values of total solar radiation $I_T$ are computed using the commercial thermal simulation software TRNSYS [14] based on Meteonorm data specific to the city of Meknes (Latitude: 33°89’ N, Longitude: 5°54’ W). The external wall surface solar absorptivity is taken equal to 0.55 [15].

The implicit finite difference method [16] is applied to solve the transient 1D heat conduction equation.

Equations are solved using matrix functions in Matlab [17]. The accuracy of the implicit finite-difference method is assessed by checking the model and making sure that its results are grid and time-step independent.

2.3. Economic model for the insulation thickness optimization

The optimum economic insulation thickness represents the value providing the lowest total life-cycle cost.

Using cooling transmission loads as input data, and based on the present worth method, an economic model is set for the determination of the optimal insulation thickness.

Cooling transmission loads are calculated from June to September. The day 15 of each month is considered as a representative day for the whole month.

The hourly variation of the inside surface heat flux is expressed as follows [18]:

$$q_i = h_i(T_{x,L} - T_i)$$

By integrating the instantaneous inside surface heat flux over a 24h period, daily total loads are calculated and then, yearly cooling loads are obtained by the addition of daily loads over the summer period considered from June to September.

Afterwards, the cost of energy consumption during a building lifetime of $N$ years is given by [19]:

$$C_{enr} = PWF \left( \frac{Q_c}{COP} \frac{C_{el}}{(3.6 \times 10^6)} \right)$$

$\textit{PWF}$ is the present worth factor, $Q_c$, $C_{el}$ and $COP$ represent the annual cooling transmission loads per unit area, the cost of electricity for cooling and the cooling system performance, respectively.

The total cost is the sum of the cost of energy consumption and the cost of insulation material. The total cost per unit area of wall is given by:

$$C_t = C_{enr} + C_i = PWF \left( \frac{Q_c}{COP} \frac{C_{el}}{(3.6 \times 10^6)} \right) + C_{ins} L_{ins}$$

$C_{ins}$ is the cost of the insulation material by unit volume and $L_{ins}$ is the insulation thickness.

Annual energy savings $A_s$ are obtained by the division of the difference between the energy costs of the wall without insulation and the wall with optimum insulation thickness by the present worth factor $PWF$.

The payback period $P_b$ is defined as the insulation cost divided by annual energy savings, and is calculated as follows:

$$P_b = \frac{C_i \cdot L_{ins(opt)}}{A_s}$$

All the parameters needed for the above economic calculations are summarized in Table 2.
Table 2. Parameters used in calculations.

| Parameter                        | Value          |
|----------------------------------|----------------|
| Electricity cost, $C_{el}$ [20]  | 0.1346 $/kWh  |
| Coefficient of performance, $COP$ [21] | 2.5             |
| Insulation cost, $C_{ins}$ [22]  | 100 $/m^3      |
| Interest rate, $g$ [23]          | 2.25 %         |
| Inflation rate, $i$ [23]         | 1.8 %          |
| Lifetime period, $N$ [24]        | 20 years       |

3. Results and discussion
The optimum insulation thickness is determined based on a life cycle cost analysis using cooling transmission loads as its main inputs.

The variation of the energy consumption cost, the insulation cost and the total cost in respect to insulation thickness for the two configurations studied are depicted in figures 2 and 3.

![Figure 2](image)

**Figure 2.** Costs variation with insulation thickness for the external wall structure: (a): south orientation, (b): east orientation, (c): north orientation and (d): west orientation.

It is clearly shown from figures that the energy cost decreases, while the insulation cost knows a linear increase with the increase of the insulation thickness. The total cost, which represents the sum of energy and insulation costs, allow the determination of the optimum insulation thickness. It corresponds to the lowest value shown by the total cost curve.
For the roof configuration, the optimum insulation thickness is obtained as 7 cm, whereas for the external wall configuration, optimum insulation thicknesses are obtained as 2 cm for the north orientation and 4 cm for south, east and west orientations.

Table 2 summarizes the values of optimum insulation thicknesses, minimum total costs, energy savings and payback periods for the roof and all orientations of the external wall.

| Wall orientation | Optimum insulation thickness (m) | Minimum total cost ($/m²) | Energy savings ($/m²) | Payback period (years) |
|------------------|--------------------------------|---------------------------|----------------------|------------------------|
| Roof             | 0.07                           | 14.4658                   | 18.1104              | 3.0266                 |
| South            | 0.04                           | 9.1539                    | 6.6251               | 7.1528                 |
| North            | 0.02                           | 5.6154                    | 1.7205               | 20.42                  |
| East             | 0.04                           | 10.9222                   | 10.2275              | 5.3417                 |
| West             | 0.04                           | 10.4861                   | 9.7949               | 5.5092                 |

One can note that the minimum and maximum total costs are provided respectively by the northern external wall and the roof structure.

Figure 3. Costs variations with insulation thickness for the roof structure.

Figure 4. Energy savings for roof and external wall.
However, in terms of energy savings, the roof insulation achieves energy savings of 63.41, 43.52, 90.5 and 45.91% more than south, east, north and west orientations, respectively (Figure 4).

Regarding the payback period, the smallest value is provided by the roof structure, followed by the east, west, south and north facing external walls.

Finally, as presented in figure 5, the use of hemp wool with optimal thicknesses for the thermal insulation of a Moroccan building has reduced annual air conditioning requirements by 77% for the roof. For the external walls, this reduction reached approximately 68% for the south, east and west orientations, and 50% for the north orientation.

![Figure 5. Annual cooling transmission loads required by roof and external walls.](image)

4. Conclusion

In this study, the dynamic thermal performance of a Moroccan typical building whose roof and external walls are insulated with hemp wool is investigated. The building is exposed to the dynamic thermal conditions specific to the city of Meknes.

Firstly, a computer program was developed in Matlab and a finite difference method was used to provide a numerical solution of the transient heat transfer equation through a multilayer wall.

Afterwards, considering a building lifespan of 20 years and based on a life-cycle cost analysis, optimum insulation thickness, energy savings and payback period were determined through the development of an economic model where the yearly cooling transmission loads are used as main inputs. Optimum insulation thicknesses are obtained as 7 cm for the roof, 4 cm for south, east, and west orientations, and 2 cm for the north orientation.

The lowest optimum insulation thickness is obtained by the north facing wall since it provides the lowest annual cooling loads. It can be considered as the most economical case. Nevertheless, this orientation gives negligible energy savings and very high payback period.

Finally, a comparison between an uninsulated building and an insulated one showed that annual cooling requirements can be reduced by at least 77 and 65% respectively, when the roof and external walls are insulated with optimum thicknesses of hemp wool.

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