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Analysis of Heat Mitigation Potential of Coir Mat and Perlite Layers vs Green Roof Systems

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Abstract

This study explores the heat mitigation potential of coir mats and green facades applied to roofs. Being situated near the equator, buildings are subjected to intense solar radiation due to the sun's proximity and minimal declination angle. Consequently, roofs transfer a substantial amount of heat into indoor spaces, making effective thermal regulation strategies essential. Roof insulation emerges as a key method for managing indoor temperatures, with sustainable, locally sourced, climate-friendly, and low-cost materials being particularly favorable. In this research, the performance of roof insulation using coir mats and green plants is evaluated, with a focus on their sustainability, affordability, and environmental benefits, alongside their ability to mitigate heat. The study focuses on the analysis of the experimental study which compares the thermal performance of various insulation materials, including coir mats with perlite and green roofs, against an uninsulated reference roof. Measurements of heat flux and surface temperatures during both daytime and nighttime are taken to assess the insulation's effectiveness. The resulting data is analyzed to identify key factors affecting indoor heat load, with a detailed focus on the heat mitigation potential of the coir mat-perlite combination and green roofing solutions. It is found that perlite and green roof combination is superior to the green roof in lowering the net heat load for the whole day of 24 hours. The green roof which is doing well during the daytime is trapping the heat liberation during the night. The heat liberation of green roof at night is 28.98% and that for coir mat stacked perlite is 38.48%.

Keywords: Heat mitigation, coir mat stacked perlite, green roof, solar hours, non-solar hours

INTRODUCTION

Buildings are responsible for a substantial portion of global energy consumption and greenhouse gas (GHG) emissions, with estimates placing these contributions at 35–40% and 35% [1–3], respectively. This highlights the need for significant reductions in energy use within buildings to help maintain climate stability, specifically aiming to keep global warming below 2°C relative to pre-industrial levels. Since people spend over 90% of their lives indoors, the bulk of energy in buildings is used for space heating, cooling, and ventilation, primarily through energy-intensive systems [4–6] like air conditioning. Transitioning to passive, less energy-demanding methods is crucial [7, 8] to achieving near-zero GHG emission buildings.

Passive techniques can deliver thermal comfort inside buildings with little or no reliance on mechanical or electrical systems. While some techniques may still require minimal energy for components, such as fans or pumps, studies suggest that the energy consumed by these devices is negligible, allowing these systems to be

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classified as passive [9]. Among passive strategies, the roof plays a critical role, as it is the most exposed part of a building to direct sunlight, often contributing up to 50% [10, 11] of heat load in smaller buildings during the summer.

A green roof, which incorporates a layer of vegetation, is one such passive technique. It involves a layered system, including a waterproof membrane, soil, and vegetation, to reduce energy demand. The roof is a key focus for passive measures due to its exposure to solar radiation. Several methods can be employed to reduce heat gain through the roof, including shading, increasing roof thickness, improving the roof's albedo (reflectivity), insulating, and using water-based systems, such as roof ponds.

Increasing the heat transfer rate of heat transfer equipment is an ever-lasting topic in thermal engineering. Due to the advantages of light weight, high specific surface, high thermal conductivity, metal foam is a good extending surface for heat transfer enhancement.

MATERIALS AND METHODS

The methodology involved setting up two cubicles for the experiment, with one having an uninsulated roof and the other featuring two types of roof insulation. The insulated roof used a layer of coir mat stacked with perlite placed on top of one cubicle. Both cubicles measured 1.4 m in length, 1.14 m in width, and 1.5 m in height and were constructed on the rooftop of a four-story building at TKM Engineering College, located at coordinates 8.9142° N, 76.6320° E in South India (Figure 1). The specifications for the Reinforced Cement Concrete (RCC) roof slab used in the cubicle construction are detailed in Table 1.

Table 1. The specification of roof slab (IS 2000:456).

Area (L x B)	1.4 m x 1.14 m
Compressive strength	20 MPa
Mixing ratio of Cement: Sand: Aggregate	1: 1.5: 3
Diameter of the iron rods	8 mm
Mesh size	100 mm x 100 mm
Thickness of slab	100 mm
The thickness of the slab, including plastering	120 mm (10 mm thickness on top and bottom surface)

Both cubicles were equipped with doors to allow access for sensor placement, inspection, and maintenance. Since the cubicles were identical, any environmental changes affecting one would equally impact the other. This setup ensured that heat transfer through the walls and ventilation effects were neutralized, making any observed variations in the cubicles solely attributable to differences in roof insulation.

Figure 1. Experimental set up with dry coir mat and perlite [12].

T-type thermocouples having an accuracy of ±0.1°C are used for temperature measurements [12]. They are placed on both sides of the roof surface by chipping some plaster and grouting cement. Heat flux sensor (Omega HFS-3) is fixed on the inner roof of the bare and testing roof to measure the heat flux coming through the roof. All the sensors are connected to the data acquisition system (Key sight, Agilent 34972A). Weather data is obtained from a weather station installed in the vicinity of the experimental area.

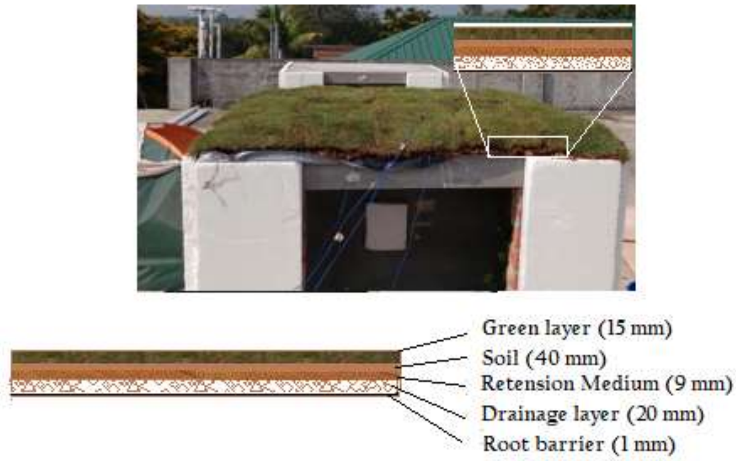

Figure 2. Experimental set up with green roof [12].

The data obtained from the experimental study Figures 1 and 2 for 72 hours for each case is analyzed for the heat mitigation potential of the green roof and the stacked coir mat and perlite. The basic equation for finding the heat transfer by solar radiation, convection and conduction is given by Equations (1) and (2). Obviously, solar radiation is the main component of heat addition to the roof during the daytime as shown in Figure 3.

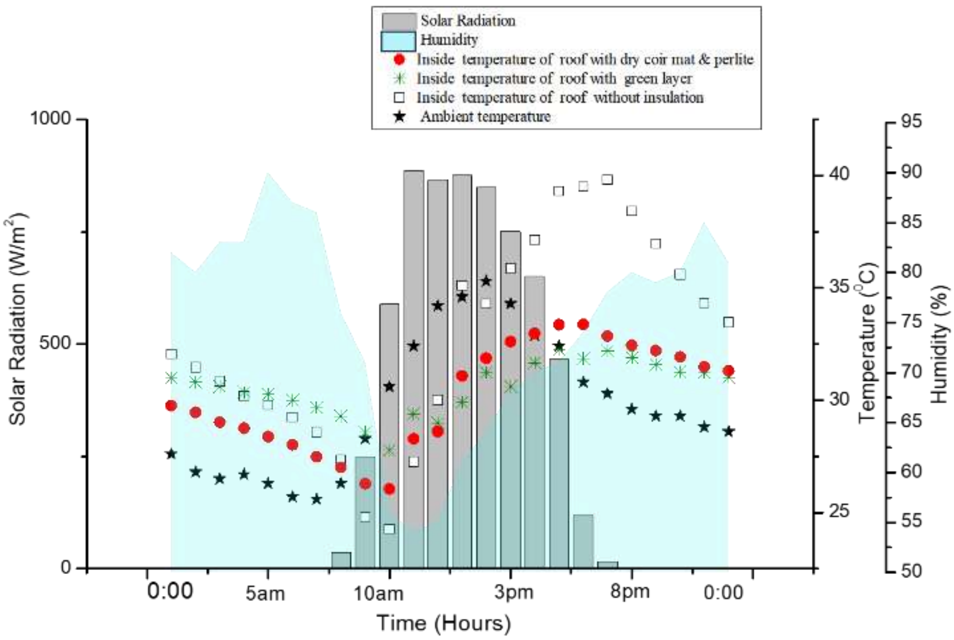

Figure 3. Variation of inside roof surface temperature with solar radiation.

RESULTS AND DISCUSSIONS

The solar radiation, wind velocity, temperature and heat flux are obtained from the sensors and weather station are substituted in the Equation (1) below to find the different modes of energy interactions with that of roof. The heat energy that is falling on the substrate of the green roof is assumed to be transmitted through the roof slab. Here, S is the hourly solar radiation, Ʈ is the transmittivity, ε is the emissivity, T is the temperature, h is the convective heat transfer coefficient is the shape factor, σ is the Stefan Boltz man constant is the thermal conductivity of material of roof slab and x are the thickness of the roof slab.

$$-k_{roof}\frac{\partial T}{\partial x} = \tau_{green}\ \alpha_{ground}\ S + F\tau_{green}\ \mathcal{E}_{sky}\ \mathcal{E}_{ground}\ \sigma\left(T_{sky}{}^{4} - T_{ground}{}^{4}\right)$$

$$-\ h_{out}\left(T_{ground} - T_{air}\right) + \frac{(1-\tau)\mathcal{E}_{green}\ \mathcal{E}_{ground}\sigma\left(T_{green}{}^{4} - T_{ground}{}^{4}\right)}{\mathcal{E}_{green} + \mathcal{E}_{ground} - \mathcal{E}_{green}\ \mathcal{E}_{ground}} \quad (1)$$

First term on the right-hand side gives the radiation from the sun that is absorbed by the ground after the green layer. The second term gives the radiation exchange between the sky and ground through the green layer. The third term gives the convection heat transfer of the ground with ambient air. The fourth term gives the radiation exchange with the green layer and ground, which is neglected in this case, since it has very negligible impact. Heat flux calculation over a coir mat with perlite under dry conditions is challenging due to its roughness, porosity and dynamic behavior of the climatic conditions. The temperature distribution in the coir mat is also different due to varying environmental parameters. It is assumed that stacked coir mat and perlite are acting as a facade which is very porous. So, there will be always a circulation of air through the pores (Figure 4). The velocity of air is drastically reduced by the coir mat and the perlite. Because of the porosity of the coir mat and perlite, the velocity of the air is assumed to be reduced up to 85% in this case.

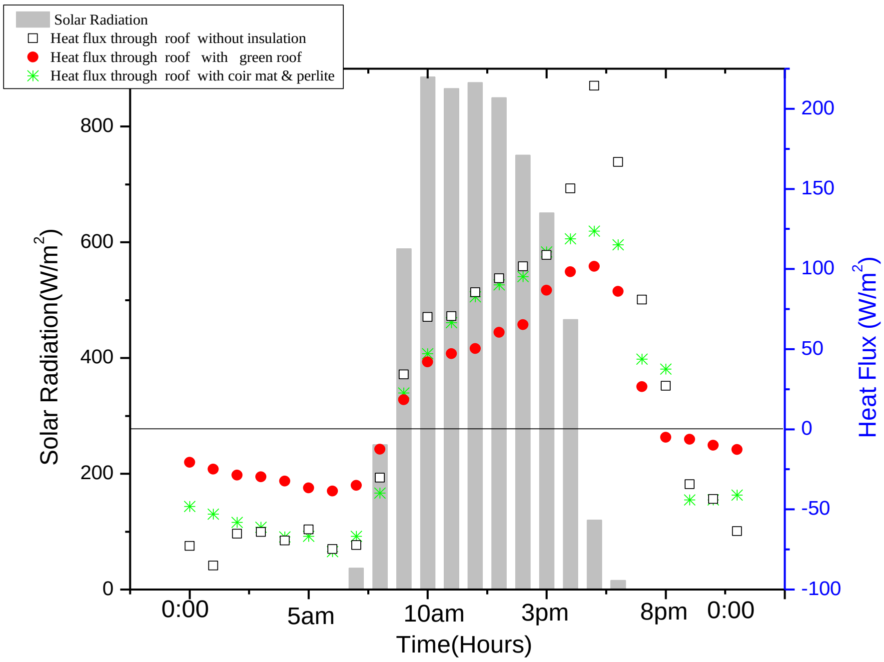

Figure 4. Variation of heat flux through roof with solar radiation.

Hourly energy transfer of all the term is calculated with Equation (2), for the energy interaction of the roof slab with the surroundings [13]. The solar radiation, temperature, ambient temperature and air velocity are obtained from experimental data. The graph obtained for the analytical study is given below. The hourly energy is calculated for finding the 24 hours of data is shown in Figures 5 and 6. Here the solar radiation effect is a prominent factor for the heat input, which is blocked by the coir mat. The transmittivity of the coir mat is taken as 0.3. The perlite bed again blocks the solar radiation and the heat conduction during the daytime [13].

$$-k_{roof}\frac{\partial T}{\partial x} = \tau_{\text{coir}}\ \alpha_{roof}\ S + \tau_{\text{coir}}\ \tau_{\text{perlite}}\ \varepsilon_{\text{sky}}\ \varepsilon_{\text{roof}}\ \sigma\left({T_{sky}}^4 - {T_{roof}}^4\right) - h_{\text{roof}}\left(T_{roof} - T_{air}\right) \quad (2)$$

The radiation exchange with the sky is again hindered by the coir mat and perlite and is given by the first term in Equation 2. From the analytical data, the radiation exchange with the roof is effectively blocked by coir and perlite. At the same time, the porous nature of coir mat and perlite is very favorable for the liberation of heat so the net heat load for the 24 hour is low, compared with the green roof. For the case of green roof, cooling effect is imparted by the evapotranspiration of the vegetative parts during the daytime. But during the nighttime the long wave radiation forms the vegetative parts will block the liberation of heat from the roof to the outside. The net effect is that the cooling effect is decreased by the blocking effect when a period of 24 hours is considered.

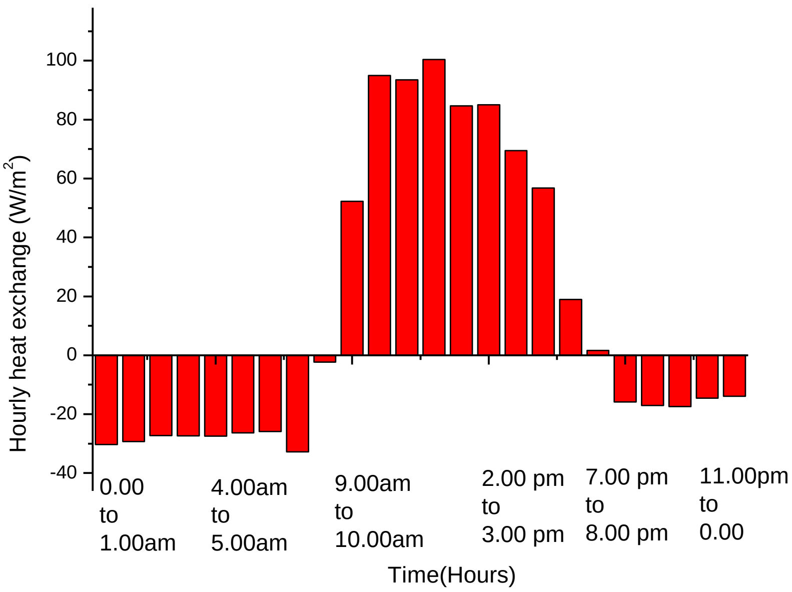

Figure 5. Net heat interaction of coir mat with perlite for an entire day.

The analysis indicates that both heat gain and heat loss occur at the roof due to various heat exchange mechanisms. When insulation is applied, the amount of heat entering through the roof decreases compared to a roof without insulation. However, the insulation also reduces the roof's ability to release heat. Figure 7 illustrates the heat gain and loss for two different insulation setups compared to an uninsulated roof. The heat gain and loss for each insulated scenario are normalized against the corresponding values for the uninsulated roof, providing a comparative view of their performance.

It can be observed that the use of insulation significantly reduces the amount of heat added to the roof compared to the bare wall scenario (100%). With double insulation, consisting of a coir mat and perlite, the heat addition is reduced to 35.98%. Using green roof, heat addition is lowered to 58.72% compared to bare roof.

The heat rejection capabilities of the insulated roof are evaluated against the bare roof. A bare roof has the best heat rejection capability, which decreases when insulation is applied. For example, only about 28.98% of the heat is rejected when green roof is used. This is due to the long wave radiation of the vegetative parts of the green roof during wee hours. This percentage increases to about 38.48% when coir and perlite are used. It should be noted that when assessing the performance of heat insulation over an entire day, it was ensured that the indoor temperature did not exceed a tolerable level at any time.

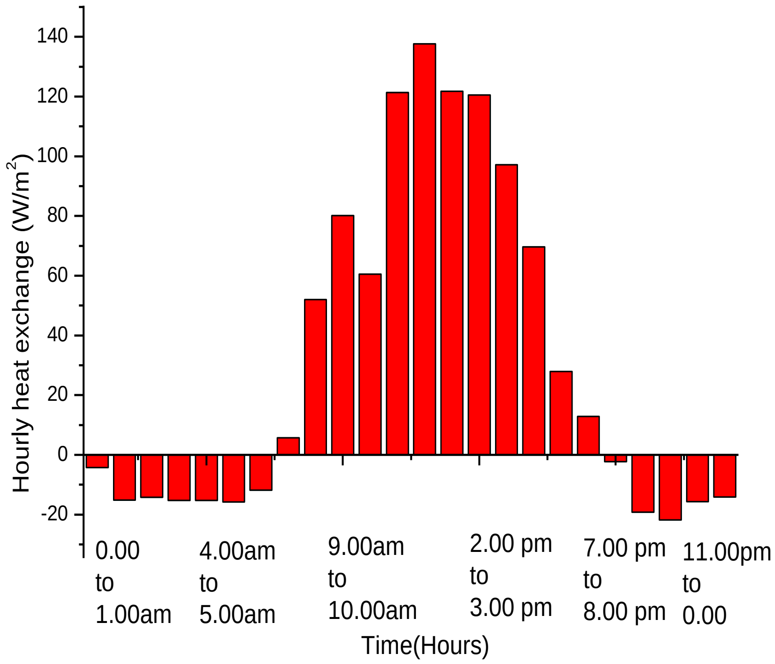

Figure 6. Net heat interaction of green roof for an entire day.

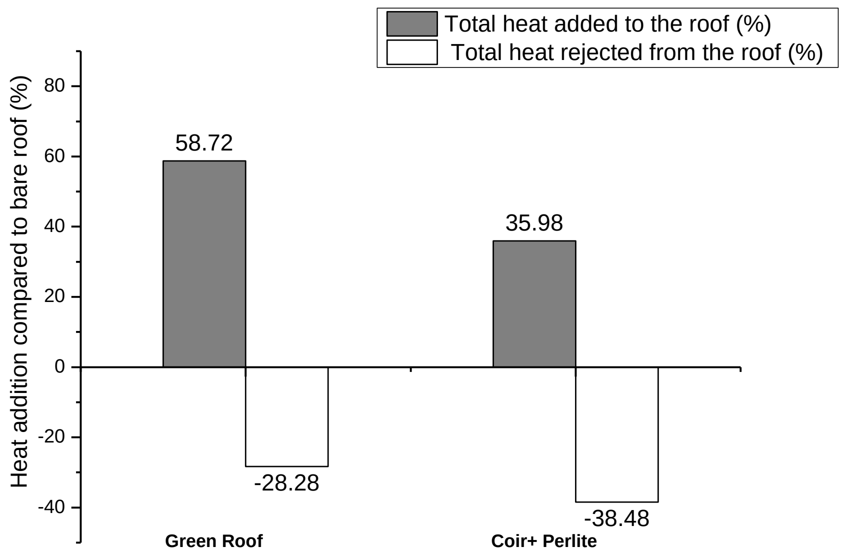

Figure 7. *Heat flux through two insulation at a glance per day*

CONCLUSIONS

Numerical analysis of the experimental work is conducted for the green roof and stacked coir mat and perlite. The maximum value of heat addition to the green roof is found to be 140 W/m^2 for the case of green roof. When the roof insulation with stacked coir mat and perlite is analyzed, it is found to be only 100 W/m^2. Though the heat mitigation ability is appreciable for the daytime in case of green roof, the heat liberation capacity of the same is not significant. But for the case of stacked coir mat and perlite, the heat mitigation is very significant and the heat liberation for it during the wee hours is also very prominent compared to that of green roof. The heat added to the roof through the green roof is 58.72% compared to the bare roof during the daytime and the heat liberation is 28.98% during the nighttime. For the case of stacked coir mat and perlite its heat addition is only 35.98% and heat liberation is 38.48%, respectively. So a stacked coir mat and perlite can be considered as a better alternative for green roof considering its heat mitigation potential.

Abbreviations and Subscripts

T Temperature (K)
k Thermal conductivity (W/mK)
S Solar radiation (W/m^2)
h Convective heat transfer coefficient (W/m^2K)
σ Stephen Boltz man Constant (5.67×10^{-8} W/m^2K^4)
x Distance (m)
α Absorption coefficient
ε Surface emissivity
F Form factor
τ Transmittivity
roof Roof Slab
ground Substrate soil
sky Outer space of atmosphere

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