Traditional Earth Architecture as a Tool for Sustainability and Adaptation to Climate Change of Heat and Cold Extremes

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Abstract. The design of sustainable architectural and urban spaces should be one of the essential pillars of any strategy for sustainable development and adaptation to climate change, particularly for the population living in rural areas who suffer from cold during winter and heat during the summer. This paper focuses on the traditional earth-based materials buildings and tries to see to what extent the building envelope could be improved to achieve and further confirm the objectives: improving thermal comfort and reducing heat loss through the traditional envelope (walls, roof, glazing, low floor). The paper is based on bioclimatic architecture principles and adopts passive energy efficiency in two different climatic contexts, hot and cold. The analysis of the approach method includes three issues: 1) the bioclimatic analysis of the environment/site including the building ambiance; 2) thermal comfort; and 3) thermal performance. The methodological tools are based on the bioclimatic analysis of the site and the ambiance for the first two issues; and the prescriptive approach of Moroccan thermal regulation for the third issue. The built environment constructed with traditional materials, once improved, is able to prove that it is respectful of the environment and without any risk to the user's health. In addition, this traditional architecture confirms the objectives of sustainable development.

Introduction

Climate change is one of our century's most complex societal and environmental challenges, and Morocco is not immune to its effects, particularly cold and heat. As a result, the energy issue is at the heart of discussions between the various stakeholders, given the importance of the social, economic, and environmental stakes for a sustainable architecture capable of withstanding more extreme climatic conditions, very cold in winter, and very hot in summer.

The training of architects and urban planners has a major role to play in mastering these social, environmental, and energy transition challenges. The aim is to provide them with the key knowledge they need to take account of the challenges of the energy transition in their professions and to identify the techniques and methods for integrating these challenges into their professional practices.

Moreover, sustainability requires a global understanding of systems and interdisciplinary collaboration between architecture, urban climate design, economics, and engineering (civil, thermal, and energy engineering, etc.). The design of sustainable architectural and urban spaces for users must be one of the essential pillars of any strategy for sustainable development and the fight against climate change, particularly for people in rural areas who suffer from the cold in winter and the heat in summer.

In Morocco, people are beginning to understand that investment in environmental quality, thermal and energy performance, is an asset and a source of sustainable savings. Energy labeling, which will directly impact the value of Morocco's built environment, will certainly bring about a change in mentality and culture among the population and those involved in the act of building.

Heritage built with traditional materials, once improved, can prove that it is environmentally friendly and poses no risk to the health of users. Sustainable development considerations call for energy efficiency on the one hand and a drastic reduction in greenhouse gas emissions on the other.

The United Nations Sustainable Development Goals (SDGs) and the National Sustainable Development Strategy remind us of the goals, specific objectives, and challenges, including SDG7: Access to sustainable energy; SDG11: Make cities and human settlements inclusive, safe, resilient, and sustainable; and SDG13: Take urgent action to combat climate change and its impacts.

Today, buildings are generally connected to the electricity grid and sometimes exploit other energy sources to meet user needs. This means they have to adapt to the local climate and resources while respecting the principles of bioclimatic architecture and thermal regulations during the design phase. The latter must satisfy two essential requirements to achieve the building's energy efficiency objectives: reduced energy consumption and improved thermal comfort, by using the Moroccan building energy efficiency regulations [1].

This paper focuses on the built environment constructed using traditional earth-based materials and looks at how we can improve the building envelope to further confirm the objectives mentioned: improving thermal comfort and reducing heat loss through the traditional envelope (walls, roof, glazing, low floor). To achieve this, we apply the principles of bioclimatic architecture and adopt passive energy efficiency measures in two different climatic contexts, hot and cold.

The analysis of the approach uses three thematic inputs: 1) bioclimatic analysis of the environment/site and building; 2) thermal comfort; and 3) thermal performance. The methodological tools are based on those relating to the bioclimatic analysis of the site and environment for the first two issues (thermal comfort indices from the Thermal Comfort Standard, NF ISO 7730) [2]; psychrometric/bioclimatic charts by Givoni [3], Szokolay [4]; Mahoney Tables [5]; and the prescriptive approach of the Moroccan thermal regulations for the third issue.

Principles of Bioclimatic Architecture

The building envelope (exterior walls, openings, roof, and basement floor) is a major lever for reducing energy needs and improving energy efficiency. A well-designed building envelope is crucial for providing lasting protection to the building's occupants from various environmental factors such as wind, cold, rain, frost, heat, and so on. In winter, it minimizes heat loss to the outside, while maximizing solar energy gain through glazed surfaces. Conversely, in summer, a good building envelope helps to keep the interior cool.

In both cases, the insulating capacity of the materials making up the envelope plays a decisive role. A good building envelope is also an effective way of improving interior comfort for occupants while minimizing the impact of construction on the environment (ecological materials, integration into the landscape, reduction of noise pollution).

Architectural choices have a major impact on a building's thermal performance. This is why, right from the pre-project phase, it is important to apply a few principles that will reduce a building's heat loss in winter and prevent it from overheating in summer. The main recommendation concerns the orientation of the building and the presence of openings to optimize solar gains. There are other generally accepted rules of the art, such as the compactness of the construction, which limits the surface area of walls in contact with the outside for a given volume, and therefore heat loss, as well as the layout of interior spaces. The architecture of the building must also anticipate summer comfort by protecting openings and bay windows.

Construction techniques and materials are constantly evolving to provide ever greater comfort and energy savings. The principles of bioclimatic architecture and thermal regulations are simple and easy to implement.

Bioclimatic analysis and local materials in two relevant climatic sites in Morocco: Midelt (cold climate) and Errachidia (warm climate)

Each site has its characteristics closely linked to the environment and climate. The architectural design must take these considerations into account to benefit from the advantages and protect against the constraints and disadvantages.

Figure 1: Built heritage in rural areas in the Province of Midelt

Figure 2: Earth-built heritage in the Errachidia Province

Bioclimatic analysis tools of the sites and interior ambiances:

Concept of thermal comfort:

Thermal comfort is defined as a state of satisfaction with the thermal environment. It is determined by the dynamic balance established by heat exchange between the body and its environment. In other words, it means being in good thermal conditions everywhere and at any time, in terms of air temperature (Ta in °C), relative humidity (RH in %), speed of air movement (Va in m/s), …. If we think in terms of the first two parameters, thermal comfort would be characterized by an average air temperature of 24°C and average relative humidity of around 48%, knowing that $20°C \leq Ta \leq 28°C$ and $28\% \leq RH \leq 68\%$. These intervals may undergo a slight change when the speed of air movement is added.

Comfort indices and strategies for evaluating thermal comfort:

The two indices, PMV- predicted mean vote, and PPD - PPD-predicted percentage dissatisfied, are part of the Thermal Comfort Standard (NF ISO 7730).

The following application allows these indices to be calculated for the two climatic contexts, cold in Midelt during the winter and hot in Errachidia during the summer. The simulation is done with the following parameters:

-In Errachidia, user activity is light with summer clothing; the air temperature is taken equal to 30°C and the average radiation temperature approximately 29°C; the airspeed is 1 m/s and the relative humidity is 45%.

-In Midelt, user activity is also light with winter clothing; the air temperature taken is equal to 18°C and the average radiation temperature approximately 19°C; the airspeed is 0.2 m/s and the relative humidity is 50%.

PMV takes into account various environmental and personal factors. The formula to calculate PMV is complex and typically requires the use of specialized software or calculators. Here is a simplified form of the equation:

$$PMV = M - W. \quad (1)$$

Where:
M represents the heat balance between the human body and its environment, taking into account factors like metabolic rate, clothing insulation, and air temperature.
W represents the work done by the body to maintain thermal balance.

In practice, detailed calculations for M and W are more involved and require input data on factors such as air temperature, humidity, clothing insulation, metabolic rate, and air velocity.

PPD is typically calculated based on the PMV. The formula for calculating PPD is also complex and involves statistical models. A simplified form of the equation is as follows:

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) . \quad (2)$$

This equation provides an estimate of the percentage of occupants who may be dissatisfied with the thermal conditions in the space based on the PMV value.

The simulation results show that we are a little far from a comfortable situation if nothing is done. We have also noticed that the indices remain in the same order of estimation for the two climates: a PMV of 1 (1.02) and a PPD close to 25% (26.9%) for Errachidia and a PMV of -1 (-0.92) and a PPD also close to 25% (22.9%) for Midelt.

We then focus on the bioclimatic approach using psychrometric charts and other bioclimatic tools. The climatic study through monthly climatic data (variations of the maximum and minimum average temperature, the maximum and minimum average relative humidity, the average precipitation, and the direction of the prevailing winds) of the nearest station characterized by its geographical position (longitude, latitude, and altitude), allows to draw the Bioclimatic Chart or Psychrometric Chart. It is a global decision support tool for the bioclimatic project making it possible to establish the degree of necessity for implementing major options to maintain thermal comfort of the environment.

This bioclimatic approach makes it possible to identify optimal comfort for the different months of the year. A comfort zone indicates the limits, for temperature, air humidity, etc., within which the climate is considered comfortable. The comfort zone is, among other things, used as an instrument to know when to use an active form of heat or cold production.

Givoni and Szokolay bioclimatic charts:

The bioclimatic diagrams of Givoni and Szokolay find their usefulness as soon as the climatic conditions deviate from the polygon or comfort zone: they suggest the constructive and functional solutions that must be adopted to design a suitable building: insulation of the envelope, ventilation, thermal inertia, solar protection, use of passive systems and, if necessary, active ones (heating and cooling).

The architectural and technical arrangements, as well as the interventions planned for the environments to remedy fluctuating climatic conditions, will correspond to the zones of influence, established by the Givoni chart and taken up by Szokolay.

From a perspective of comparison, we instead present the bioclimatic diagram of Szokolay applied to the climates of Midelt and Errachidia, which gives the same recommendations as those of Givoni, but with more precision at the level of the comfort zone framed by the main parameters of comfort: the minimum and maximum temperature and relative humidity for each climatic context. For example, the Szokolay diagram specifies the average comfort limits between 19.5°C and 25.5°C with an average of 40% relative humidity in Midelt and 21°C and 27°C with an average of 35 % relative humidity in Errachidia.

The Szokolay diagram recommendations for sites and indoor environments in Midelt are:
-Strong thermal inertia for summer;
-Passive heating through internal supplies for October, April and May;
-Active heating for the winter season and quite cold months like November and March.

The Szokolay diagram recommendations for the sites and interior environments in Errachidia are:
-Natural ventilation with dehumidification especially for September;
-High thermal inertia with night ventilation during summer;
-Passive heating through internal supplies for fairly cold months;
-Active heating during the night for the winter season.

Mahoney Tables:

The bioclimatic approach based on the Szokolay diagram is supplemented by the use of Mahoney Tables intended to summarize and analyze the climatic data of the place, to formulate and prioritize recommendations for ambiance. These tables are considered to be a simple tool to assist in bioclimatic architectural design, which makes it possible to have the first qualitative recommendations in terms of architectural arrangements, in particular simple indications on the mass plan, the shape of the building, the orientation, the inertia of the roof and the external and internal walls, the size and percentage of the openings to the surface area of the facades.

The following is a summary of the Mahoney Tables recommendations for the site of Midelt:
-Compact ground plan with north-south orientation (along the east-west longitudinal axis);
-Spacing between buildings: Compact mass plan;
-Openings: Average openings (20 to 40%);
-Walls: Massive exterior walls, phase shift time of more than 8 hours;
-Roofs: Thick, heavy roofs, phase shift time of more than 8 hours.

The following is a summary of the Mahoney Tables recommendations for the site of Errachidia:
-Compact ground plan with interior courtyard;
-Openings: Average openings (20 to 40%);
-Walls: Massive exterior walls, phase shift time of more than 8 hours;
-Roofs: Thick, heavy roofs, phase shift time of more than 8 hours;
-Space to sleep at night outdoors.

Inertia and thermal phase shift: the case of raw earth for example:

The thermal phase shift of a material or an element of the building envelope (wall or roof) plays a major role in the summer thermal comfort of the building. It represents the time between when the temperature is highest outside and when it is highest indoors. This is the time it takes for the heat to penetrate inside. This often makes it possible to avoid using costly air conditioning.

The phase shift time depends on the thickness as well as the thermal conductivity of the materials. It therefore depends on the speed of heat diffusion through the wall made up of the material or layer materials. Then the diffusivity and the phase shift time are given by the following equations:

$$a = \lambda / (\rho \times C) \ (\text{m}^2/\text{hours}). \tag{3}$$

$$\text{the phase shift time} = 1.38 \times e \times \sqrt{a} \ (\text{hours}). \tag{4}$$

Where:
-ρ is the density of the material (kg/m^3);
-C is the specific heat capacity of the material (J/kg/K) (Basic relationship: 1 KWh = 3600 KJ);
-λ is the thermal conductivity of the material (W/m/K);
-e is the wall thickness (m).

Raw earth has an important thermal property, inertia because this material has the conditions necessary to obtain it: thermal capacity, thermal diffusivity, and thermal effusivity. For example, 40 cm thick rammed earth has a thermal phase shift of around 12 hours, and the thermal capacity is about 510 W/m^3 °C for rammed earth and 380 W/m^3 °C for adobe. Thanks to its low thermal diffusivity of 2.53 10^{-3} m²/h (approximately 5.92 10^{-3} m²/h for fired brick and 5 to 6 10^{-3} m²/h for stone), the earth offers the advantage of damping and a significant phase shift in variations and external thermal inputs.

Thermal performance of construction elements made from local earth-based materials:

The thermal quality of an element of the built environment envelope can be evaluated through the U value, called thermal conductance or surface transmission coefficient of the wall, roof, or window, expressed in W/m² °C; its inverse expresses the overall thermal resistance. For a composite construction element separating two ambiances, the U value is calculated according to the following formula:

$$1/U = 1/h_i + \Sigma(e/\lambda) + \Sigma R + 1/h_e. \quad (5)$$

Where:
-e/λ is the thermal resistance specific to the different layers of materials constituting the composite construction element;
-R is the thermal resistance of other composite element materials;
-$1/h_i$ and $1/h_e$ are the interior and external surface thermal resistances;
For a vertical construction element (wall, glazing): $1/h_i + 1/h_e = 0.17$ m²°C/W.
For a horizontal construction element (roof, upward flow): $1/h_i + 1/h_e = 0.14$ m²°C/W.
For a horizontal construction element (floor, downward flow): $11/h_i + 1/h_e = 0.22$ m²°C/W.

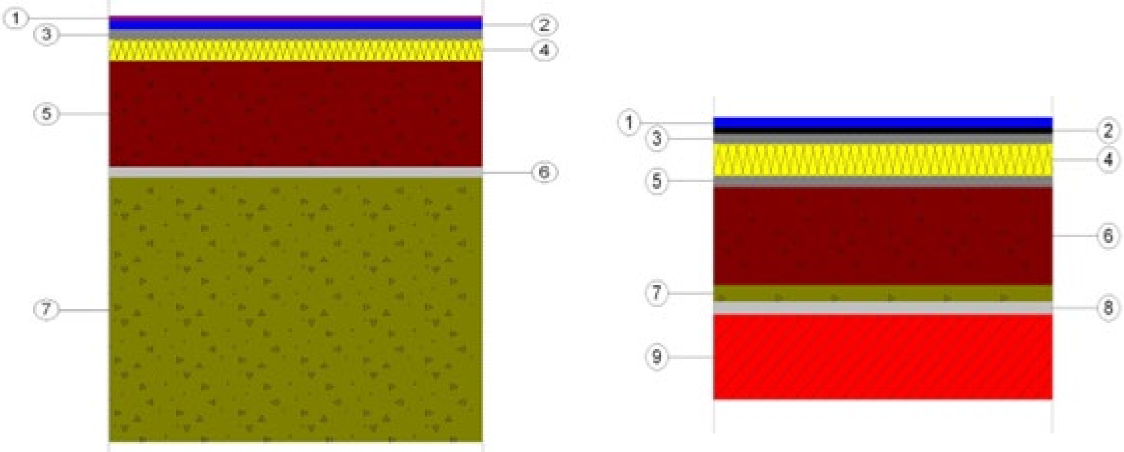
An estimation according to experience can be put forward to assess the value of U and therefore the thermal quality of each element of the envelope, and all issues will depend on the climatic context:
- Poor thermal quality: U value greater than 1.5 W/m² °C;
-Average thermal quality: U between 1 and 1.5 W/m² °C;
- Fairly good thermal quality: U between 0.8 and 1. W/m² °C;
- Good thermal quality: U between 0.5 and 0.8 W/m² °C;
- Very good thermal quality: U between 0.3 and 0.5. W/m² °C;
- Excellent thermal quality: U value less than 0.3 W/m² °C;

From the Thermal Regulation of Constructions in Morocco, two methods of verifying the conformity of buildings about thermal and energy performance: the performance approach and the prescriptive approach. The so-called performance approach defines the annual heating and air conditioning needs (expressed in kWh/m².year), according to the climatic zone and the type of building. The reference indoor temperatures for heating and air conditioning are 20°C and 26°C respectively. For humidity, the reference values are 55% and 60% respectively for winter and summer.

The so-called prescriptive approach consists of setting the technical specifications expressed, for each type of building and each climatic zone, in the form of maximum thermal transmission coefficients (U value) of the roof, exterior walls, low floor, windows as well as the equivalent solar factor of windows and the thermal resistance of low floor, depending on the Overall Rate of Bay Windows. The prescriptive approach is only applicable in the case where this rate is less than 45%.

Application to the envelope of the earth-built heritage:

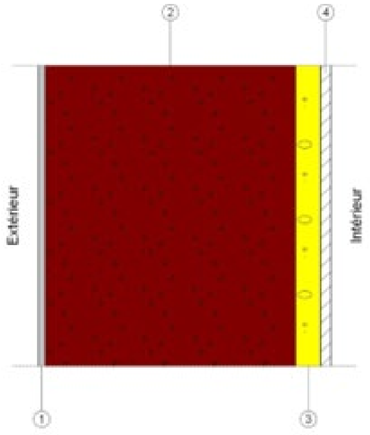
The configurations of the construction elements including the thicknesses of the different layers of materials (Fig. 3a and Fig. 3b) seem to respect the thermal regulations of the normal envelope of a traditional earth-based built framework in the 2 sites.



Ground floor layers
1- Carpet, textile covering: 1 cm
2- Ceramic/porcelain: 1.5 cm
3- Cement mortar: 2 cm
4- Glass wool: 4 cm
5- Clay or silt: 20 cm
6- Lime coating: 2 cm
7- Sand and gravel: 50 cm
Total thickness: 80.5 cm
Thermal resistance: 1.34 m²K/W

Roof terrace layers
1- Ceramic/porcelain: 1.5 cm
2- Asphalt: 1cm
3- Cement mortar: 1.5 cm
4- Glass wool: 5 cm
5- Cement mortar: 1.5 cm
6- Clay or silt: 15 cm
7- Sand and gravel: 2.5 cm
8- Lime coating: 2 cm
9- Heavy softwoods: 13 cm
Total thickness: 43.0 cm
U-value: 0.49 W/m²K

Figure 3a: Thermal characteristics: the ground floor thermal resistance and the roof terrace U value according to the prescriptive approach. [1]



Wall layers
1- Lime coating: 1.5 cm
2- Pise, cob, stabilized earth concrete, compressed earth blocks: 50 cm
3- Wood fiber panels: 5 cm
4- Current plaster for interior coating: 2 cm
Total thickness: 58.5 cm
U-value: 0.51 W/m²K

Figure 3b: Thermal characteristics: the wall U value according to the prescriptive approach. [1]

The glazing of this built frame must be double-glazing for both climates. Other bioclimatic considerations already mentioned and recommended should also be applied in an integrated manner with the provisions of thermal regulations.

Conclusion

The climatic dimension and the consideration of climate are at the heart of architectural design and push traditional architecture to deal with extreme climates, hot during the summer and cold during the winter. Climate architecture or bioclimatism concretizes this action by trying to combine and apply the principles of bioclimatic architecture, the use of bioclimatic analysis and evaluation tools based on climate data, and finally compliance with regulations, the thermal current of the envelope of the traditional built frame. This, which is considered a third skin, after ours and clothing, plays the role of mediator between the exterior climate and a comfortable and efficient interior environment in terms of thermal and energy.

Traditional earth-based architecture is certainly characterized by a great inertia of the structure making it possible to ensure thermal comfort and the reduction of energy consumption (electricity, firewood, etc.) or even the limitation of the use of active heating systems or air conditioning. The thermophysical properties of the raw earth are significantly improved by the gradual addition of natural products like as olive pomace, date palm fibers, or straw.

References

[1] Royaume du Maroc, Bulletin Officiel, Décret N° 2.13.874 Approuvant le Règlement Général de Construction Fixant les Règles de Performance Energétique des Constructions et Instituant le Comité National de l'Efficacité Energétique dans le Bâtiment. 6306 (2014) 4256-4269.

[2] ISO 7730, Ambiances Thermiques Modérées – Détermination des Indices PMV et PPD et Spécifications des Conditions de Confort Thermique, AFNOR, Paris, 1994.

[3] B. Givoni, Comfort, climate analysis and building design guidelines, in: Energy and Buildings Vol. 18, 1992, pp. 11-23. https://doi.org/10.1016/0378-7788(92)90047-K

[4] S.V. Szokolay, Introduction to Architectural Science. The Basis of Sustainable Design. Architectural Press, 2008. https://doi.org/10.4324/9780080878942

[5] O.H. Koenigsberger, T.G. Ingersoll, A. Mayhew, S.V. Szokolay, Manual of Tropical Housing and Building: Climatic Design. India: Orient Longman, 1973.