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THERMAL BEHAVIOR ASSESSMENT OF TWO TYPES OF ROOFS OF THE DOMINICAN VERNACULAR HOUSING

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Abstract. *The Dominican vernacular architecture, based on the indigenous bohio with Spanish influence, is built with natural materials, such as the royal palm (Roystonea Hispaniolana) and the cana palm (Sabal Dominguensis). This model of housing has remained practically unchanged for five centuries, responding adequately to the Caribbean tropical climate. In the twentieth century, start to replace the traditional palm leaf roof by a corrugated sheet zinc, significantly affecting the temperature inside these houses and altering the conditions of living comfort. For this reason, the aim of this research is to evaluate the thermal behavior of two roof types of vernacular housing. One type is a cana palm leaf roof and the other is a corrugated sheet zinc roof. The houses are in the towns of Villa Sombrero and Sabana Buey, Peravia Province, in the southwest of the Dominican Republic, a region with a Tropical savanna climate (Aw) according to the Köppen-Geiger climate classification. The climate is characterized by temperatures from 20°C to 38°C, with rainfall below 500 mm per year. The technique and tools used for this research are: Infrared Thermography (IRT) and digital thermometer for measure of thermal properties of roof materials, a thermometer and hygrometer to measure the relative humidity and temperature inside and outside of the houses, and carbon monoxide (CO) and carbon dioxide (CO2) meter. Passive IRT is used to measures the temperature differences of a structure that are generated under normal conditions. The results indicate that there is a difference in temperature between one type of roofing material and the other. Finding that houses with palm leaf roofs have lower temperature than corrugated sheet zinc roof and present a temperature difference between the interior and exterior.*

1 INTRODUCTION

The use of thatch roof is as ancient as the construction of the first houses. Thatch roofing is a traditional roofing method that involves using dry vegetation. Since the industrial revolution, many thatched roofs have been replaced by metal sheets. From the industrial revolution onwards, many thatched roofs were replaced by metal sheets, which was a new material that promised many advantages over the other. However, when using it, no changes were made in the design and one material was simply replaced for another, affecting the thermal comfort inside the buildings[1]. For this reason, the aim of this research is to evaluate the thermal behaviour of two roof types of vernacular housing. One type is a cana palm leaf roof and the other is a corrugated sheet zinc roof.

In 2012, Pedro T. Navarro González carried out his doctoral thesis "Study of the roof frames of rural and vernacular construction in Gran Canaria. Structural and constructive analysis"[2], were refers to structural and constructive elements, such as roofs. In 2013, Molina and Fernández carried out a comparative analysis of the thermal envelope and energy demand between two types of housing, the *palloza* and the traditional house, in the mountain area of Os Ancares, in the northwest of Spain, by studying the energy use of straw on roofs[3].

In Peru, the thermal behaviour of the *mojinete* roof was analysed from the particularity of its shape, use of materials and location of openings and its response and adaptation to the local climate at the region of Moquegua that is hot and low rainfall [4]. In Brazil, a thermal study evaluate the thermal efficiency of three roofing materials (fibre cement tile, recycled tile, and thatched roofs) used in shelters for girolando calves and show that the recycled tiles and thatched roofs provided reductions of 18.7 and 14.6% in radiant thermal load [5].

While in 2016, Chandel, Sharma and Marwah, carried out a review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions, where the main features studied were: built mass design, orientation with respect to sun, space planning, openings, sun space provision, construction techniques, and building and roof materials [6]. In 2018, a doctoral thesis analysed and compared the thermal behaviour of two roofs, one metallic and the other made of concrete, through measurements and simulations, being able to measure their behaviour[7].

2 CASE STUDIES.

Four houses were assessed for this research all located in the Baní Valley, province of Peravia, in the south of Hispaniola Island. Two of them with roofs of cana palm leaves (B-1 and B-2) and two with roofs of corrugated zinc sheets (B-3 and B-4), The B-1 is located in Villa Sombrero and B-2, B-3, B-4 in Sabana Buey (Fig. 1).

Figure 1. The four houses assessed.

Both towns are located on the old Camino Real, which connected the city of Santo Domingo with the west of the island. All the *bohios* were built in the second half of the 19th century, which can be verified by the data offered by the owners and by the presence of cast-iron nails, used before the XX century were began the commercialization of the industrialized nails. The floors of the four houses are made of polished cement. A concrete sidewalk has been placed around all the houses.

2.1. Description.

The *bohios* B-1 and B-2 with a Cana palm leaf roof is a type of vernacular housing commonly used in the Valle de Baní, consisting of a simple volume with a rectangular floor plan, with a gabled roof and small eaves that protect the four facades. Its supporting structure is based on wooden forks, buried in the ground, joined at the top by the sill, on which rests the lock that supports the thick cover of cane palm leaves (*Sabal dominguensis*). The walls of the house and the internal divisions are made of planks of royal palm (*Roystonea hispaniolana*) placed horizontally, overlapping and nailed to the *horcones* or posts, which in this region are usually made of mahogany (*Swietenia mahagoni*) or creole oak (*Catalpa longissima*). For the structure of the roof, we used uncarved sticks or poles from various local timber trees (Fig.2).

Figure 2. *Bohios* (B-1 and B-2) with a cana palm leaf roof.

Both *bohios* have a door in the middle of their main facade and four windows, two on each side of the door. On the back façade facing the patio, they also have a door placed in the center and four windows, two on each side of the door. The spatial distribution of the interior consists of a central area divided by two low walls, called handrails or *balaustres*, which define the living and dining areas. On both sides are the four rooms, one on the right and two on the left side of the *bohio*. The kitchens and latrines are located outside the *bohios*, where there is also usually an *enramada* or covered terrace.

The B-3 and B-4 huts, located in Sabana Buey, have a supporting structure, materials and construction methods similar to those of the B-1 and B-2 huts, but with the difference that the roofs made of cana palm leaves were replaced years ago by corrugated zinc sheets, which are nailed to a structure made of already industrialized wooden rods and belts, usually made of pine. The roofs are gabled with short eaves, with the main facade being somewhat more pronounced (Fig.3). In these houses the zinc roofs are broken to achieve a greater speed in the fall of the water and move them away from the facades. Both cases have an annex at the back, to integrate the kitchens into the house and add another bedroom. The interior walls, as in B-1 and B-2, remain at the height of the sills, allowing air to flow over them. The B-3 also has fans over the doors, which contribute to the good ventilation of the interior of the hut.

Figure 3. *Bohios* (B-3 and B-4) with corrugated zinc sheets on roofs.

2.2 Dominican climate and the environment condition

Dominican Republic is in the Caribbean, in the tropical zone of the northern hemisphere, at latitude 18°44.142' N and longitude 70°9.759' W. It classified subtropical climate that varies according to the place, due to the topography and the trade winds of the northeast. In general, the geography of the country has created two types of climate: tropical rainforest climate (Af) and tropical savanna climate (Aw), according to the Köppen-Geiger climate classification[8]. The climatic variations are marked, ranging from arid to very humid.

Peravia Province is in the southern region of the country, approximately 60 km west of the city of Santo Domingo, belongs to the coastal plains of the Caribbean. On average, the warmest month is August with a maximum 38.2°C. The lowest months is January with a minimum 20.5°C. The average relative humidity is 65.7% with average precipitation 77.64 mm, and average wind speed 4.375 m/s. (Fig.4). Average monthly hours of sunshine are 9 hours[9]. These climatic conditions (hot and humid) and the properties of the material affect the thermal comfort of buildings, causing a significant increase in the indoor temperature of the building.

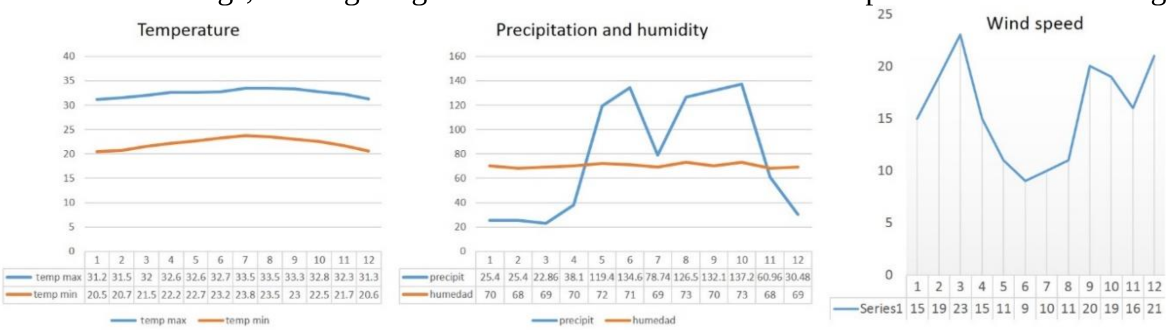

Figure 4. Environmental conditions of Peravia, Dominican Republic.

3. MATERIALS AND METHODS

Non-destructive techniques (NDT) were used to evaluate the houses. The equipment used was hygrometer, Tpi 1010ª Outdoor/Indoor Air Quality Meter (AQM), Infrared Thermography (IRT) and Surface Temperature. Also, an official weather stations in the vicinity were consulted and the National Meteorological Office (ONAMET). The measurements were taken during the warmest period, from June 08th to September 28th, 2019. Some additional measurements were taken on June 08th and July 9th, 2019, between 9:30h to 15:40h in a sunny day.

3.1 Environmental condition

The temperature and humidity were measured with an Extech RHT20 Datalogger hygrometer. Four hygrometers were installed in the houses: two inside and two outside the houses. The sampling rate was every 1800 seconds (30 minutes), from 0:21h am to 23:51h. The additional measurements taken on June 08th and July 9th and were done with a Tpi 1010a Outdoor/Indoor Air Quality Meter (AQM) that measure carbon dioxide (CO2), carbon monoxide (CO), air temperature and relative humidity [10].

3.2 Surface Temperature

Digital Laser Thermometer was used, MASTERGRIP model CM558N. It has a temperature range between -28°C to 482°C and has accuracy +/-2°C or +/-2% (0°C to 482°C) whichever is greater +/-4 degrees C (-28°C to 0°C), with emissivity of 0.95, response time (90%): <0.5 seconds and with a Class II laser pointer. Several measurements were carried out in each roof, one inside and one outside to check the thermal jump effect.

3.3 Infrared Thermography

The study is based on passive thermography, which measures the temperature differences of the roof that are generated under normal conditions [11].Thermography images were used to analyse upper- and lower-surface thermal characteristics for the two roofing materials. The measures were taken with an infrared camera FLIR SYSTEMS model T420, FOL 18mm lens and 240 × 320 pixels IR resolution. The camera has a spectral range 7.5 to 13 micron and a field of view (FOV) of 25°x19°/0.4 meters and spatial resolution (IFOV) of 1.36 milliradians. Have an adjustable thermal range from -20°C to 650°C and for this project was set at -20°C to 120°C. The camera used for this survey meets the requirements of UNE-EN 13187:1998. The emissivity values for cana palm leaves roof are 0,75 and for corrugated zinc sheet are 0,20 (Table 1). For thermal images, an iron colour palette mode was used using reference colours: blue for coldest temperature range and yellow for warmest temperature range. This way, the coldest point can be identified on each image.

Table 1. Energy parameters of roofing materials

Material	Thickness (mm)	Roof slope	Emissivity values	Thermal transmittance U (W/m^{2}K)	Thermal resistance R (m^{2}K/W)	Thermal conductivity λ (W/mK)	Density ρ (kg/m^3)	Specific heat cp (J/kg·°C)
Cana palm leaves	600	45°	0,75	0.35	11.1 14.3	0,04 - 0,07	240	180
Corrugated zinc sheet	0,7	20%	0,20	2,20	0,0001	60 112,2	7,18	0.3898

National Society of Master Thatchers (NSMT), 2012 [12] / Fluke Corporation, Emissivity values of common materials, 2007 [13]

4 RESULTS AND DISCUSSION

4.1 Environmental Conditions

The recorded outdoor temperatures were maximum 38.2°C @08/18/19 at 12:21:01 in Sabana Buey; minimum 24.2°C @09/18/19 06:51:01 in Villa Sombrero; with an average of

30.6°C. The recorded outdoor Relative Humidity (RH) was maximum 88.7%RH @09/10/19 at 01:51:01, minimum 37.7%RH @08/21/19 at 12:51:01, average 65%RH. The recorded indoor temperatures were maximum 36.8°C @08/21/19 at 13:21:01, minimum 22.5°C @09/18/19 06:51:01, average 28.8°C. The recorded indoor Relative Humidity (RH) was maximum 83.5%RH @08/28/19 at 22:51:01, minimum 41.0%RH @07/09/19 at 13:21:01, and average 62.6% RH (Table 2).

Table 2. Average of environmental conditions indoor/outdoor

	Indoor			Outdoor			Indoor			Outdoor		
	Temp. Max. °C	**Temp. Min.** °C	**Temp. Avg.** °C	**Temp. Max.** °C	**Temp. Min.** °C	**Temp. Avg.** °C	**RH Max. %**	**RH Min. %**	**RH Avg. %**	**RH Max.** %	**RH Min.** %	**RH Avg.** %
B-1	32.8	22.5	27.7	37.7	24.2	30.3	82.4	53.7	68.9	74.8	39.8	65.7
B-2	32.2	23.8	28.1	38.2	24.4	30.7	83.5	53.1	67.1	88.7	37.7	64.7
B-3	36.8	26.1	30.1	38.2	24.4	30.7	78.5	45.7	61.4	88.7	37.7	64.7
B-4	34.8	25.5	29.3	38.2	24.4	30.7	74.9	41.0	53.1	88.7	37.7	64.7
			28.8			**30.6**			**62.6**			**65.0**

Air quality measurements indicate that B-1 has a higher concentration of CO2 indoors than other samples. It is possible that this is because the house is closed all day, which prevents it from renewing air. But in general, all the houses have great amount of co2 in comparison with the outside (Table 3).

Table 3. Outdoor/Indoor Air Quality CO2

<table>
<tr><th>Samples</th><th>Indoor</th><th>Outdoor</th><th>Range</th></tr>
<tr><td>B-1</td><td>1930 ppm</td><td>1612 ppm</td><td>350-1,000 ppm: typical level found in occupied spaces with good air exchange</td></tr>
<tr><td>B-2</td><td>1918 ppm</td><td>1743 ppm</td><td rowspan="2">1,000-2,000 ppm: level associated with complaints of drowsiness and poor air</td></tr>
<tr><td>B-3</td><td>1888 ppm</td><td>1753 ppm</td></tr>
<tr><td>B-4</td><td>1899 ppm</td><td>1748 ppm</td><td rowspan="2">2,000-5,000 ppm: level associated with headaches, sleepiness, and stagnant, stale, stuffy air; poor concentration, loss of attention, increased heart rate and slight nausea may also be present.</td></tr>
<tr><td>Average</td><td>1909 ppm</td><td>1714 ppm</td></tr>
</table>

4.2 Surface Temperature

The average outside surface temperature of the cana palm leaf roof was B-1: 38.5°C, B-2: 46.5°C and inside B-1: 30.1°C, B-2: 32.3°C., and the average outside surface temperature of corrugated zinc sheet was B-3: 47.5°C, B-4: 49.2°C, and inside B-3: 50.5°C, B-4: 48.5°C. We can observe the differences surfaces temperatures between the cana palm leaf and corrugated zinc sheet.

4.3 Infrared Thermography

Through thermal images (Fig. 5) we can observe some variations in temperatures of both upper and lower surfaces. In the case of the cana palm roof in B-1, the maximum outside temperature is 44.3°C and inside temperature is 31.8°C, with a difference of 12.5°C, while the minimum outside temperature is 34.8°C and the inside temperature is 27.5°C, with a difference of 7.3°C. B-2 present the maximum outside temperature in 54.9°C and inside temperature is 33.4°C, with a difference of 21.5°C, while the minimum outside temperature is 36.2°C and the inside temperature is 30.2°C, with a difference of 6°C.

On the other hand, in the case of corrugated zinc sheet in B-3, the maximum outside temperature is 51.6°C and the minimum inside temperature is 50.5°C, with a difference of 1.1°C, while the minimum outside temperature is 42.5°C and the inside temperature is 35.4°C, with a difference of 7.1°C. B-4 present the maximum outside temperature in 55.5°C and inside temperature is 54.2°C, with a difference of 1.3°C, while the minimum outside temperature is 41.4°C and the inside temperature is 36.9°C, with a difference of 4.5°C.

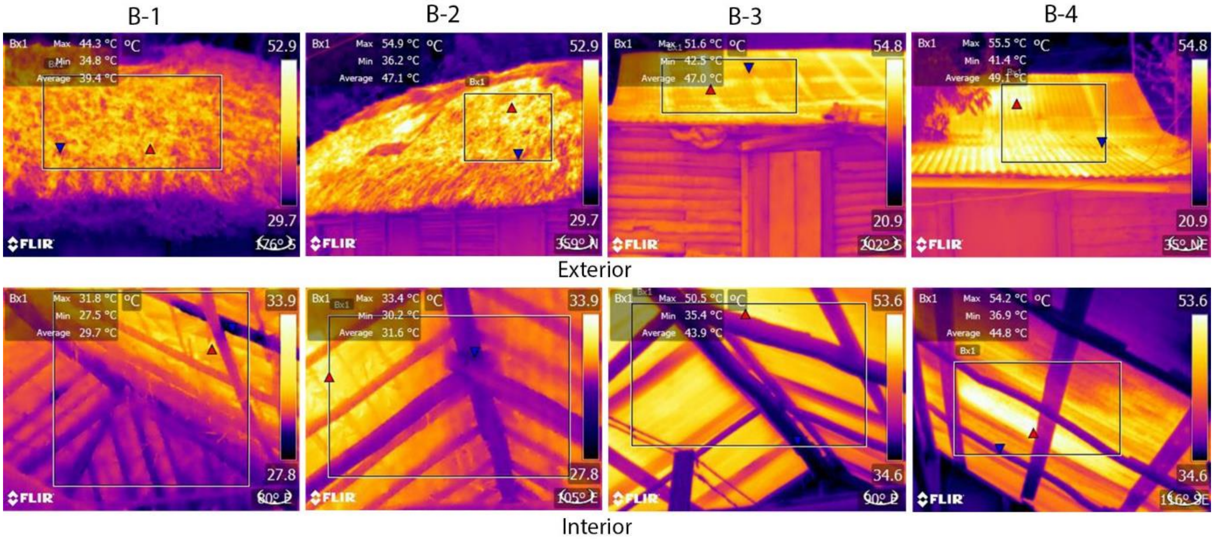

Figure 5. Exterior – interior thermal images of the roof

5 CONCLUSIONS

The cana palm leaf showed better thermal efficiency than corrugated zinc sheet, providing lower values of radiant heat load and surface temperatures, as well as lower temperatures inside the houses. In the case of cana palm roof the maximum difference temperature between outside and inside is 12.5°C and 21.5°C, while in the corrugated zinc sheet this difference is 1.1°C and 1.3°C, obtaining in the interior practically the same temperature as in the exterior.

We can observe that the indoor ambient temperature at B-1 and B-2 is similar to the maximum surface temperature of the roof material. In the case of B-3 and B-4 there is a great difference between these temperatures, due to the construction system that creates some openings between the sills and the roof, allowing the inside ventilation.

Using infrared thermography, it was possible to produce heat maps to quantify surface temperatures and thus observe and evaluate the thermal efficiency of both materials. This process helped to understand the processes of heat transfer between surfaces, confirming in this research that the thatch roof is much cooler and transmits less heat to the interior than the metal roof.

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