Low-Cost Thermal Retrofit Strategy for Residential Buildings in Tropical Regions: Experimental Assessment of Roof Insulation Technologies

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Abstract*– Significant heat gains from metal roofs cause residential buildings in tropical developing nations to use more electricity for cooling. Through an experimental evaluation of commercially available roof insulation technologies appropriate for residential buildings in Honduras, this study suggests a low-cost thermal retrofit technique. Under actual outside tropical circumstances, four different roof types were evaluated: fiberglass insulation, reflective aluminum insulation, uninsulated aluminum roofing, and reflective thermal coating. To evaluate cooling demand, annual power consumption and economic savings whole-building energy simulations carried out in eQUEST were combined with surface temperature measurements collected using infrared thermography. Experimental results demonstrated that fiberglass insulation provided the highest thermal performance by significantly reducing heat transfer through the roof. When compared to traditional uninsulated metal roofs, simulation results showed cooling energy savings of up to 41.16%. The proposed low-cost thermal retrofit strategy is a workable solution for existing houses in tropical climates since it calls for few structural changes and makes use of reasonably priced materials that are easily found in the local market. Beyond its technical contribution, this study shows how affordable passive cooling solutions can enhance family energy efficiency, promote sustainable residential development, mitigate climate change, and increase regional resilience in developing nations.

***Keywords*- Building energy efficiency, Roof insulation, Sustainable buildings, Thermal retrofit, Tropical climate.**

I. Introduction

Buildings account for a large share of global energy consumption. They account for approximately 36% of global final energy consumption, with cooling demand increasing rapidly in tropical regions due to urbanization and climate change [1]. In addition, they are also responsible for about 37% of global emissions [2]. Every year, there is an increase in energy demand from buildings and households, especially in tropical countries where ambient temperatures are high ranging from 28 to 35°C throughout the year, particularly during the daytime. These ambient temperatures drive residences and buildings to seek in-building cooling solutions to achieve thermal comfort.

Metal roofs made of lightweight materials are commonly employed in tropical developing countries for housing because of their cost-effectiveness, durability, and simple installation process. Nevertheless, such roof structures do not perform well thermally due to their tendency to absorb large amounts of solar radiation and to quickly transfer heat to interiors. Consequently, people need to resort to the use of mechanical cooling equipment to achieve comfortable indoor temperatures, which leads to higher electricity consumption. Such a problem is typical of Honduras, where metal roofs are commonly installed in residential buildings. Honduras is adopted as a representative case study of tropical developing countries.

Passive cooling technologies have emerged as an effective alternative for reducing cooling loads without increasing energy consumption. Among these strategies, roof insulation, reflective coatings, radiant barriers, and cool roofs have received considerable attention because of their ability to minimize solar heat gains through the building envelope while improving indoor thermal comfort. Experimental studies conducted under tropical climatic conditions have demonstrated that insulation materials such as fiberglass, radiant barriers, and reflective insulation can significantly reduce roof heat transfer and indoor temperatures [3].

Several articles address similar topics: Rawat and Singh conducted a comparative study of roof performance in different regions using simulations on various prototypes [4]. Hernández-Pérez analyzed the effects of traditional and solar-reflective coatings on heat transfer in roofs in Mexico[5]. Soubdhan et al. determined the influence of insulation materials on roofs in tropical countries using small-scale test cells [6].

In the Honduran context, previous studies have demonstrated the potential of sustainable energy technologies to improve Honduras's energy sector and reduce dependence on conventional electricity generation [7]. Although previous investigations have demonstrated the effectiveness of passive roof insulation technologies, several important research gaps remain. Many studies have focused exclusively on laboratory experiments or numerical simulations, while only a limited number have combined field measurements with whole-building energy modeling under real tropical climatic conditions.

Furthermore, most available studies evaluate individual insulation technologies independently and rarely assess commercially available low-cost retrofit solutions considering

their thermal, energetic, economic, and environmental performance simultaneously. These limitations reduce the practical applicability of current research, particularly for existing residential buildings in developing countries where affordability is a key factor. Developing affordable thermal retrofit strategies for existing residential buildings represents an important opportunity to improve energy efficiency while supporting sustainable urban development and climate resilience in tropical developing countries.

Similar to these studies, this research aims to compare different materials that reduce the thermal load in buildings, with the difference being that experimental measurements are conducted on a prototype under real-world conditions, and simulations are performed in eQuest, providing us with an overview from both perspectives.

The remainder of this paper is organized as follows: Section II describes experimental methodology and simulations. Section III presents experimental and simulation results. Section IV discusses the implications for sustainable residential development, and Section V points out the conclusions for this research.

II. Methodology

This section explains the methodology used for the study. Figure 1 shows a diagram illustrating the four fundamental steps of the study methodology.

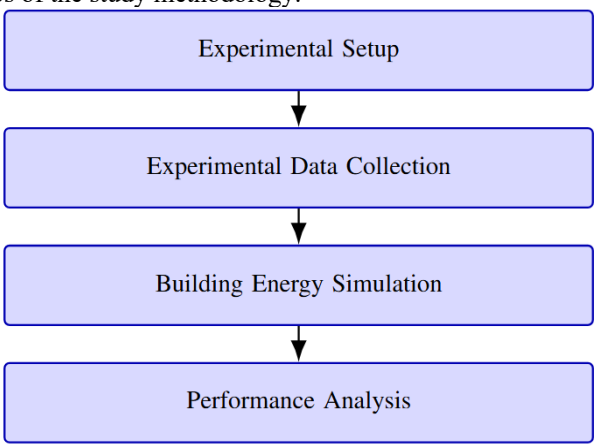


Fig. 1 Research Methodology Flowchart

A. *Experimental setup*

To carry out this research, three commercially available thermal retrofit technologies were selected, in addition to an uninsulated Aluzinc roof used as the reference case. The selected insulating materials were thermal paint, fiberglass, and reflective aluminum. These materials were chosen because of their availability on the Honduran market, ease of application, low cost, and common use in homes. It was necessary to build and install a specially designed platform that would simulate a residential roof.

The platform consists of four 5-foot-long sheets of aluzinc, each with a different insulation configuration: one sheet without insulation, another with thermal paint applied to the top surface, a third with fiberglass on the underside, and a fourth with reflective aluminum on the underside.

This structure was installed outdoors on a plot of land, allowing for direct exposure to weather conditions and thus ensuring an accurate and realistic comparison of each type of insulation's performance in terms of thermal efficiency. The structure is shown in Figure 2.

A mesh was required for installing the fiberglass, as it is a very delicate material. This type of mesh is commonly used in construction and insulation applications to support materials such as fiberglass This type of mesh is commonly used in construction and insulation applications to support materials such as fiberglass. It is very useful for preventing the insulation from shifting and provides stability in ceilings and walls.



Fig. 2. Roof Simulation Structure

The structure was divided into four sections to install the materials needed to conduct the necessary tests: (i) uninsulated Aluzinc roofing (reference case), (ii) Aluzinc roofing coated with reflective thermal paint, (iii) Aluzinc roofing insulated with reflective aluminum, and (iv) Aluzinc roofing insulated with fiberglass.

B. *Experimental Data Collection*

To collect data, a thermal imaging camera was used to take temperature measurements. To obtain relevant and consistent data, measurements were taken hourly over four consecutive days. The temperature data were recorded using Excel so that the results could be analyzed using graphs. The ambient temperature was recorded. For each of the materials used, the temperature of both the top and bottom surfaces was measured using Equation 1.

$$\Delta T = T_{top} - T_{bottom} \quad (1)$$

Where:

- ΔT is the Temperature Difference [°C]
- T_{top} is the temperature at the top of the structure [°C]
- T_{bottom} is the temperature at the bottom of the structure [°C]

In addition, the thermal transmittance of each material was calculated for each of the materials studied. Thermal transmittance, or the thermal transmittance coefficient, is the ability of materials to allow energy to pass through them. Thermal resistance and thermal transmittance depend on the thickness of the material [8]. This was calculated using Equation 2.

$$U = \frac{q}{\Delta T} \quad (2)$$

Where:

- U is thermal transmittance [W/m² °C]
- q is heat flux density [W/m²]
- ΔT is the Temperature Difference [°C]

Heat flux density is calculated using Equation 3.

$$q = -k\frac{dT}{dx} \quad (3)$$

Where:

- q is heat flux density [W/m²]
- k is thermal conductivity [W/m °C]
- $\frac{dT}{dx}$ is the Temperature gradient across the material [K/m]

Finally, the thermal resistance value was calculated using Equation 4; this value is commonly used to measure the thermal performance of insulating materials. In other words, it measures the material's resistance to heat flow and depends primarily on the material's thermal conductivity, density, and thickness.

$$R = \frac{\Delta T}{q} \quad (4)$$

Where:

- R is thermal resistance [m² °C /W]
- q is heat flux density [W/m²]
- ΔT is the Temperature Difference [°C]

C. Building Energy Simulation

In this stage, the thermal load through the roofs is calculated using a computer program. Calculating the thermal load through the roofs makes it possible to estimate the heat gained or lost through the roof due to solar radiation, indoor and outdoor temperatures, as well as the building's walls and the insulation materials used in both the roof and walls.

eQUEST is used for this stage, where the dimensions of the built prototype are configured. The area is defined, and the different roofs to be studied, as well as doors and windows, must be specified in the simulation even if they are not present in the physical prototype. Building energy simulations were used to estimate annual cooling demand, electricity consumption, and the associated reduction in greenhouse gas emissions. To capture the effect of the roof retrofitting techniques used, the wall system and its thermal performance were kept constant for all the simulations carried out. The wall system therefore remained constant for all the scenarios tested, and any variations seen in terms of cooling load and power consumption can be attributed to the roof systems used. Wall materials have an impact on the heat transfer process in a building due to the conduction of heat into the building.

D. Performance Analysis

The thermal performance of each roof configuration was evaluated using two experimental indicators: Temperature Difference, lower surface temperature, and the Heat Reduction Index (HRI) shown in Equation 5.

$$HRI = 1 - \frac{Tbottom}{Tref} \quad (5)$$

Where:

- HRI is the heat reduction index [%]
- T_{bottom} is the temperature at the bottom of the structure for each insulation material [°C]
- T_{ref} is the temperature used for reference of the uninsulated Aluzinc sheet [°C]

Thermal stability was assessed using the standard deviation of the measured lower surface temperatures, where lower variability indicates more stable thermal behavior throughout the day using Equation 6.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (6)$$

Where:

- Σ is the standard deviation of the measured temperatures [°C]
- n is total number of temperature measurements [-]
- x_i is the individual temperature measurements [°C]
- $\bar{x}$ is the mean temperature of the corresponding dataset [°C]

Finally, each of the parameters studied was analyzed and compared across the different materials. The indicators evaluated and the methods used are shown in Table I.

TABLE I
INDICATORS ANALYSIS

Indicator	Evaluation Method
Upper surface temperature	Infrared thermography
Lower surface temperature	Infrared thermography

Indicator	Evaluation Method
Temperature difference (ΔT)	Experimental measurements
Thermal parameters	Experimental measurements and calculations
Standard deviation	Statistical analysis
Annual cooling demand	eQUEST simulation
Annual electricity cost	Energy cost calculation
CO_2 emission reduction	Emission factor calculation

III. RESULTS AND DISCUSSION

The results and discussion are presented in detail in this chapter.

Since the focus of the research is to find a low-cost solution, Table II shows the typical market prices for each of the materials used.

TABLE II
TYPICAL MARKET PRICE OF THE EVALUATED ROOF RETROFIT TECHNOLOGIES IN HONDURAS

Material	Unit	Typical Market price*
Uninsulated roof	m²	—
Thermal paint	USD/m²	4.0–6.0
Aluminum insulation	USD/m²	5.5–8.0
Fiberglass (50 mm)	USD/m²	7.0–10.0

*Approximate retail prices based on commercially available products in the Honduran market. Prices may vary depending on supplier, thickness, and installation costs.

Figure 3 shows the completed experimental study prototype and the materials used.



Fig. 3 Final experimental setup

Temperatures were measured for each of the materials studied during the test days; Figure 4 shows a graph illustrating how temperatures changed over time for the top surface.

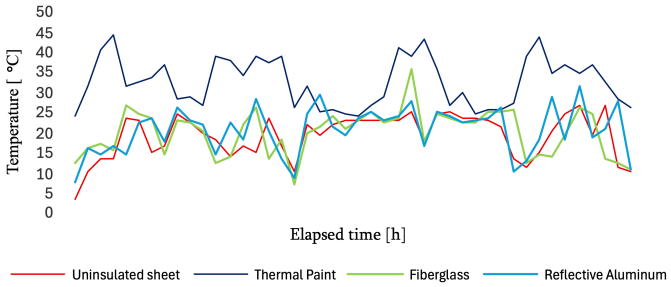


Fig. 4 Top Surface Temperature over four consecutive days (hourly measurements).

Reflective aluminum keeps temperatures lower, which is consistent with its ability to reflect most solar radiation. Reflective aluminum significantly reduces the temperature of the upper surface, indicating its high ability to reflect radiation. The lines corresponding to the uninsulated sheet and fiberglass fall within intermediate ranges, suggesting that these materials absorb some radiation, but not as much as the thermal paint. The thermal paint reaches the highest peaks, which could indicate that it absorbs more radiation and retains it.

Figure 5 shows the temperatures from the bottom surface. Temperatures are more uniform, but the uninsulated sheet allows for greater heat transfer, while insulated materials (aluminum and fiberglass) seem to better moderate heat transfer inward. The uninsulated sheet tends to have slightly higher temperatures, indicating greater heat transfer inward. Fiberglass and reflective aluminum are the most effective at reducing heat transfer to the underside. Thermal paint performs somewhere in between.

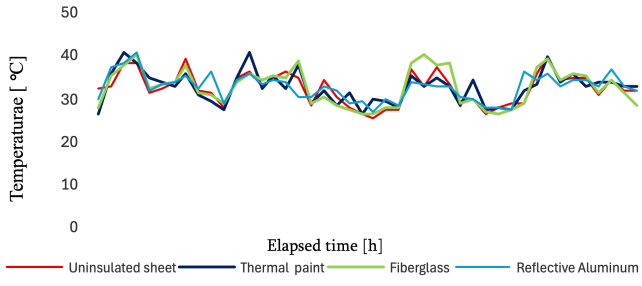


Fig. 5 Bottom Surface Temperature over four consecutive days (hourly measurements)

The average temperature difference (ΔT) obtained for the fiberglass insulation was 13.28°C, followed by the reflective aluminum insulation with 12.63°C and the reflective thermal coating with 11.94°C. These values were consistently higher than those of the reference uninsulated Aluzinc roof, confirming that the evaluated retrofit solutions effectively reduced heat transfer through the roof. Among the tested materials, fiberglass insulation provided the best thermal performance by maintaining the largest temperature difference between the exterior and interior roof surfaces.

To assess the thermal stability of the roofs during the experiment, standard deviations of the temperatures on the lower surfaces were calculated. Low standard deviations mean more stable thermal characteristics. That means the insulating material can reduce the effect of fluctuating solar radiation and provide temperature stability.

Among all roofs being studied, the aluminum insulation showed the lowest standard deviation value (3.086°C), which shows the highest thermal stability. The uninsulated Aluzinc roof and the reflective thermal coating demonstrated nearly equal standard deviations (3.678°C and 3.688°C, respectively).

However, the fiberglass insulation had the highest standard deviation (4.246°C), but it demonstrated the highest temperature difference and provided the best thermal insulation performance. It means that the fiberglass insulation was the most effective insulating material, but not the most stable one.

Table III shows the results of the HRI calculations.

TABLE III
HRI RESULTS

Material	HRI Range	Overall Performance
Thermal paint	–18% to 19%	Moderate
Fiberglass	–22% to 14%	Balanced
Reflective Aluminum	–25% to 13%	Moderately Positive

Overall, none of the materials maintains a consistently positive heat reduction rate. Reflective aluminum and fiberglass appear to show more stable and positive performance in various sections of the graph, outperforming Thermal Paint.

Reflective aluminum appears to have the highest positive peaks (indicating a greater ability to reduce heat) and fewer negative drops, which could indicate better overall performance in reducing heat.

Thermal Paint is the least effective, as its fluctuations are more pronounced and feature more negative values. Fiberglass performs somewhere in between, being more stable than Thermal Paint but less effective than Reflective Aluminum at certain key moments. This suggests that context and environmental conditions can significantly influence the effectiveness of each material as a thermal insulator.

Table IV shows the results of the thermal indicators calculated: Thermal transmittance and resistance.

TABLE IV
THERMAL INDICATORS

Material	Thermal transmittance [W/m² °C]	Thermal resistance [m² °C /W]
Uninsulated sheet	2.87	0.0000083
Thermal Paint	2.7389	0.0165
Fiberglass	0.373	2.33
Reflective Aluminum	0.5529	1.46

As shown in Table IV, fiberglass insulation exhibited the best thermal performance, presenting the lowest thermal transmittance (0.373 W/m²·°C) and the highest thermal resistance (2.33 m²·°C/W). Reflective aluminum insulation also demonstrated good insulating properties, while the reflective thermal coating provided only a moderate improvement. In contrast, the uninsulated Aluzinc roof showed the highest thermal transmittance and the lowest thermal resistance, confirming its poor thermal insulation capacity.

TABLE V
EQUEST SIMULATION RESULTS

Material	Cooling energy [kWh]	Cost of Cooling energy [$]	Annual Hours outside the comfort range [h]
Uninsulated sheet	3,557.2	906.5	729
Thermal Paint	2,808.65	715.5	402
Fiberglass	2,094.35	533.4	351
Reflective Aluminum	2,386.68	607.9	394

Table V shows that implementing thermal insulation technologies in roofs results in cost savings. The highest percentage of savings observed is 41.16% for fiberglass. Reflective aluminum yields cost savings of 32.93%, and paint yields savings of 21.06%. Since the walls were kept at a

constant structure in all the simulation cases, the variation in annual cooling energy is seen mainly based on the roof improvement approach. But in a real-life house, wall construction material, thickness, orientation, thermal mass, and sun exposure could also influence the cooling requirement and therefore, alter the share of the roof in the heat gain.

Finally, we calculated the carbon dioxide emissions released into the atmosphere because of the energy used to cool each of the materials. Using an emission factor of 0.67 kg/kWh [9], we obtained the results shown in Table VI.

TABLE VI
CARBON DIOXIDE EMISSIONS

Material	CO_2 emissions [kg CO_2]
Uninsulated sheet	2,383.32
Thermal Paint	1,881.8
Fiberglass	1,403.21
Reflective Aluminum	1,599.08

The results show that carbon dioxide emissions are proportional to electricity consumption, as shown in Table V. The material that generates the fewest emissions into the atmosphere is fiberglass. However, it is the most expensive solution per square meter, as shown in Table 2. For each case study, it is recommended to analyze the area requiring thermal insulation and conduct a cost-benefit analysis.

Initial cost is one of the factors to consider when choosing a thermal retrofit option; however, initial cost does not reflect the entire economic performance of an insulating material. Service life, maintenance needs, aging effect, and replacement rate may play a big role in determining the overall cost of the retrofitting effort.

This research, the experimental investigation was limited to the thermal performance of the tested insulation materials in outdoor environment, and no long-term aging and service life test were carried out. As such, it was impossible to experimentally determine the actual service life of thermal paint, fiberglass, or reflective aluminum insulation materials being evaluated. The cost figures listed in Table II should, therefore, be taken as the initial investment cost only. To obtain a complete economic evaluation, further research should take into consideration the service life and replacement rate of each insulating material as well as installation, maintenance, and replacement costs. Thus, life cycle cost and payback period could be calculated.

IV. CONCLUSIONS

An experimental and simulation study was conducted to identify low-cost solutions for reducing the thermal load in homes. Four scenarios were studied: a ceiling without thermal insulation, a ceiling with fiberglass insulation, a ceiling with thermal paint, and a ceiling with reflective aluminum. Tests were conducted to determine the best material to use to support the energy resilience of homes, reduce energy consumption, and create more sustainable housing. The following results were obtained:

- Using thermal imaging camera measurements, it was determined that fiberglass is the most efficient material, with a temperature reduction of up to 41.16%, followed by reflective aluminum at 32–35%, and heat-reflective paint with an average reduction of 18–22%.
- The EQUEST analysis showed that fiberglass achieved the greatest reduction in thermal loads and energy consumption, resulting in annual savings of $373.1 compared to the uninsulated sheet, while heat-reflective paint and reflective aluminum achieved savings of 21% and 33%, respectively.
- Fiberglass insulation produces the lowest amount of carbon dioxide emissions into the atmosphere in terms of the cooling energy used for this material, at 1,403.21 kg of CO2, compared to uninsulated panels, which generate 2,383.32 kg of CO_2, representing an approximate reduction of 41%. This supports the energy transition and more sustainable homes that help the environment, while also promoting energy resilience in households in tropical countries.

One of the major limitations of this research is that, although the experimental part was indeed conducted outdoors, the test roof did not actually replicate indoor conditions since it was not a fully enclosed surface as a house would be; therefore, the data collected does not fully represent the internal behavior of a home or building.

However, despite these limitations, the project was successfully carried out thanks to the use of eQuest simulations, which provided us with a better perspective and understanding of each of the materials used. It is hoped that this research will serve as a foundation for others to implement these changes in their homes and to continue the research under more controlled conditions that more closely resemble those of a building, to obtain more accurate results.

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