Control of Solar Radiation on Roofs and Thermal Performance in Buildings along the Peruvian Coast

Martín Wieser

Pontificia Universidad Católica del Perú PUCP, Lima, Perú.

ABSTRACT: Most of the Peruvian coast is a desert with very mild and predictable weather. Rooftop control of the prevailing very intense solar radiation directly affects indoor thermal conditions. This study seeks to identify building thermal performance under various roof conditions. Three modules were built with similar characteristics using the construction systems most frequently used in the region: adobe blocks, cement blocks and wood boards. Air temperature data during sunny summer days was recorded, applying and combining different roof solutions: lightweight, insulation, thermal mass and shading. Thermal comfort limits were identified using the adaptive method, confirming that it is possible to achieve and maintain comfort levels throughout the day without the need for artificial systems, to the extent that thin, lightweight or uninsulated materials are avoided. It was found that incorporating a shade-giving element to the rooftop was the most effective strategy for improving indoor thermal conditions, thus demonstrating the importance of shading in this particular climate environment, as opposed to new standards that focus almost exclusively on the envelope's thermal transmittance and the current trend to construct increasingly lighter buildings, without insulation or solar protection.
Keywords: Thermal Comfort, Thermal Performance, Passive Cooling.

INTRODUCTION

The central and southern coastal strip of Peru, a desert that is home to about half of the country's population, has exceedingly moderate temperatures due to the constant presence of cool breezes coming from the cold ocean water. Daily thermal oscillation is relatively low, while the verticality of the solar path results in very high radiation, with annual daily averages usually above 5 kW/m^2. Precipitation is very low, generally with an accumulated annual average below 20 mm.

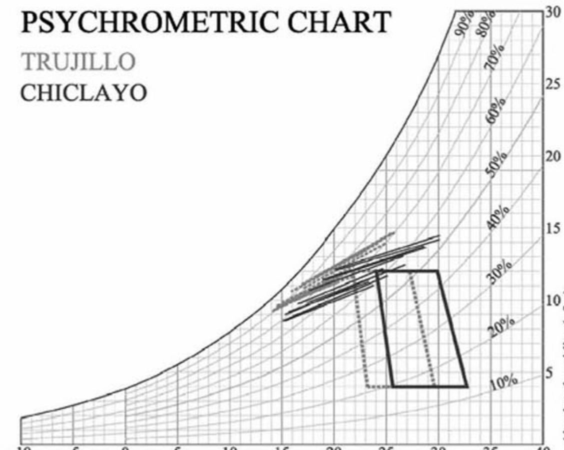

Figure 1: Typical days and comfort zone in the cities of Trujillo and Chiclayo, as per Szokolay procedure (2014, p. 128).

Under these conditions, controlling solar radiation on rooftops is essential in order to attain comfortable indoor thermal conditions during the summer months. Radiation control on rooftops in traditional adobe, *tapial* (rammed earth) or *quincha* (mud-covered reed frame) buildings was, since pre-Hispanic times, achieved through the incorporation of a layer of mud (thermal mass) over reeds or similar materials. Starting in the early 20th century, with the progressive introduction of reinforced concrete, the thermal mass logic was maintained by applying thin bricks over a thick layer of concrete with poor cement content. The thickness and permeability of the layer additionally allow for absorption of the scarce precipitation that does take place, making sloping roofs unnecessary.

At present, buildings are usually constructed using increasingly lightweight structures without an effective solar control strategy. In some cases, even the conventional solution is dispensed with, leaving only an exposed solid thin concrete slab. Under these circumstances, thermal conditions inside homes during the sunny summer months end up being far worse than those experienced outdoors.

There is no existing specific study that focuses on this problem nor, in general, on the performance of rooftops under Peruvian coastal weather conditions. Recently approved current standards are limited to requiring a certain level of roof and wall insulation (thermal transmittances), but fail to consider the possibilities provided by mass or shading to attain thermal comfort.

METHODOLOGY

Three experimentation modules were built in the San Pedro de Lloc area, each using a different wall construction system, but with the same dimensions, orientation, openings and coloring characteristics.

San Pedro de Lloc is located at a latitude of 7.43° south, 44 meters above sea level and at distance of 8 kilometers from the coastline. This location was chosen because temperatures are usually slightly higher and direct solar radiation is more frequent than in other parts of the Peruvian coast.

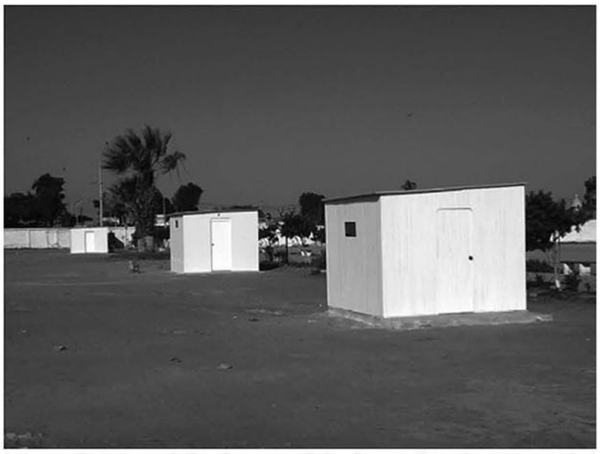

Figure 2: View of the three modules located in the 'Mansiche' fairgrounds in the outskirts of the town of San Pedro de Lloc (La Libertad, Peru).

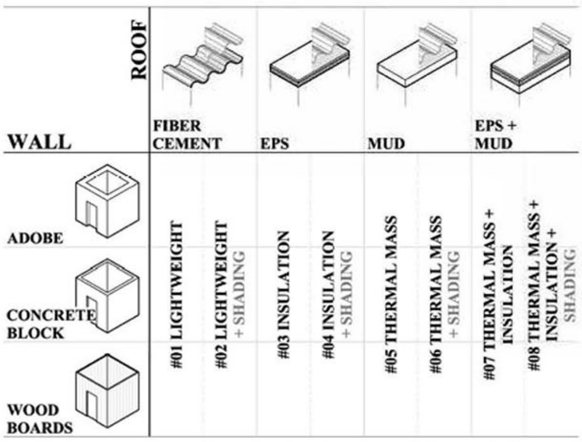

Figure 3: Diagram showing the three modules and the eight roofing options.

Dimensions (axial) for all modules are 3.0 m x 3.0 m x 2.5 m. The specific wall solutions were as follows (see details in Figure 4):

Module 01: adobe walls – a traditional alternative with high thermal mass, still widely used in rural areas and coastal villages.

Module 02: concrete block walls – a medium thermal mass solution which, as with baked clay perforated brick, is usual in higher-income urban and peri-urban areas.

Module 03: wood board walls – a low thermal mass solution that is increasingly being used as a temporary option by low-income families in urban coastal areas.

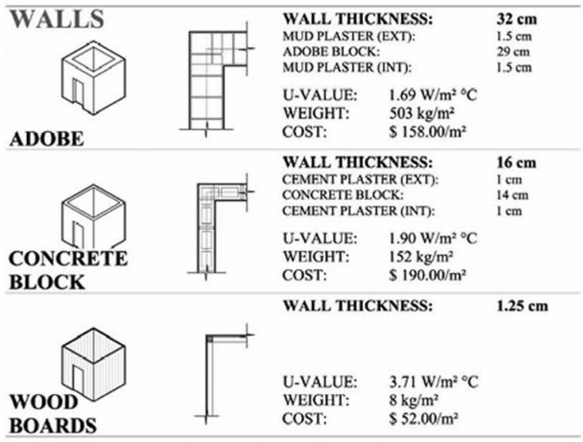

Figure 4: Detail of module walls and approximate thermal transmittance values (U-value), weight and cost.

In each of the modules, eight different roof solutions were implemented with a similar reflection factor (see details in Figure 5):

Roof 01: corrugated fiber cement sheet (low thermal mass and little insulation) – the least expensive solution, increasingly used as a provisional roof.

Roof 02: above material (Roof 01) plus shading (lightweight galvanized corrugated steel sheet over ventilated structure).

Roof 03: sheet in combination with EPS – a low thermal mass and high insulation solution still little known in the country.

Roof 04: above materials (Roof 03) – plus shading.

Roof 05: mud layer over reeds – traditional solution, with medium thermal mass and medium insulation, increasingly less used.

Roof 06: above materials (Roof 05) – plus shading.

Roof 07: sheet in combination with EPS (Roof 03) over mud layer (Roof 05) – solution with medium thermal mass and high insulation.

Roof 08: above materials (Roof 07) – plus shading.

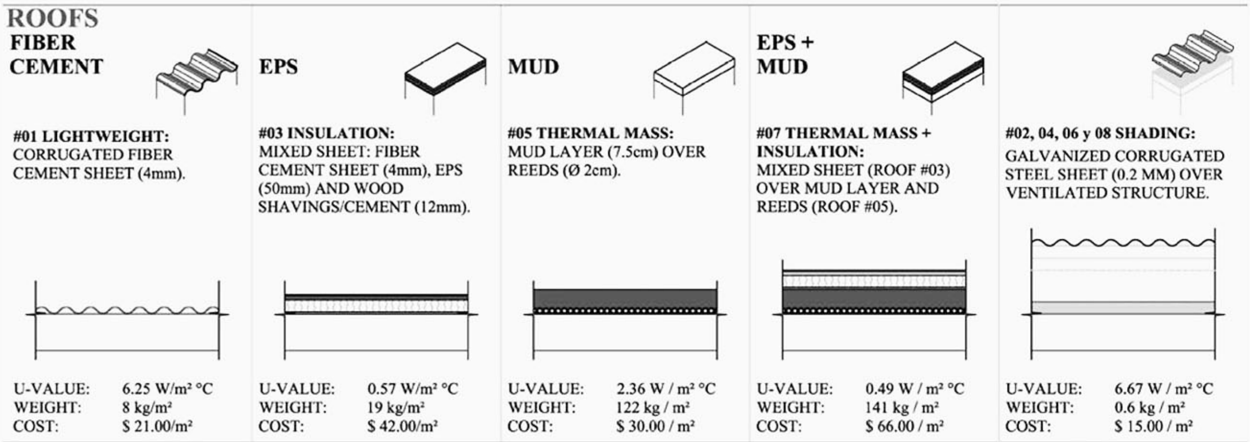

Figure 5: Detailed roof options and approximate thermal transmittance values (U-value), weight and cost.

Solar path verticality and the small openings and orientation (North and South) of the modules prevented the entrance of significant direct solar radiation. Since the modules have different wall thicknesses, window frames were installed flush with outer wall surfaces so that the effect of the limited direct solar radiation on indoor thermal conditions would be similar.

Consistent with the small openings found in traditional buildings in the area, sometimes even lacking front windows, it was decided to create a minimum amount of ventilation to allow for a continuous outflow of the hottest air. An air entry opening was left below the door (1 cm x 80 cm) facing West and an air outflow high window (5 cm x 35 cm) facing North. Considering an average wind speed of 5.2 m/s, the volume flow rate is approximately 89 m^3/h, which ensures some 4.6 air changes per hour (calculation based on Bainbridge & Haggard 2011, p. 120).

Indoor and outdoor air temperature and relative humidity were measured in the warmest months (between February and April 2015) during 7 to 10 continuous days for each roof option, provided a minimum of three consecutive sunny days had occurred. Data loggers (Onset Hobo Model H8-003-02) suspended from the center of the modules were used, hanging 1.2 m above the floor. The temperatures obtained on each of the consecutive sunny days for each of the eight roofs were averaged. A marked similarity in outdoor conditions was observed; the greatest differences did not exceed the total average values by more than 1.4°C. As a result of this last fact, adjusting results by mathematical sequences prior to comparison did not significantly alter the original results.

Figure 6: View of the concrete block module with galvanized corrugated steel sheet over ventilated structure as roofing.

Finally, to assess the results obtained, thermal comfort limits were identified using Adaptive Comfort principles (Nicol & Humphreys, 2002), considering free-running buildings. Assuming an average daily outdoor temperature (To) of 25.5°C, obtained from actual onsite measurements, the resulting comfort temperature (Tc) was 27.27°C. The authors themselves suggest that ruling out any changes in ventilation, clothing and/or activity conditions, limits may be extended up to +/-2°C, but these may be extended more should there be any change in such conditions. Based on these principles, comfort limits were finally established at 29.27°C (2°C more) during the warmest hours and 24.27°C (3°C less) during the coldest hours.

RESULTS

The graphic results obtained, as well as comfort zone limits, are shown below (see Figures 7, 8 and 9).

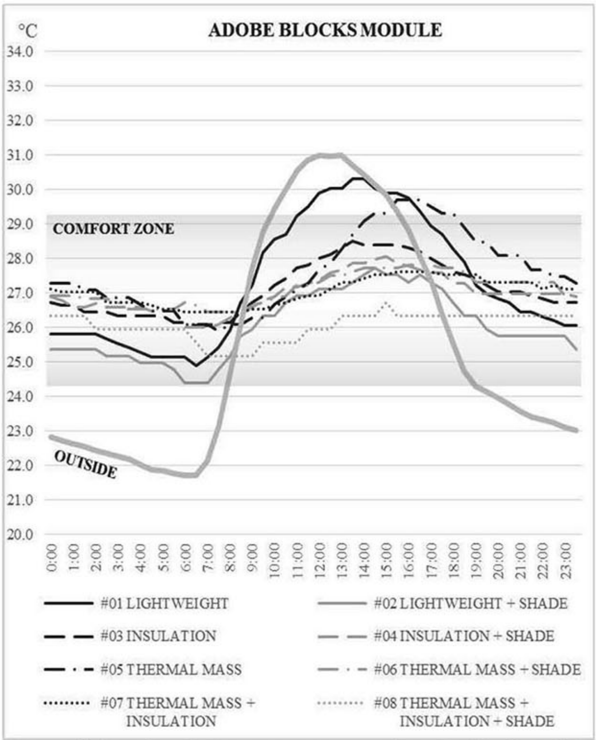

Figure 7: Results of air temperature readings inside the adobe module.

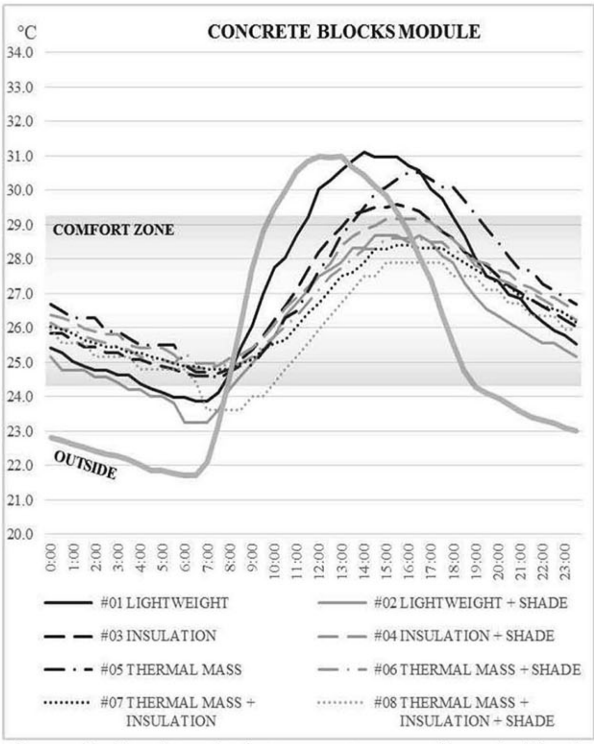

Figure 8: Results of air temperature readings inside the concrete block module.

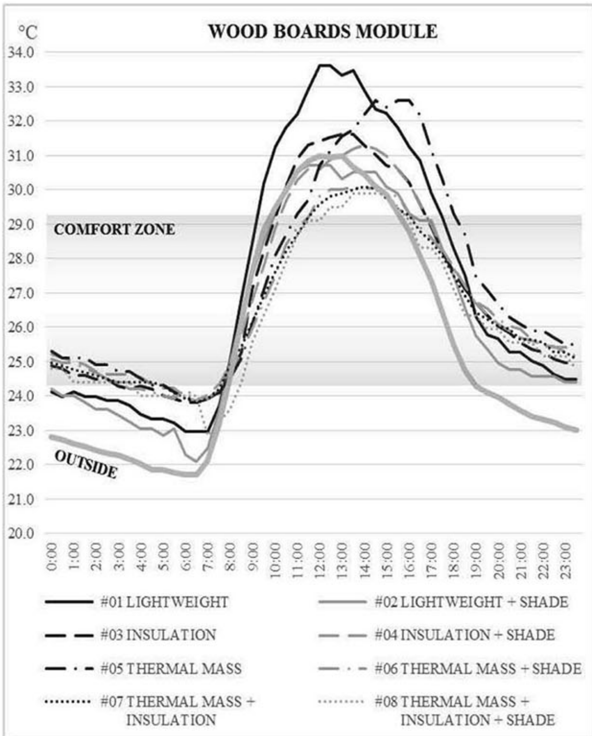

Figure 9: Results of air temperature readings inside the wood board module.

Using time counts (as percentages of 24 hour-periods) of periods when there is thermal discomfort inside each of the solutions, the results are displayed in the matrix below:

PERCENTAGE OF TIME WITHOUT THERMAL COMFORT (%)							
	WALL >	ADOBE		CONCRETE		WOOD	
	ROOF V	COLD	HEAT	COLD	HEAT	COLD	HEAT
#01	LIGHTWEIGHT	0	23	15	25	33	33
#02	LIGHTWEIGHT+ SHADE	0	0	21	0	33	27
#03	INSULATION	0	0	0	15	17	27
#04	INSULATION+ SHADE	0	0	0	0	10	27
#05	THERMAL MASS	0	17	0	23	0	31
#06	THERMAL MASS+ SHADE	0	0	0	0	19	19
#07	THERMAL MASS+INSULATION	0	0	0	0	10	17
#08	THERMAL MASS+INSULATION+ SHADE	0	0	13	0	19	15

Figure 10: Percentage of time when there is thermal discomfort, by wall and roof conditions.

The best performance is clearly achieved by the adobe module. The only conditions when there is no thermal comfort due to overheating of indoor air during early afternoon hours are with the lightweight roof and, to a lesser degree, with the packed mud layer (thermal mass). Incorporating shading over the roof ensures comfort in all additional conditions, as well as very low indoor thermal oscillation: around 3°C in the case of the lightweight roof, and 1.5°C in the case of shading plus thermal mass.

In the case of the concrete blocks module, the range of indoor thermal oscillation is appreciably broader, with periods of discomfort in the hours around noon, occurring, as with the adobe module, both with the lightweight and with packed mud (thermal mass) roofs. This occurs to a lesser degree with the insulated roof. In addition, discomfort from cold also occurs in the hours after midnight and early morning hours with the lightweight, lightweight + shading and thermal mass + insulation + shading roof options.

Thermal conditions in the wood module are extremely unfavorable. Thermal oscillation is much broader (from 7°C to 11°C), while the time lag is markedly reduced. In all cases, thermal discomfort conditions are present both during the day (heat) and in the hours after midnight and during early morning (cold). Incorporating shading in this specific case is essentially irrelevant, because while heat discomfort is slightly diminished, nighttime cold discomfort is increased.

CONCLUSIONS

Both roofing and wall configurations directly affect the possibility of obtaining thermal comfort inside the spaces. In all cases, the light weight and high transmittance of components result in the most unfavorable conditions for obtaining comfort, with temperatures almost 5°C above the comfort level and around 3°C above outdoor temperature at the hottest time of day. Generally, insulation, mass and shading strategies significantly improve thermal performance in the different modules. Adding each of these strategies also proves to progressively improve performance.

Incorporating insulation in the roof clearly improves thermal performance in the adobe and cement block modules, but improvement is very limited in the case of the wood module. Mass has a more limited performance, but adding shading does provide as much improvement as insulation. Thermal mass plus insulation results in the solution that provides most comfort and stability. Incorporating shading – except in the case of insulation, where improvement is negligible – has been shown to be the strategy that has the most impact on controlling temperature increases at noon. It is also the least expensive and, in general terms, provides better results than using insulation or thermal mass separately.

In keeping with the recommendations and bioclimatic diagrams of authors such as Givoni (1992) and Szokolay (2014), ventilation, thermal mass and shading have also been found to be the most appropriate strategies for this type of climate. However, though in areas very close to the ocean traditional buildings occasionally use medium thermal mass and are well-ventilated, it can be stated that, in general, a higher thermal mass in walls and roofs is, together with low and controlled ventilation, the most frequent strategy in Peruvian coastal buildings. Adding shading to roofs has been shown to be very effective in this scenario and it is important to consider it as an option to insulation in current local regulations.

ACKNOWLEDGMENTS

This research has been made possible thanks to funding and support from the Provincial Municipality of Pacasmayo (La Libertad), the Architecture and City Research Center (CIAC - *Centro de Investigación de la Arquitectura y la Ciudad*) of the Pontificia Universidad Católica del Perú, and the Research-Action Project "Transversal, acciones de integración en el territorio peruano" (Transversal, Integration Actions in the Peruvian Territory) (2011-2016) ARES-Belgium and PUCP-Peru.

REFERENCES

Bainbridge, D., & Haggard, K. (2011), *Passive Solar Architecture: Heating, Cooling, Ventilation, Daylighting and More Using Natural Flows*, Chelsea Green Publishing.

Givoni B. (1998), *Climate Considerations in Building and Urban Design*, John Wiley & Sons, New York.

Givoni B. (1998), 'Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods', *Energy and Buildings*, 28(1): p. 25-32.

Nicol J.F. & Humphreys M.A. (2002), 'Adaptive thermal comfort and sustainable thermal standards for buildings', *Energy and Buildings*, 34(6): p. 563-572.

Szokolay S. (2014), *Introduction to Architectural Science: The Basis of Sustainable Design*, Routledge, New York.