

Comparative Analysis of Thermal Performance of Painted, Finned, and Plain Roofs in Arid and Temperate Climates: Insights from Kuwait City and Vancouver

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Abstract. This paper presents a comparative analysis of the thermal performance of three common roofing types - painted, finned, and plain for buildings with customary materials without insulation- in two contrasting climatic contexts: Kuwait City and Vancouver. Experimental data were collected on hourly basis for the surface temperatures for 4 months in winter of Kuwait. Utilizing ASHRAE methods, we simulated the dynamic thermal behaviour of these roofing materials to assess their suitability for mitigating energy demands and enhancing indoor thermal comfort of a building with 127 m² rooftop surface area. Our findings reveal distinct thermal characteristics associated with each roofing type in the respective climates. In Kuwait City's arid environment, the painted roof emerges as the optimal choice, demonstrating superior performance in reducing thermal loads during hot months while posing challenges related to increased heating demand in cooler seasons with 4.5°C reduction by painted roof. Conversely, in Vancouver's temperate climate, the painted roof exhibits continuous outward conduction of heat, contributing to elevated heating demands throughout the year despite its effectiveness in maintaining lower temperatures compared to the indoor environment. This study highlights the importance of considering climatic factors and seasonal variations in selecting roofing materials to achieve optimal energy efficiency and indoor comfort. These findings can assist decision-making processes for architects, engineers, and policymakers aiming to enhance building performance and sustainability across diverse climatic regions.

1 Introduction

The demand for reducing cooling energy consumption in buildings has become a significant concern globally, particularly in regions like Kuwait where extreme temperatures necessitate heavy reliance on air conditioning for buildings built from customary materials without insulation. In this literature review, we explore the effectiveness of cool roof technologies in mitigating energy consumption and enhancing sustainability in building cooling systems. We

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focus on various cool roof methods, including cool roof coatings, composite roofs, and shingled roofs, and compare their performance in different geographical contexts.

Cool roof coatings, characterized by their reflective properties, have been extensively studied for their potential in reducing energy consumption. Seifhashem et al. [1] conducted research on the application of acrylic cool roof paint in a retail warehouse building in Australia, reporting a decrease in roof temperature and subsequent energy savings. Conversely, Bozonnet et al. [2] found no significant changes in indoor operative temperatures when cool roof paint was used on buildings in France, attributing this to the country's strict insulation standards. De Masi et al. [3] highlighted the degradation of solar reflectance in white acrylic paint over time, raising concerns about its long-term efficacy. Composite roofs, constructed using various materials and methods, offer another avenue for enhancing energy efficiency in building cooling systems. Kolokotroni et al. [4] investigated the use of phase change materials (PCM) and cool roofs to mitigate urban heat islands in the USA, reporting significant energy savings of up to 54% with PCM roofs. Lie et al. [5] demonstrated the potential of adaptive shape-morphing materials in building envelopes to enhance energy efficiency, while Habibi et al. [6] advocated for carefully selected roofing materials to achieve substantial energy savings. Shingled roofs, made from materials such as wood, ceramic, and asphalt, have gained attention for their potential in reducing energy consumption. Alchapar and Correa [7] conducted a study on various shingle and tile materials, as well as cool roof coatings, finding that certain materials increased roof temperatures and were therefore not recommended for heat reduction. Salem et al. [8] introduced a new finned roof concept that reduces the roof surface temperature by using fins to shade the roof and passively reduce its surface temperature.

The efficacy of different cool roof methods varies depending on factors such as geographical location, climate, and building characteristics. While some studies, such as those by Shittu et al. [9] and Androutsopoulos et al. [10], reported significant energy savings and temperature reductions with cool roof coatings in specific regions, others, such as the study by Kim et al. [11], observed varying effects across different seasons and climates.

The primary aim of this paper is to undertake a comparative analysis of the thermal efficiency of three prevalent roofing materials (painted, finned, and plain) within two distinct climatic environments: Kuwait City and Vancouver. The study seeks to evaluate the impact of these roofing types on energy consumption and indoor thermal comfort in uninsulated buildings.

2 Experimental work

The study uses an innovative design of roof tile that was first introduced by Salem et al. [8], crafted from 3 mm aluminium sheets. The tile features 130 mm wide sheets, bent and riveted onto the main tile at a 35-degree angle, and spaced 90 mm apart (see Fig. 1). This configuration ensures consistent shading of the main tiles year-round. The selection of the fins' tilt angle and spacing was informed by Kuwait's peak solar altitude angle of 83 degrees on June 30th [12].

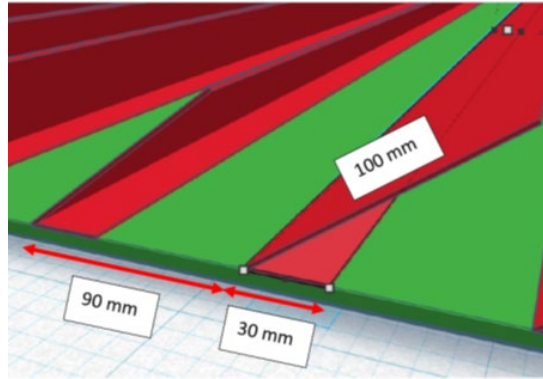


Fig. 1. Sketch of the aluminium finned roof.

The study involved testing the finned tile alongside two flat tiles: one plain and one coated with metal cool roof coating. Each tile was positioned atop 5 cm thick XPS foam boards to isolate them from the floor, effectively blocking the thermal effects originating from the floor mass. To mitigate the impact of wind, the tiles were situated near a building wall. Additionally, all tiles were oriented southward to eliminate shading effects, as illustrated in Figure 1. Sol-air temperatures were measured at the centre of each tile by affixing two thermocouples to the lower surface of the tiles. Sol-air temperature, as defined by ASHRAE Fundamentals [13], represents a hypothetical outdoor air temperature that, in the absence of radiation changes, would result in the same rate of heat entry into the surface due to incident solar radiation, radiant energy exchange with the sky and outdoor surroundings, and convective heat exchange with the outdoor air. Sol-air temperature can be calculated as:

$$T_{sol-air} = T_o + (\alpha/h_o) I_t - \varepsilon \cdot \delta R/h_o \quad (1)$$

$$Q_{Roof} = UA(T_{sol-air} - T_a) \quad (2)$$

where

T_o outside air temperature in °C

α absorption coefficient of the wall surface

I_t total solar radiation incident on the wall in W/m²

h_o outdoor heat transfer coefficient by radiation and conduction in W/(m²°C)

ε emissivity coefficient of the outer surface

δR difference between radiation incident on the surface from the sky and the environment minus radiation emitted by a blackbody at its temperature in W/m²

Q_{Roof} thermal load (Whr)

U overall heat transfer coefficient (W/m²·°C)

A total surface area (m²)

T_a ambient temperature (°C)

Equation (1) illustrates that sol-air temperature is the sum of the outdoor air temperature and the effects of incident radiation absorbed by the surface, minus the effects of emitted radiation to the sky and surroundings. ASHRAE Fundamentals suggest a standardized value of $\varepsilon \cdot \delta R/h_o$ as 3.9 °C for all surface types, assuming constant hemispherical emittance. ASHRAE Fundamentals also proposes specific values for α/h_o (0.026 for light colours and 0.052 for dark colours). However, field measurements by Al-Saud [14] revealed significant differences in sol-air temperatures for different roof colours. Measured temperatures were found lower than that calculated ones by almost 10 °C.

Hourly $T_{sol-air}$ temperatures were recorded from November 2023 to February 2024 using two data loggers with 8 K-type thermocouples (see Figure 2 left). The data loggers can record data every one second and the accuracy of the thermocouples are within 0.1 °C. The testing

system is shown in Figure 2 (right). Figure 3 presents the hourly $T_{sol-air}$ data for the three types of tiles on November 30th, 2023. During daylight hours, the plain tile exhibits the highest temperatures. Conversely, during nighttime, both the finned and plain tiles register nearly identical temperatures to the outdoor air. In contrast, the painted tile shows the lowest nighttime temperatures, with a temperature differential of approximately 4.5°C.

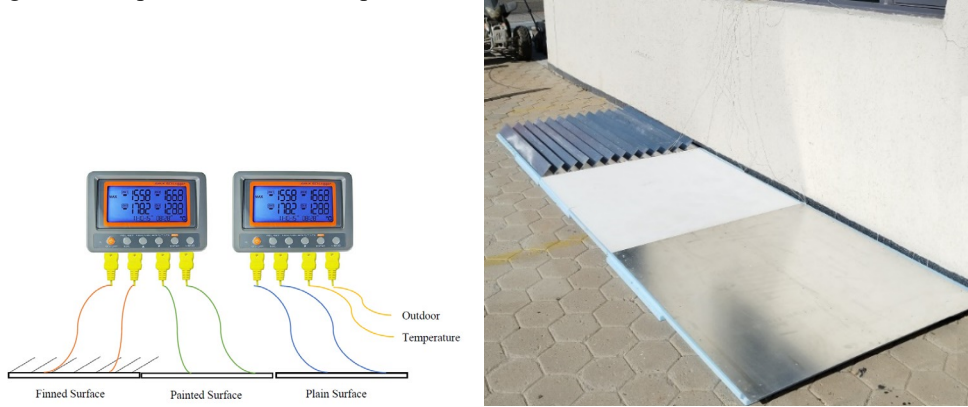


Fig. 2. The three aluminium tile configurations, finned, painted and plain, (left) data logger sketch, (right) the testing surfaces.

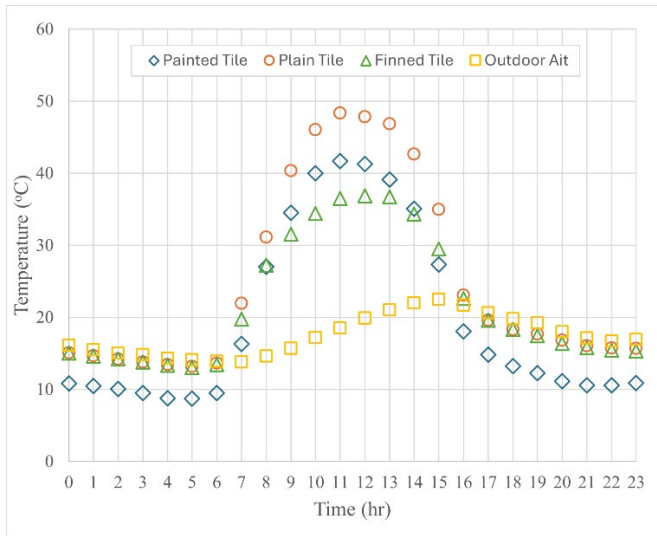


Fig. 3. $T_{sol-air}$ for different types of roofs in comparison with outdoor air temperature (Kuwait City, November 30th, 2023).

To enhance the understanding of the thermal influence of the roof tiles, a total floor area of 1366 ft² (127 m²), representative of typical residential buildings in Kuwait, was employed as a benchmark for evaluating the cooling and heating energy demands across different urban contexts. This building's floor area served as a conduit for thermal conduction through the roof, facilitating a comprehensive analysis of the tiles' impact.

In our study, the terms $\epsilon \cdot \delta R/h_o$ and a/h_o were derived from the actual sol-air temperature data and found to be 0.048 and 1.8 for the finned tile, 0.075 and 1.8 for the plain tile and 0.021 and 4.5 for the painted tile. Figure 4 shows the fitted $T_{sol-air}$ along with the actual ones for period between December 1st to 5th 2023.

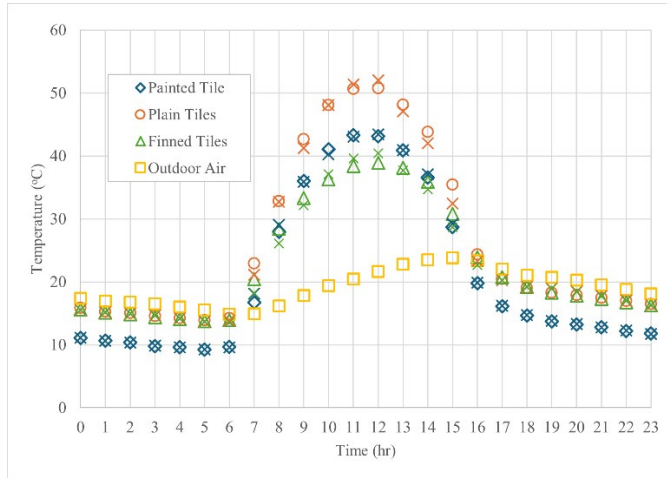


Fig. 4. Actual average sol-air temperature vs fitted values (x) (for Kuwait City, December 1st to 5th, 2023).

3 Calculated results

The fitted terms, $\epsilon \cdot \delta R/h_o$ and α/h_o , were used to evaluate the $T_{sol-air}$ for the entire year for both Kuwait City and Vancouver City to calculate the hourly thermal load using Equation (2) through the roof for the entire year. The Monthly heating/cooling loads are shown in Figure 5 and 6 for Kuwait City and Vancouver City, respectively.

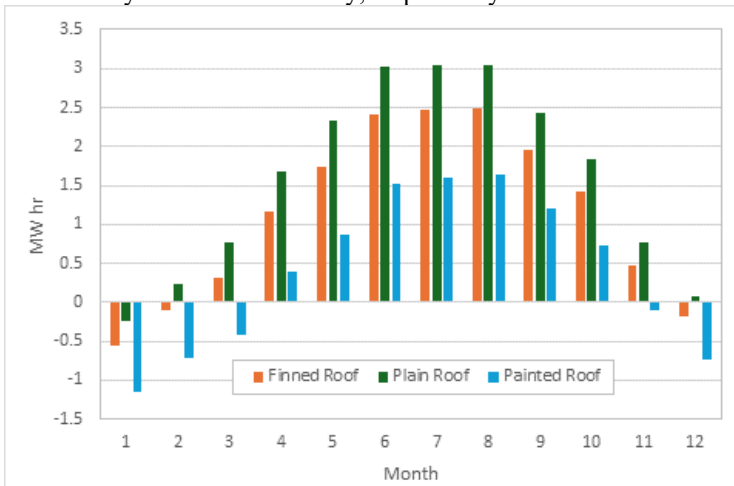


Fig. 5. Monthly average roof thermal load (Kuwait City).

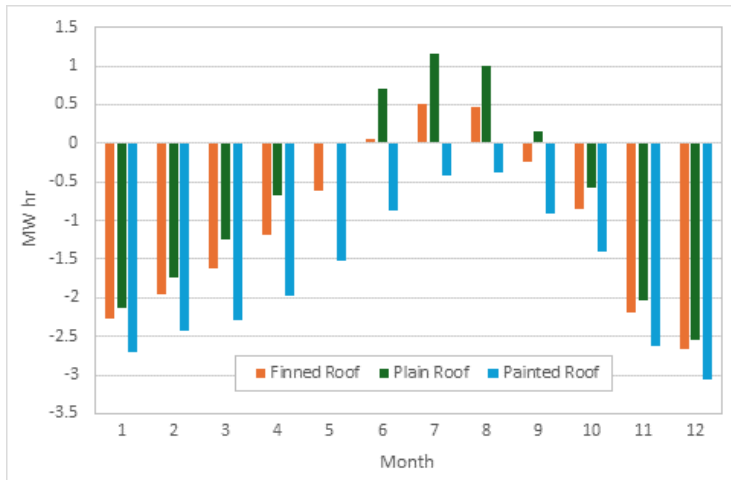


Fig. 6. Monthly average roof thermal load (Vancouver City).

In this study, we investigated the thermal performance of three types of roofs - painted, finned, and plain - in both Kuwait City and Vancouver, as shown in the above figures. Our findings reveal contrasting thermal behaviours of these roof types in the two distinct climatic contexts. The performance of different roofing materials under varying climatic conditions is crucial for optimizing building energy efficiency and mitigating thermal discomfort.

For Kuwait City, Figure 5, characterized by hot and dry summers, the results indicates that the painted roof exhibits superior performance in terms of thermal load reduction during the hot months from April to October. The painted roof demonstrates the lowest thermal load among the three types during this period, suggesting its effectiveness in minimizing heat transfer into the building interior and reducing the need for cooling. However, Figure 5 reveals a notable drawback associated with the painted roof in Kuwait City. During other months, particularly in the cooler seasons, the painted roof tends to maintain lower surface temperatures, leading to increased heating demand within the building. This phenomenon underscores the importance of considering seasonal variations and the overall annual energy balance when evaluating the suitability of roofing materials in arid climates like Kuwait City.

In contrast, the thermal performance of the painted roof in Vancouver, characterized by milder temperatures and higher precipitation levels, presents a different scenario. Figure 6 indicates that the painted roof consistently maintains lower temperatures compared to the indoor environment in Vancouver. While this may seem beneficial for reducing cooling demand during warmer periods, it also results in a continuous inward conduction of heat, contributing to higher heating demand throughout the year. This observation suggests that the advantages of the painted roof in terms of minimizing cooling requirements may be offset by its adverse impact on heating demands, particularly in climates with prolonged heating seasons such as Vancouver.

4 Conclusion

This study compares the thermal performance of three roofing types (painted, finned, and plain) in Kuwait City and Vancouver. The findings reveal contrasting behaviours of these roof types in the two different climatic contexts. In Kuwait City, the painted roof demonstrates superior performance in reducing thermal loads during hot months, but it poses challenges related to increased heating demand in cooler seasons. In Vancouver, the painted

roof maintains lower temperatures compared to the indoor environment, but this leads to continuous inward conduction of heat and elevated heating demands throughout the year.

- One of the key challenges highlighted in the study is the impact of seasonal variations on the thermal performance of roofing materials which requires annual analyses.

- The study reveals trade-offs between cooling and heating demands associated with the painted roof. While it effectively reduces cooling demand in Kuwait City, it increases heating demand in cooler seasons. Similarly, in Vancouver, the painted roof maintains lower temperatures but contributes to higher heating demands.

- Another challenge is to achieve overall building energy efficiency by considering the interaction between roofing materials and other building components.

- The findings of this study are specific to Kuwait City and Vancouver and may not directly apply to other locations.

Overall, this study highlights the importance of considering climatic factors, seasonal variations, and the interplay between cooling and heating demands when selecting roofing materials to achieve optimal energy efficiency and indoor comfort in different climates.

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