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Analyzing the Thermal Efficiency of Roofing Materials in Hot and Dry Climatic Conditions

Shubham Gupta[1], Ar. Prajakta Ganu[1]

[1] *VESCOA*

Abstract

Roofing material selection plays a critical role in controlling indoor thermal comfort in hot and dry climates such as Prayagraj, northern India, where summer temperatures frequently exceed 45°C (India Meteorological Department [IMD], 2022). In such conditions, roofs are a primary source of heat gain, increasing dependence on energy-intensive cooling systems (Oke, 1987; Givoni, 1998). The objective of this study is to evaluate the thermal efficiency of traditional and modern roofing materials using U-value and R-value analysis to identify suitable passive cooling alternatives (Szokolay, 2014). The materials examined include indigenous systems such as khaprail (baked clay tiles), thatch (wild grass), bamboo mat roofing, and brick vault construction, along with commonly used modern systems such as reinforced cement concrete (RCC) slabs and galvanized iron (GI) sheets. The study adopts a analytical approach supported by secondary data obtained from literature review and established material property databases. Thermal performance is assessed through evaluation of U-values, R-values, heat transfer characteristics, and surface heat exchange behavior, along with their impact on indoor thermal comfort (Bureau of Energy Efficiency [BEE], 2017; ASHRAE, 2021). Preliminary results indicate that traditional materials such as thatch and clay tiles demonstrate higher thermal resistance and reduced heat gain compared to RCC and GI roofing systems (Singh et al., 2019). The study contributes to sustainable and climate-responsive building design by identifying energy-efficient roofing alternatives

Keywords; Thermal performance, roofing material, U value, R value

INTRODUCTION

Prayagraj, located at approximately 25.4358° N latitude and 81.8463° E longitude, faces very hot summers (India Meteorological Department [IMD], 2022). In May–June, maximum temperatures often cross 45°C, and heatwave days are common (IMD, 2022). This puts direct stress on roofs because they receive the highest solar load during the day (Oke, 1987). Recent government and weather records also flag Prayagraj among the hotter districts in Uttar Pradesh during extreme heat events (IMD, 2022).

In low-rise Indian buildings, the roof is a major pathway for heat gain (Sharma, 2019). Many studies report that roofs can contribute a significant proportion of the total heat entering a building during hot seasons (Oke, 1987; Givoni, 1998). Therefore, improvements in roof design and material selection can directly enhance indoor thermal comfort and reduce cooling energy demand (Bureau of Energy Efficiency, 2017; Szokolay, 2014).

Policy also recognizes the roof's importance. The Energy Conservation Building Code (ECBC 2017) sets performance limits for the building envelope by climate zone and encourages strategies like high Solar Reflectance Index (SRI) finishes and better roof U-values for hot-dry/composite regions (Bureau of Energy Efficiency, 2017). However, the code is performance-based and does not prescribe one single material; actual results depend on the full assembly (outer finish, insulation, air gaps, deck, ceiling).

There is, notwithstanding, little local evidence in North Indian situations such as Prayagraj of a continuum of buildings between RCC slabs with weathering courses and GI-sheet sheds, clay-tile overlays and more recent composite roofs (e.g., metal deck + insulation + air gap + false ceiling; RCC + cool coat + insulation; PUF/PIR sandwich panels; ventilated double-skin). Performance is also affected by local construction customs, financial constraints and maintenance. This creates a clear research gap: the need for measured and comparable data specific to local climatic conditions rather than generalized findings from other regions or laboratory studies

Hence, this research is aimed at the comparison of composite roof build-ups applicable to the building stock and budgets of Prayagraj based on simple and reproducible measures (surface temperature, interior temperature, and calculated U-value). By generating location-specific evidence, the work is geared towards identifying commonly used composite roofing materials in residential and institutional structures, analysing their thermal performance (heat gain, insulation value, surface temperature), evaluating their ability to regulate indoor temperature, assessing their impact on cooling energy demand, and formulating recommendations for suitable roofing materials in hot and dry climates such as Prayagraj.

LITERATURE REVIEW

Thermal performance of roofing materials is a critical factor in hot and dry climates, where roofs contribute significantly to heat gain in buildings. Key parameters such as thermal conductivity (k-value), thermal resistance (R-value), density, and specific heat capacity influence the rate of heat transfer through roofing systems (ASHRAE, 2021; Bureau of Energy Efficiency, 2017).

Traditional materials such as thatch, clay tiles, and bamboo-based systems generally exhibit lower thermal conductivity and higher insulation capacity due to their porous structure and air-trapping characteristics, resulting in improved indoor thermal comfort (Givoni, 1998; Szokolay, 2014). In contrast, modern materials such as RCC and metal sheets tend to have higher heat transfer rates when used without insulation, leading to increased indoor temperatures (Bureau of Energy Efficiency, 2017).

Recent studies highlight that composite roof systems incorporating insulation layers, air gaps, and reflective surfaces perform significantly better than single-layer roofing systems and can reduce indoor temperatures in hot climates (Sadineni et al., 2011; Singh et al., 2019). However, there is limited location-specific research for cities like Prayagraj, indicating the need for comparative analysis of locally used roofing materials.

AIM OF THE RESEARCH

To evaluate and compare the efficiency of different roofing materials in hot and dry climates with the goal of reducing heat gain through roof.

Objectives

- To identify common composite roofing materials used in residential and institutional buildings.
- To analyze the thermal performance (e.g., heat gain, insulation value, surface temperature) of these materials.
- Comparing traditional vs. modern composite roofing systems in terms of indoor temperature regulation.
- To assess how material choice impacts cooling energy demand.
- To provide recommendations for optimal roofing material use in hot and dry regions like Prayagraj.

METHODOLOGY

The study is based on a literature-based analytical approach. Thermal properties of selected materials are obtained from standard references such as ASHRAE, ECBC 2017, and relevant IS codes. The methodology involves selection of commonly used roofing materials, collection of their thermal properties, and evaluation of their performance using thermal resistance (R-value) and overall heat transfer coefficient (U-value). Standard heat transfer equations are used for the calculation of R-values and U-values. The analysis focuses on comparing the thermal performance of different materials and composite roof assemblies under hot and dry climatic conditions.



Fig. 1: Methodology of Research

Source: Author

This figure shows how research is going to be done layer to layer.

Selection Criteria for Roofing Material

The selection of roofing materials is based on several factors, roofing material can be selected in many ways, some of them are Climatic suitability, local availability, modern material, thermal properties, Economic feasibility, durability and maintenance, structural compatibility, cultural and heritage, aesthetics and functional. In this study, we are taking into consideration locally available materials commonly used for roofing keeping in mind old and modern material.

The choice of roofing materials can be explained by the fact that they are locally available and effectively match the hot climate in Prayagraj and the building tradition in the locality.

These Customary tiles are glazed with clay and are referred to as Khaprail (Clay Tiles), which are found on temples and older houses. They are still in use in some of the heritage buildings in Prayagraj. They remain available

around the area, thus it was reasonable to incorporate them in the study



Fig. 2: Khaprail a clay tile, Prayagraj
Source: https://www.dreamstime.com

Bamboo and thatch is mostly utilized in villages. It is used by people in small houses, sheds or temporary shelters. The bamboo and thatch can be readily found, and virtually anyone in these regions is familiar with the use of bamboo and thatch. The study of this technique assists us in comprehending the conventional rural constructions



Fig. 3: Thatch with bamboo frame
Source: https://capereed.com

The city is full of RCC Flat Roofs. RCC slabs are available in most of the modern houses, schools and shops. These are hard, inflammable and quite straightforward to assemble. We also incorporated

RCC roofs as a comparison of the modern ways and the old ones.



Fig. 4: RCC plat slab
Source: https://capereed.com

GI Sheet Roofing appears in most of the markets, halls and small shops. These sheets are readily available in the local markets and used in temporary buildings or Semi-permanent buildings. Due to the high number of people using them, it was considered the right thing to do.

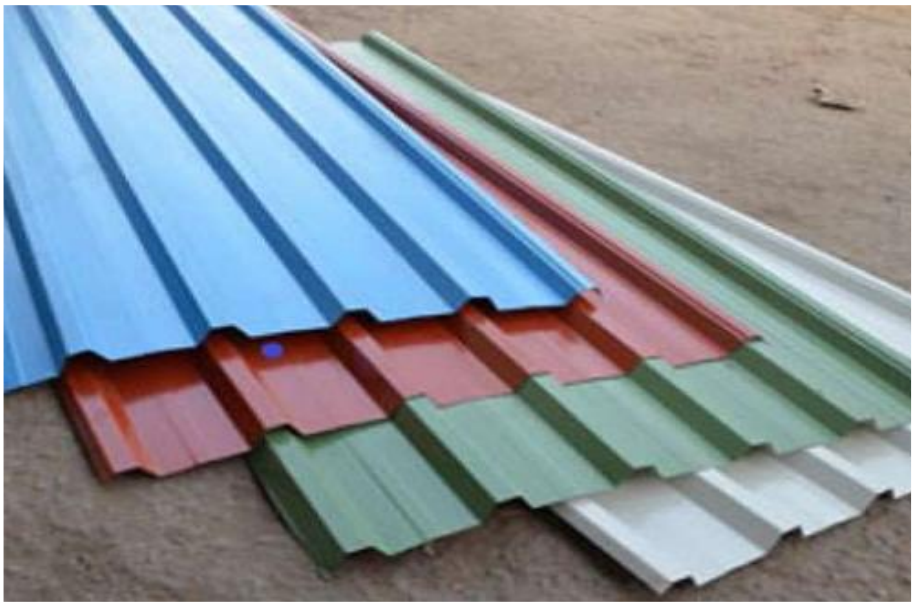


Fig. 5: Gi sheet
Source: https://www.tradeindia.com

Data Collection

The data for this study is collected through secondary sources including standard reference documents such as ASHRAE Handbook, Energy Conservation Building Code (ECBC 2017), and relevant Indian Standards (IS codes). These sources provide reliable and widely accepted values for thermal properties such as thermal conductivity (k), density, and specific heat capacity of building materials.

For each selected roofing material, standardized values of thermal properties are adopted to ensure consistency and accuracy in analysis. Since material properties may vary depending on composition, moisture content, and manufacturing conditions, representative

values commonly used in building design practice have been considered.

In addition to material properties, data related to roof assemblies, insulation layers, and surface treatments have been collected from published research papers and case studies. This allows a comparative understanding of both traditional and modern roofing systems under similar climatic conditions.

Table 1: Thermal Properties of Selected Roofing Materials

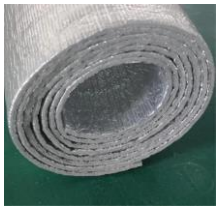
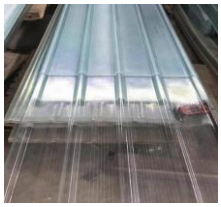
Source: Author and many other sources mention below

Sr.no	Material	Conductivity (W/m·K)	Density (kg/m³)	Specific Heat (J/kg·K)	Thickness (mm)	R-Value (m²·K/W)
M1	Bamboo	0.15	600	1600	20	0.13
M2	Thatch	0.07	120	1500	150	2.14
M3	Clay Tiles (Mangalore)	0.85	1800	840	20	0.02
M4	RCC (150 mm)	1.58	2400	880	150	0.095
M5	Galvalume Sheet	45.0	7850	500	1	0.00005
M6	Roof Insulation (PUF/XPS)	0.028	35	1400	50	1.78
M7	Translucent Tile	0.2	1200	1250	5	0.025
M8	Local Timber (Rafter/Purlin)	0.14	650	1600	50	0.36

The thermal performance of roofing systems is evaluated based on composite assemblies. U-values are calculated at the system level and not for individual materials

Table 2: Details of **selected** Roofing material

Source: Author and many other sources mention below

Material specification	M1	M2	M3	M4
Details	 **Fig. 6**: Bamboo	 **Fig. 7**: Thatch	 **Fig. 8:** Khaprail tiles	 **Fig. 9:** RCC slab 150mm thick
Source	https://www.indiamart.com	https://syntheticthatch.in	https://www.freepik.com	https://www.indiamart.com
Material specification	M5	M6	M7	M8
Details	 **Fig. 10**: Galvalume sheet	 **Fig. 11**: Roof Insulation	 **Fig. 12:** Translucent tiles	**Fig. 13**: Local  timber

Source	https://www.indiamart.com	https://www.indiamart.com	https://www.justdial.com	https://www.justdial.com

Calculation of Thermal Resistance and U-Value

The thermal resistance (R-value) of each layer is calculated using the following formula:

R = Thickness / Thermal Conductivity (k)

The total thermal resistance of a composite roof is obtained by summing the resistance of all layers:

$R_{total} = R_1 + R_2 + R_3 + \ldots$

The overall heat transfer coefficient (U-value) is calculated as:

$U = 1 / R_{total}$

Sample Calculation (RCC + Insulation Roof)

For RCC slab of 150 mm thickness: $R_{RCC} = 0.15 / 1.58 = 0.095\ m^2K/W$

For insulation layer of 50 mm thickness: $R_{insulation} = 0.05 / 0.028 = 1.78\ m^2K/W$

Total resistance: $R_{total} = 0.095 + 1.78 = 1.875 \approx 1.88\ m^2K/W$

U-value:

$U = 1 / 1.88 = 0.53\ W/m^2K$

Similar calculations are carried out for all roof assemblies to determine their thermal performance.

Table 3: Composite roof Assembly Details

Source: Author

Sr.no	Roof Assembly Type	Layer Composition	Total R-Value ($m^2 \cdot K/W$)	U-Value ($W/m^2 \cdot K$)	Performance
R1	RCC Slab (Basic)	150 mm RCC	0.10	10.0	Very Poor
R2	RCC + Insulation	RCC (150 mm) + 50 mm insulation	1.88	0.53	Moderate
R3	RCC + Insulation + Air Gap	RCC + insulation + air gap + ceiling	2.50	0.40	Good (ECBC compliant)
R4	Clay Tile Roof	Clay tile + air gap + wooden support	1.50	0.67	Good
R5	Metal Sheet (Basic)	Galvalume sheet	0.02	50.0	Very Poor
R6	Metal + Insulation	Sheet + insulation + false ceiling	2.20	0.45	Good
R7	Thatch Roof	Thatch + bamboo structure	2.10	0.48	Good
R8	Metal Sheet + Clay Tile	Galvalume sheet + air gap + clay tile overlay	1.80	0.55	Moderate to Good
R9	Clay Tile + Thatch Roof	Clay tile + thatch layer + bamboo support	2.40	0.42	Very Good (Near ECBC)

RESULTS AND FINDINGS

The results show that single-layer roofing systems such as RCC (U = 10.0 W/m^2K) and metal sheets (U = 50.0 W/m^2K) have very poor thermal performance and result in high heat gain. The addition of insulation significantly improves performance. RCC with insulation reduces the U-value to 0.53 W/m^2K, and further improvement is achieved with air gaps (U = 0.40 W/m^2K), meeting ECBC standards.

Traditional systems such as thatch (U = 0.48 W/m^2K) and clay tile roofs (U = 0.67 W/m^2K) perform better due to natural insulation and air pockets.

The best performance is observed in composite systems, especially clay tile + thatch (U = 0.42 W/m^2K), which provides high thermal resistance and improved indoor comfort.

CONCLUSION

The study confirms that roofing material selection significantly affects thermal performance in hot and dry climates. Single-layer systems are thermally inefficient, while composite roof assemblies with insulation and air gaps perform effectively. Traditional and hybrid systems, especially clay tile and thatch combinations, provide better thermal efficiency and can reduce heat gain.

Therefore, the use of composite and insulated roofing systems is recommended for improving indoor comfort and reducing cooling energy demand in regions like Prayagraj.

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