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Experimental evaluation of the thermal performance of coir mat and green facade as wall insulation in a tropical climate

T.S. Sigi Kumar [a,b,c,*], K.A. Shafi [b,c], Rijo Jacob Thomas [b,c], Jesna Mohammed [b,c]

[a] *Department of Mechanical Engineering, Sree Chitra Thirunal College of Engineering, Kerala, India*
[b] *Department of Mechanical Engineering, TKM College of Engineering, Kerala, India*
[c] *APJ Abdul Kalam Technological University, India*

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ABSTRACT

Passive cooling techniques to minimize the indoor temperature of commercial and residential buildings are of prime importance in research worldwide. A comparison of the potential of coconut coir insulation and green facade to mitigate room heat addition in warm and humid climates prevalent in coastal South India is presented in this paper. Insulation skins like dry coir mat, wet coir mat, green facade, and coir mat with green facade were selected for building walls in the experimental study. The study was conducted during solar hours and non-solar hours on two test cubicles, of which one side wall of the cubicle is made as a reference and the other wall with different insulation. For 24 h, it was found that the dry coir mat had a heat mitigation potential of about 41.45%, whereas the wet coir mat showed 36.3%. Interestingly, it is only 6.15 % for the green facade due to its inefficiency to reject heat during non-solar hours. However, the heat mitigation potential of the green facade can be increased to 40.3% when a coir mat is added. It was also found that the coir mat can reduce heat addition to the wall and reject heat to the ambient due to its porous nature (24.47%).

Introduction

Excessive urbanization is a major threat to the sustainable development of the modern world. Through the expansion of urban areas, plants and surrounding flora will ultimately be replaced with materials with high thermal conductivity and low reflection ratio. These materials absorb solar radiation tremendously during the daytime and release stored heat during the evening. In large cities, the temperature in the city's heart is higher in the late evening than in its outskirts (the suburbs). This phenomenon is called Urban Heat Island (UHI) effect [1]. The impact of fast-growing cities, in developing countries, in particular, increases the UHI that adversely affects the Environment [7]. There is a consensus among researchers to reduce UHI and energy consumption with the use of cost-effective and eco-friendly materials having low thermal conductivity and high reflectivity for building structures [2].

However, despite the rapid growth of new buildings, the use of energy-efficient and eco-friendly technologies for heat mitigation is not gaining much attention, especially in developing countries. Worldwide energy consumption is anticipated to rise by 53%, according to the International Energy Agency (IEA). This is due to the significant increase in industrialization, urbanization, and the expected increase in population within the next ten years [3,15]. This will also increase the global temperature, which can bring unprecedented damage to the Environment, consequently affecting human health. It is reported that ecosystems and global agricultural sustainability will be massively damaged even by a mere 2 °C rise in global temperature [19].

Control of heat addition can be achieved in buildings by proper thermal insulation using energy-efficient materials [5]. Such environmentally sustainable approaches can drastically reduce total energy consumption by minimizing the demand of active cooling systems such as air conditioning units. Consequently, there will be a significant reduction in energy, since air conditioning units consume about 40–50% of the overall energy in both industrial and residential sectors. The use of passive cooling methods like applying thermal insulation on the walls is an energy-efficient option that conserves energy while providing the desired thermal comfort [4]. Thermal insulation improves energy efficiency by demanding less energy to cool the building during summer and less heat to keep it warm during winter. Control of heat addition can be achieved in buildings by proper thermal insulation using energy-efficient materials [18].

Organic insulation materials are gaining popularity due to their aesthetics, renewability, recyclability, non-toxicity and eco-friendly nature. Materials that are typically used as insulators for buildings

* Corresponding author.
E-mail address: tssigikumar@gmail.com (T.S. Sigi Kumar).

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Nomenclature

ρ	Density, kg/m^3
C	Specific heat capacity (J/kg.K)
L	Latent heat of vaporization of water, J
T	Temperature, °C
k	Thermal conductivity, W/mK
$\dot{q}.g$	Rate of internal heat generation, W/m^3
k_{coir}	Thermal conductivity of coir mat, W/mK
h_{out}	Heat transfer coefficient for convection, W/m^2K
T_{out}	Outside surface temperature, °C
T_{coir}	Temperature of the coir mat, °C
T_{amb}	Ambient Temperature, °C
T_{inw}	inside wall temperature, °C
α_{coir}	Solar absorption coefficient
ε_{coir}	Surface emissivity of coir mat
σ	Stefan Boltzmann constant (σ = 5.67e−8 (W/m^2K^4))
S	Solar radiation, W/m^2
T	Time (Hour)
IST	Indian Standard Time
F	Form factor
f	Factor of solar radiation transmitted after transpiration

include fibreglass, mineral wool, foam, and organic materials like coconut fibre and jute composites. Eco-friendly insulators are rarely used for walls, particularly in developing countries.

Coconut fibres have gained signficant attention because of their abundant availability, low cost, low thermal conductivity, and low density. Mintorogo et al. [9] studied the usage of coconut fibres as a thermal insulator laid over a concrete slab. The experiment results showed a temperature reduction in the range of 2.8 °C to 3.1 °C in the indoor air and 13 °C over the surface of the concrete slab, compared with the case without insulation. Rodríguez et al. [11] substantiated this result by finite element analysis. In this work, it is observed that the temperature of 56 °C on a concrete slab was brought down to a comfortable temperature of 28 °C when coconut fibre insulation of 0.02 m thickness was laid over it.

Green insulation options like growing plants and creepers are gaining popularity, being attractive, renewable, and eco-friendly. However, such green facade based insulators are not widely used in buildings. Price et al. [8] inferred that vertical greenery systems could bring down the Urban Heat Island effect by transpiration of plants which can reduce the air temperature around the plant by 8 °C. Pérez et al. [12] investigated the performance of green facades in Mediterranean continental climates. The results demonstrated the ability of green facades to provide shade, which reduces the temperature on the building's outer wall by an average of 5.5 °C. In the Netherlands, Perini et al. [13] established that wire rope Climber Green Wall (CGW) could decrease the mean exterior surface temperature by 2.73C.

From the literature, it is evident that coir mats and green facade based insulation skins have the potential to reduce the cooling load in buildings. The efficiency of coir mats and green facades in reducing energy consumption cannot be properly evaluated unless implemented in specific climatic conditions [14]. The southern part of India typically exhibits warm and humid climates ranging from tropical to semi-tropical to temperate. Only some experimental works for sustainable and eco-friendly wall insulation are reported in the literature for hot and humid climates. The primary aim of this study is to determine the heat insulation potential of coconut fibre as a coir mat. The study also evaluates the thermal insulation performance of a green facade using *Epipremnumaureum* and extends to combining a coir mat with the green facade.

Table 1
Properties of green facade.

Type of vegetation	Epipremnumaureum (Devils Ivy)
Solar absorptivity of the leaves	0.4 to 0.6
Leaf Area Index (LAI)	2.2
Emissivity	0.4 to 0.6
Average thickness	150 mm
Solar radiation mitigated by Evapotranspiration	60% [21]
Solar radiation blocked by shading effect	5% [21]

Mechanisms of heat transfer through the coir mat and green façade

Solar radiation and radiation from the ground are the significant sources of heat in-leak through the vertical wall. The different modes of heat transfer [16] through a green facade insulation skin are shown in Fig. 1. The heat transfer through the experimental wall with the green facade may be theoretically calculated by using the energy balance equation given below.

$$-k_{wall}\frac{\partial T}{\partial x} = h_{out}\left(T_{green}-T_{ambient}\right)+h_{green}\sigma\left(T_{sky}^{4} - T_{green}^{4}\right)+h_{ground}\sigma T_{ground}^{4} + Ff\alpha_{green}S \quad (1)$$

The first term on the right-hand side gives heat transfer by

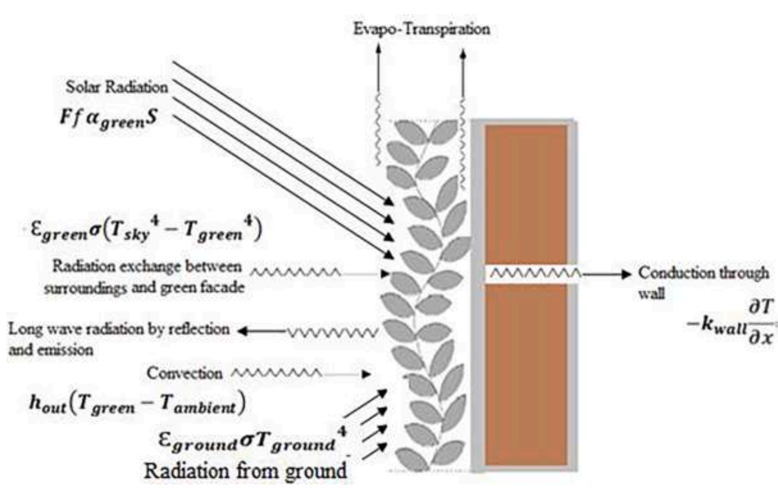

Fig. 1. Different modes of heat transfer through a green facade.

Table 2
Properties of Coir mat.

Grade	SK-1 Bleached
Porosity(ϕ)	24.47%
Water absorption capacity	112 % (IS:15868 (part 4))
Thickness	~9.4 mm
Thickness of each strand	~0.4 mm
Dry weight	2.238 kg/m^2
Wet weight	4.744 kg/m^2
Solar absorptivity	0.5
Thermal Conductivity Solid matrix	0.05 W/mK
Thermal Conductivity offluid matrix (air)	0.024 W/mK
Dry Coir mat	0.044 W/mK
Wet Coir mat	0.182 W/mK

convection, the second term gives the heat transfer by radiation exchange between the green facade and atmosphere, the third term gives heat transmitted by radiation from the ground, and the last term gives heat transmitted by solar radiation after evapotranspiration. The different terms involved are pictorially depicted in Fig. 1.

Some of the assumptions made for analysis are, i) the reflection of solar rays by the green facade is about 15%, ii) the air velocity is reduced significantly within the green facade, iii) convective heat transfer is constant in between the leaves and iv) the solar radiation mitigated by transpiration of vegetation is assumed to be 60% [21]. The general properties of green facade considered here are given in Table 1.

Calculation of heat flux through the coir mat is challenging due to its roughness and porosity. Moreover, its temperature distribution is also non-uniform and depends on thermal conductivity, sensible heat, and latent heat values. These properties are dependent on the dynamic environmental parameters that cannot be reproduced as such. The general properties of coir mat [30] are given in Table 2.

Experimental setup

The experimental setup consists of two identical cubicles of 1.2 m × 1.4 m × 1.5 m [27]. The cubicle is built using burned bricks, and all the walls are plastered with cement. The cubicles are built at the roof of the four-storied building at the Department of Mechanical Engineering, TKM College of Engineering, Kollam, Kerala, Southern India (8.9142°N, 76.632°E). This elevated area helps in avoiding the shading effect from buildings and trees. One of the cubicles has a green facade on its southern wall while the other is taken for reference with its wall left bare [29,4]. The schematic diagram of the experimental setup with a combination of a coir mat and green facade as insulation skin is shown in Fig. 2. For better utilization of direct solar radiation, the southern wall of the cubicle having 1.4 m width and 1.5 m height, is selected for the study and the southern wall of the reference cubicle is kept bare. The remaining walls and roof of both the cubicles are insulated with 50 mm thick extruded polystyrene panels to minimize heat in the leak. The heat addition into the insulated cubicle due to solar radiation is compared with that of the reference cubicle. The results are used to determine the heat mitigation capability of each insulation skin. The coir mat insulation is provided using a coconut fibre mat. The green facade is provided using a creeper plant, *Epipremnumaureum*, in a herbarium pot. This plant is selected due to its easy adaptability as a vertical creeper and low maintenance requirement.

The details of the instruments and sensors are shown in Table 3. T-type thermocouples having an accuracy of ±0.1 °C are used for measuring the wall temperatures. They are placed on the wall surface by chipping some amount of cement plaster and grouting with cement. The heat flux sensors (Omega-HFS-03) are fixed on the internal surface of the walls to measure the heat flow through them. All the sensors and thermocouples are calibrated and connected to a data acquisition system

Table 3
Instruments used and data obtained.

Sl No	Description(Make)	Data (Accuracy)
1	DAQ (Agilent)	● Temperature ● Heat flux
2	Heat flux sensorHFS-03 (Omega)	● Heat flux (1%)
3	Thermocouple T type	● Temperature (±0.1 °C)
4	Weather Station (Ambient Weather)	● Solar radiation(±3%) ● Wind velocity(0.1 m/s) ● Humidity(1%) ● Outdoor temperature (0.10C) ● Indoor temperature (0.10C) ● Rainfall (1 mm) ● Wind direction

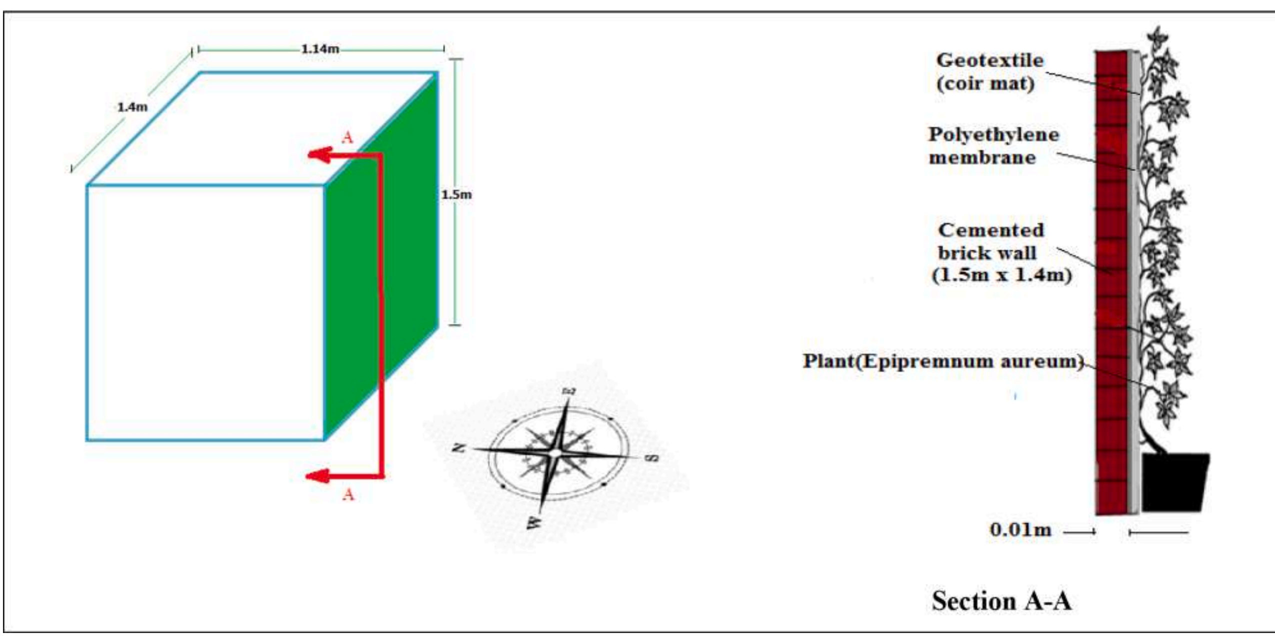

Fig. 2. Schematic diagram of the coir mat with the green facade on the southern wall of the cubicle.

Fig. 3. Photographs of the experimental set-up with four types of insulation skins: (a) Dry coir mat along with bare reference cubicle (b) Wet coir mat (c) Green facade (d) Coir mat with the green facade.

(Agilent-2992A) for real-time data collection. A door is provided on the northern side of the cubicle for access. Solar radiation, ambient temperature, humidity, wind velocity, atmospheric pressure, and precipitation data are obtained using a weather station (Ambient weather, WS-2902A) installed in the near surroundings of the experimental area.

The performance of four types of insulation skins is compared with the bare wall case. The details of the cases selected are given.

Case – I: Dry coir mat vs. Bare Wall

Case – II: Wet coir mat vs. Bare Wall

Case- III: Green facade vs. Bare Wall

Case – IV: Coir mat with green facade vs. Bare Wall

Photographs of different heat insulation skins and bare wall are shown in Fig. 3.

For each case, the experiment is conducted for 3 days (72 h), and the readings are taken at an interval of one hour. The parameters measured are i) Heat flux through the bare wall, ii) Heat flux through the insulated wall, iii) Internal surface temperature of the bare wall, iv) Internal surface temperature of the insulated wall, along with weather data. For each insulation skin the heat transfer to inside of the bare wall is computed for comparison.

The details of insulation combinations are mentioned below

Case – I

The coir mat in a dry condition is fixed over the southern side of the cubicle, as shown in Fig. 3 (a). Thermocouples are placed at the interfaces of the coir mat and wall, and over the coir mat for temperature measurements. It is ensured that there is no gap between the wall and coir mat. The thermal conductivity of dry coir fibre is determined using the thermal property analyzer KD2 Pro [17]. Since the coir mat is having porosity, the effective thermal conductivity (K_e) is calculated by the Eq. (2).

$$\text{ke} = k_a\phi + (1-\phi)k_c \tag{2}$$

where k_a is the thermal conductivity of air in the pores and k_c is the thermal conductivity of coir. The value of k_e is found to be 0.043 W/mK which is a clear indication of its insulation capability. Void space in the coir mat for finding the porosity is calculated by taking the ratio of the difference between dry weight and wet weight of the coir mat (weight of water in wet coir mat) to the density of water (1000 kg/m^3). Then the porosity of the coir mat is found by Eq. (3). Here the porosity is found as 24.47%.

$$Porosity = \frac{Total\ void\ space\ in\ the\ coir\ mat}{Geometrical\ volume\ of\ coir\ mat} \times 100 \tag{3}$$

Case – II

The coir mat is wet by spraying water over the mat during the peak solar hours from 12 noon to 2.00 pm. A polyethene skin 40 μm thick is placed between the wet coir mat and the outer wall to avoid moisture absorption by the wall in this case as shown in Fig. 3(b).

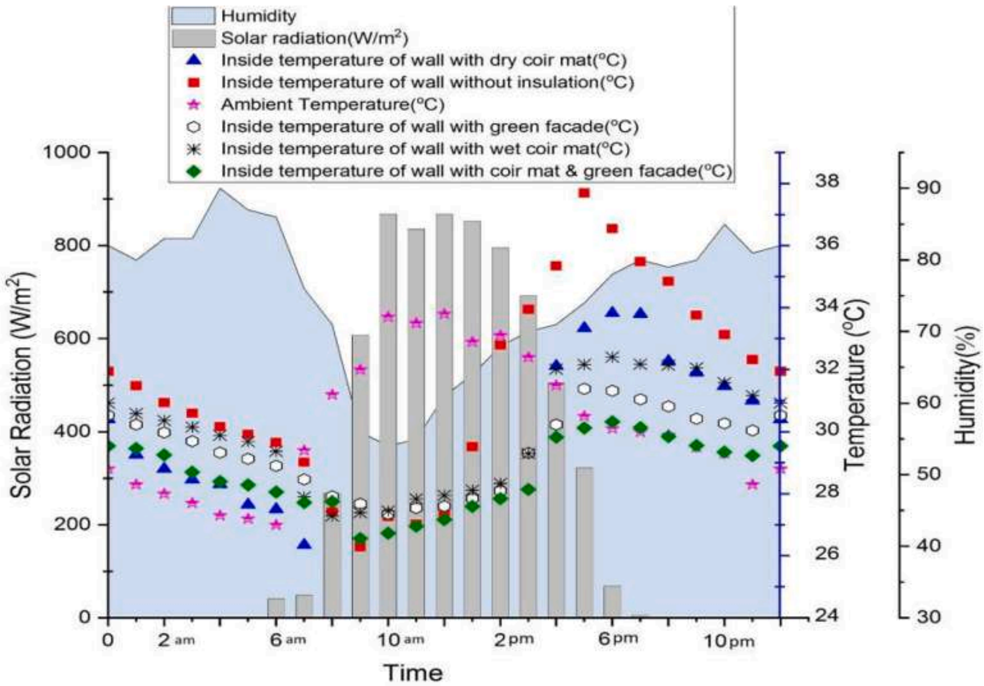

Fig. 4. Variation of the inside wall temperature with solar radiation for different insulation skins.

Case – III

The effect of evapotranspiration on heat propagation to the building is investigated in this case. A green facade insulated skin with the *Epipremnumaureum* plant is fixed to the wall with the help of an iron mesh, as shown in Fig. 3(c). The roots of the plant are dipped into a quantified amount of water in two herbarium pots that are covered to prevent evaporation. The amount of water lost due to evapotranspiration through the leaves is calculated by the decrease of water in the pots. The value of the leaf-area index [LIA] obtained in this case is 2.2 [22]. LIA is the crucial factor determining the effectiveness of vegetation coverage of green facades [10,28]. It is obtained by the ratio of the average leaf surface area to the surface area of the southern wall.

Case – IV

The combined effect of the green facade and coir mat is investigated in this case. A layer of coir mat is placed between the outer wall and the green facade to study the significance of additional insulation to mitigate heat flow through the wall. Both the green façade and the coir mat are supported by the wire mesh (Fig. 3(d)). The parameters measured for this case are the same as that of the previous cases. For each insulation combination, experiments were carried out.

Results and discussions

The heat flux and internal wall temperature for the four cases of insulations are collected and compared with that of the bare wall of the reference cubicle. The solar radiation and ambient temperature are noted for each case. Graphs have been plotted to analyze the influence of each insulation skin for its heat mitigation potential. A significant observation that can be made from the results is that the time lag for the building to get heated up has increased. Even though the ambient temperature is higher from 10.00 am to 4.00 pm, the peak temperature at the internal wall surface of the cubicle is observed between 3:00 pm to 10.00 pm. The other observations and inferences from the experiments are presented in the following sections.

Table 4
Effect of insulation on the maximum inside wall temperature.

Sl. No.	Cases	Maximum observed temperature of the inside wall (°C)	Change in maximum inside wall temperature with the maximum ambient temperature,33.8 °C (°C)	Percentage Deviation (%)
1	Bare wall	37.75	−3.90	−11.55
2	Dry coir mat	33.83	0.03	0.00
3	Wet coir mat	32.41	1.39	4.11
4	Green facade	31.39	2.41	7.31
5	Coir mat with green facade	30.33	3.47	10.27

Variation of the inside wall temperature with solar radiation for different insulation skins

With changes in solar radiation during the day, inside wall temperature also varies correspondingly. This would vary depending on the type of insulation. The changes in solar radiation and inside wall temperature of the cubicle with time for different insulation skins are shown in Fig. 4.

It is found that solar radiation is more than 500 W/m^2 from 10:00 am to 5:00 pm with a maximum value of 850 W/m^2. Also, the ambient temperature has gone up to 33 °C. However, subsequent heating inside the cubicle increased the inside wall temperature to 37.7 °C for the case without insulation. Though the temperature of the ambient air reaches its maximum around 1:00 pm, the inside wall temperature of the bare wall, dry coir mat, wet coir mat, green facade, and coir mat with green facade reaches its maximum at 6.30 pm, 7:00 pm, 7:00 pm, 6:00 pm, and 7:00 pm respectively. There is a time lag of about 4 to 7 h for different insulation, and this is due to the accumulation of heat inside the walls of the cubicle, which in turn is a clear indication of the heat capacity of the walls. It may be observed from Fig. 4 that by providing insulation, the

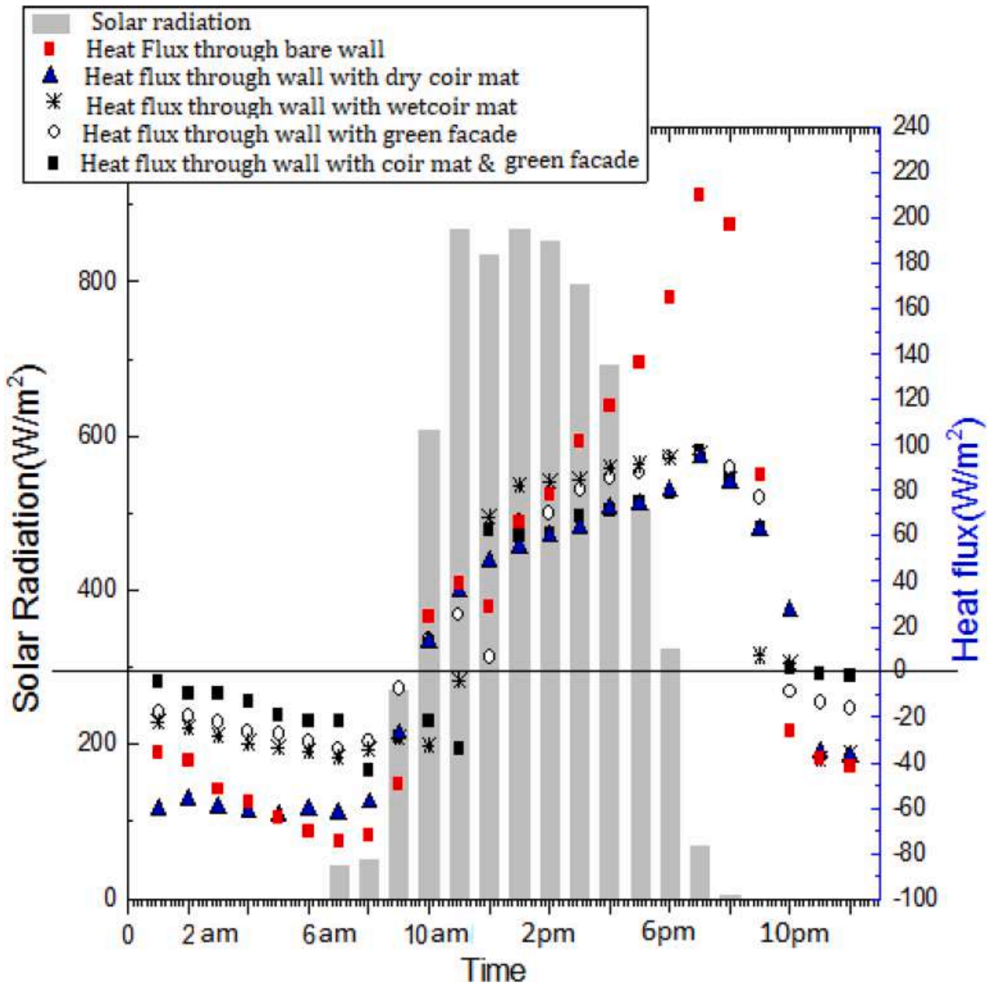

Fig. 5. Effect of solar radiation on heat flux through the wall for different insulations.

inside wall surface temperature can be decreased considerably.

The effect of different insulation combinations on the maximum inside wall temperature is provided in Table 4. The maximum value of inside wall temperature obtained for different insulation is compared with the maximum ambient temperature experienced during the daytime (here, 33.8 °C). The percentage deviation of inside wall temperature with respect to ambient is calculated for each case using Eq. (4).

$$Percentage\ deviation\ of\ temperature = \frac{T_{amb} - T_{inw}}{T_{amb}} \times 100 \tag{4}$$

The increase in the bare wall's peak temperature is −11.75 % (the negative sign shows that the inside wall temperature is more than the maximum ambient temperature). It can be observed from Table 4 that all insulations except the dry coir mat can reduce the maximum temperature inside the cubicle below the maximum ambient temperature.

Heat flux to the cubicle due to solar radiation for different insulations

Heat transfer into the cubicle through the southern wall is measured using heat flux sensors. The reduction in heat gain inside the cubicle under different insulation conditions is noted and compared. Solar radiation and corresponding changes in heat flux into the cubicle under different insulating conditions for 24 h are plotted as shown in Fig. 5. The graph shows that the heat transfer is bidirectional, i.e., from the ambient to the cubicle and after some time from the cubicle to the ambient. When the ambient temperature is higher than the inside wall temperature under solar radiation, heat will be transferred through the wall from the outside to the cubicle. The positive value of heat flux indicates that the heat is transferred from the ambient to the cubicle. This happens between 9.00 am to 9.00 pm, as depicted in Fig. 5.

Due to the higher thermal mass of the cubicle wall, in late hours, the inside wall temperature of the cubicle will become higher than the

Table 5
Heat saving, time lag, decrement factor and temperature reduction for different wall insulations.

Type of the insulation skin	Time duration for which insulated wall temperature is less than a bare wall	Heat saving compared to bare wall during 24 h (MJ/day)	Time lag (Hrs)	Decrement factor	Maximum temperature reduction compared to bare wall (°C)
Dry coir mat	9:00 am to 9:00 pm (12 hrs)	1.73	7	1.6	4.07
Wet coir mat	10:00 am to 9:00 pm (11 hrs)	1.58	6	3.0	5.25
Green facade	8:00 am to 8:00 pm (12 hrs)	0.25	4.3	3.6	6.31
Coir mat with green facade	10:00 am to10:00 pm (12 hrs)	3.31	7.5	3.9	8.41

Table 6
The flux reversal time and net heat load for different insulation for 24 h.

Cases	Specific time at which the flux change from negative to positive (IST)	Specific time at which the flux change from positive to negative (IST)	Time period for negative heat flux through the wall (Hours)	The time period for positive heat flux through the wall (Hours)	Average heat added to the cubicle (MJ)	Average heat rejected from the cubicle (MJ)	Net heat load on the cubicle (MJ)
Dry coir mat	9:00 am	10:00 pm	11	13	5.83	4.40	1.43
Wet coir mat	11:00 am	10:00 pm	13	11	5.93	2.93	3.00
Green facade	9:00 am	9:00 pm	12	12	6.00	1.92	4.07
Coir Mat with green facade	11:00 am	10:00 pm	13	11	5.48	1.73	3.75
Bare wall	9:00 am	10:00 pm	11	13	9.47	4.70	4.77

Table 7
The results of experiments at a glance.

Cases	Maximum inner wall temperature difference with ambient temperature (%)	Heat saving compared to bare wall during 24 h (MJ /day)	Time lag (Hrs)	Heat mitigation potential compared to bare wall for 24 h (%)	Heat mitigation potential during solar hours compared to bare wall during solar hours (%)	Heat retaining potential during wee hours compared to bare wall during non solar hours (%)	Time period for wall temperature below 28 °C (Hours)	Time duration of heat transfer to room due to lower inner wall temperature (Hours)
Bare wall	−11.55	–	4	–	–	–	7	13
Dry Coir mat	**0.00**	**1.73**	**7**	**41.45**	**32.16**	**32.45**	**7**	**13**
Wet Coir mat	4.11	1.58	6	36.5	32.56	32.1	6	11
Green facade	7.31	0.25	4.3	6.15	30.48	66	6	12
Coir mat with green facade	‘10.27	3.31	7.5	40.3	36.72	67	8	11

ambient. This is owing to the heat accumulated and stored inside the cubicle wall. It results in heat flow from the cubicle to the ambient, which is indicated by the negative value of heat flux. This happens from 10:00 pm to 10:00 am on the next day (Fig. 5). Heat transfer into the cubicle is maximum (positive heat flux) from 12:00 noon to 8:00 pm for almost all cases. Moreover, the peak value of heat flux is observed on the inside wall at 7:00 pm.

Heat reduction, decrement factor and time lag for different wall insulations

The period during which the inside wall temperature of the insulated cubicle is less than that of the bare wall is determined for each insulation skin. It has been noticed that the temperature reduction in the inside wall having a coir mat with a green facade compared to the bare wall is 8.41 °C and 6.31 °C for green facade alone (Table 6). In a similar study conducted during summer in Japan [20] a maximum temperature reduction of 11 °C was reported while using the green facade on walls (Table 7).

The heat saved by providing the insulation on the wall is also found for each case using the [16] Eq. (5)

$$\text{Heat saved Qs} = \sum_{0}^{24} (Q_b - Q_{in}) \times \text{A} \times \text{t} \quad (5)$$

where Q_s is the heat energy saved (J), Q_b is the heat energy through the bare wall (J), Q_{in} is the heat energy through the insulated wall (J), A is the area of the southern wall (1.5 m × 1.4 m), time(s).

Time lag, which is the representation of the delay in the temperature rise of the inside wall compared to the outer wall due to thermal mass, is calculated using the expression,

$$\text{Time Lag } \varphi = T_{o,Max} - T_{i,Max} \quad (6)$$

where $T_{o,Max}$, $T_{i,Max}$ are the time at which the maximum temperature occurs at the external and internal surfaces of the wall, respectively. The degree of reduction in temperature fluctuation of the internal wall compared to the external wall is given by the decrement factor (DF). The decrement factor [6] is determined by the expression,

$$DF = \frac{T_{o,max} - T_{o,min}}{T_{i,max} - T_{i,min}} \quad (7)$$

where $T_{o,\min}$ & $T_{o,\max}$ are the minimum and maximum temperature of the outer wall and $T_{i,\min}$ & $T_{i,\max}$ are the minimum and maximum temperatures of the inside wall respectively.

Table 5 has tabulated the period for which the inside wall temperature of the cubicle is below that of the bare wall is almost the same from 9:00–10:00 am to 9:00–10:00 pm for different insulations. The heat reduction, decrement factor, and time lag are found to be maximum for the insulation skin with a coir mat and green facade. However, it is interesting to find that the green facade has the least performance out of the different insulation skins studied. It is because the transpiration of plants helps in the reduction of heat during peak solar hours. During wee hours the green facade acts as an insulator for the walls by the long wave radiation of vegetative parts while rejecting heat to the atmosphere. Therefore, in the green facade case, the blocking and trapping effects cancel each other and the cumulative effect for a day is not significant. On the other hand, for coir mat with a green facade, additional insulation of the coir mat has helped the wall to resist heat transfer from solar radiation, resulting in more heat flux reduction.

A reduction in the heat flux was observed in a similar case study conducted in the temperate oceanic climate of Germany. Heat flux of 157kWh/day was reduced in the southern wall of a 19000 m^2 (3 stored) building using the green facade [21]. Currently, an average heat flux reduction of 32.82 $Wh/m^2/day$ on the southern wall of the experimental

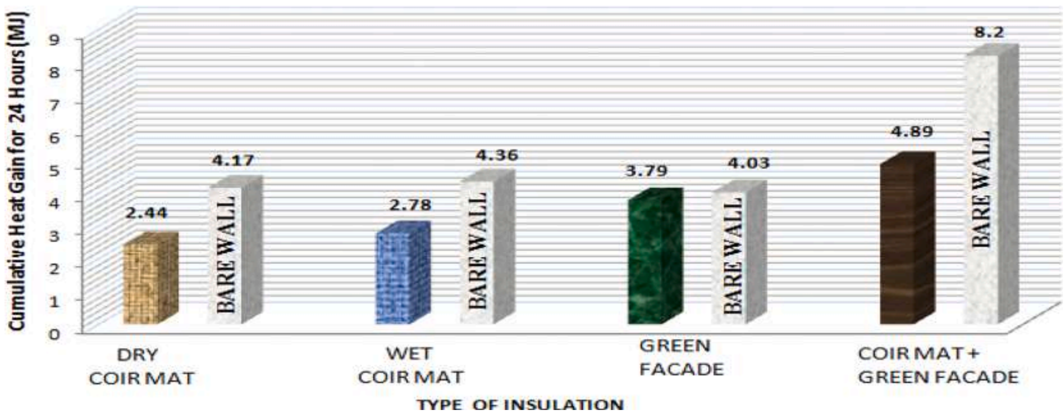

Fig. 6. Cumulative heat gain in the cubicle under different insulating conditions.

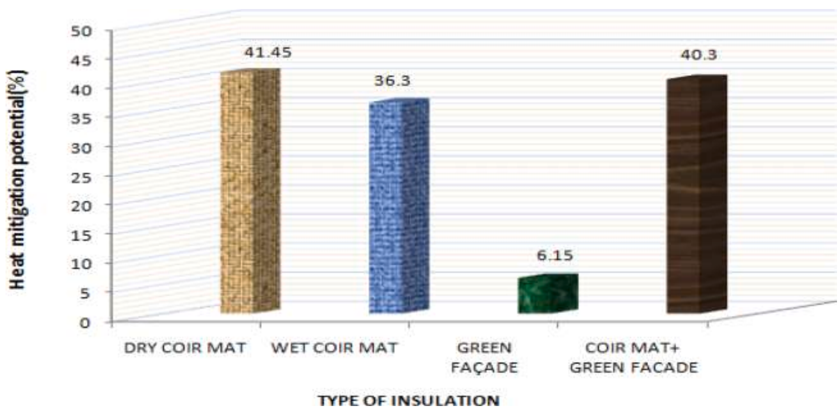

Fig. 7. Heat mitigation potential of different insulations for 24 h.

cubicle is observed in the case of the green facade. From the simulation study [26], a reduction in the temperature of 0.7–13 °C was observed on the outer surface of the brick wall by virtue of the green facade and an average heat flux reduction of 2 to 33 W/m^2 was reported during the summer of US. In the present work, using the green facade, a maximum temperature reduction of 6.31 °C at the exterior wall and an average heat flux reduction of 3.84 W/m^2 were obtained throughout the day in the insulated wall when compared to the bare wall.

It can be observed that the time lag is maximum (7.5 h) for the coir mat with the green façade and is minimum (4.3 h) for that with the green facade. The decrement factor is increasing in the order; dry coir mat, wet coir mat, green facade and coir mat with the green facade. Though the decrement factor (DF) is higher (3.6) for the green façade alone, the heat saving for 24 h is very low (0.25), as shown in Table 5.

Heat mitigation potential of different insulations

Heat mitigation potential for 24 h

The cumulative heat gain on the inside of the wall for all four cases is shown in Fig. 6. Cumulative heat gain is calculated as the summation of

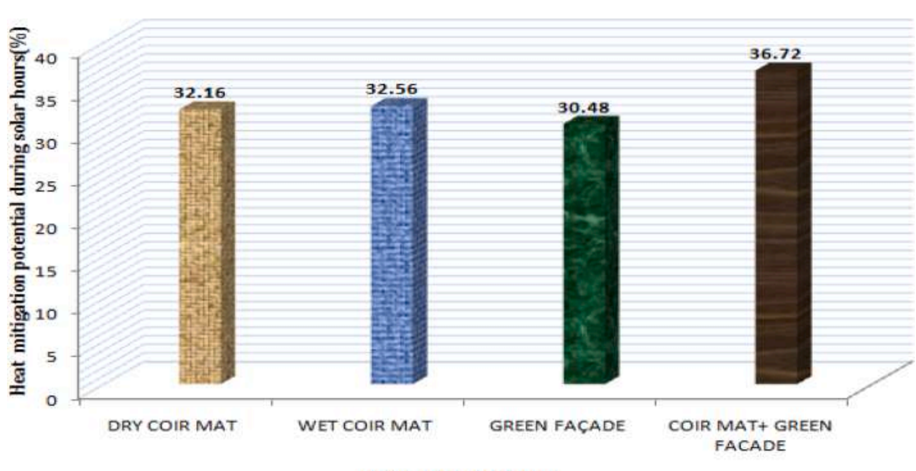

Fig. 8. Heat mitigation potential of different insulations during solar hours.

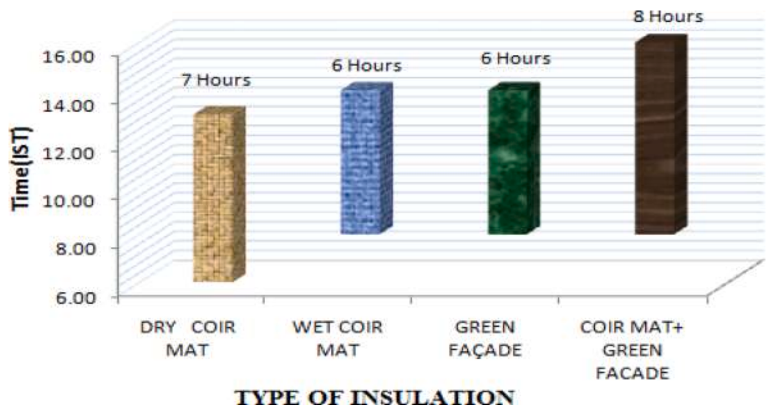

Fig. 9. Time period for the wall temperature below 28 °C.

heat flux over 24 h multiplied by the exposed surface area of the southern wall. The average heat mitigation potential can be calculated by the expression [7]. Where ΣQ_b and ΣQ_{in} are the cumulative heat gain for 24 h through bare wall and insulated wall, respectively.

$$A\ verage\ heat\ mitigation\ potential = \frac{\Sigma Q_b - \Sigma Q_{in}}{\Sigma Q_b} \times 100 \tag{8}$$

The average heat mitigation potentials for different test conditions are shown in Fig. 7. It can be observed that while insulating the bare wall with dry coir mat, the heat transferred to the cubicle reduces by 41.45%. On spraying water on coir mat, heat transfer through the wall decreases by 36.26%. This is due to the wet coir mat's increased heat capacity, which prevents the dissipation of heat from the cubicle to the outside during the night. For the green façade alone, the blocking effect during solar hours is almost nullified by the trapping effect during the night compared to the bare wall. So the heat mitigation potential for 24 h is only 6.15%.

Similar behaviour was reported from an experimental study in the equatorial climate of Singapore [23]. It is observed that the green facade had no significant reduction in cooling load for 24 h though an average reduction in the temperature of 4.36 °C was observed on sunny days. When the green facade is coupled with a dry coir mat, the heat mitigation potential becomes more prominent by the evapotranspiration of the green façade and the insulation ability of the dry coir mat. In the present study, overall heat mitigation for 24 h increased to 40.3% though the heat rejection to the ambient air during the wee hours is significantly less.

Heat mitigation potential during solar hours

The heat mitigation capacity of various insulations for solar hours is plotted in Fig. 8. It is worth noting that, against popular belief, the heat mitigation potential of a green facade for solar hours is not appreciable when compared to the case of the coir mat insulated wall. It is interesting to find that the performances of all the insulations taken for this study are more or less the same during the solar hours. During solar hours, insulation with coir mat and green facade has slightly better heat reduction capability (36.72%) among all insulations studied. A temperature reduction of 3.7 °C and cooling load reduction of 20.02% achieved using the green facade on the wall was reported in a mathematical study in the Mediterranean climate of Greece [24]. In the present work, the performance of the green facade confirms this observation and heat flux reduction when compared to the bare wall is 30.48% during solar hours with a maximum reduction of inside wall temperature by 6.31 °C (16.74%).

Flux reversal time of different insulations and its significance

During solar hours, the heat will be transmitted from the ambient into the cubicle, and as time passes, i.e. during late-night, the heat will start getting transmitted from the cubicle to the ambient. The heat flux transferred from the ambient to the cubicle is considered positive and vice versa. This behaviour is termed as flux reversal. The time of flux reversal for different insulations is shown in Table 6. The time duration for which heat is transferred to the cubicle is considered as the period of positive heat flux.

In all four cases, flux reversal time changes from negative to positive (Heat addition to the cubicle side) between 9:00 am and 11:00 am. However, in the case of a dry coir mat, the time taken for heat added to the cubicle is longer than the time taken for the heat rejection from the cubicle. Ironically, a more extended heat addition period indicates a positive outcome of thermal insulation since it indicates that the temperature inside the cubicle will be lower than the outside temperature for a more extended period. Therefore, the period for which heat is added to the cubicle is the time duration for which it is "cooler" than the outside space. For the green facade, the time of heat addition and heat rejection are equal and are about 12 h. The period of heat addition for the coir mat with green facade and wet coir mat is 11 h each. Therefore, experiments show that, out of the different insulation options considered, the dry coir mat is a better performer having a positive period of 13 h. The bare wall also has a longer heat addition (positive heat flux) period of 13 h, but it has a very high heat addition (9.47 MJ) compared to the insulated wall (Table 4).

Time period for which the wall temperature is below 28 °C

The objective of insulating the wall is to maintain the comfort condition inside the cubicle for the maximum possible time duration. The time duration for which the inside wall temperature of the cubicle is less than 28 °C is shown in Fig. 9. In the case of dry coir mat, it is 7 h. For both wet coir mat and green facade, it is 6 h. The time duration for which the inside wall temperature is less than 28 °C is from 6:00 am to 1:00 pm for dry coir mat. When the coir mat is watered, the period less than 28 °C extends from 8:00 am to 2:00 pm. When the coir mat is added to the green facade, the period becomes 8 h and it extends from 8:00 am to 4:00 pm. For sustaining the temperature below 28 °C during peak hours of solar radiation, the coir mat with the green facade is better than other insulations.

In the case of bare wall, the temperature inside the building rises from 11:00 am onwards due to solar radiation. The cubicle with a dry coir mat sustains a temperature below 28 °C by blocking solar radiation by its low effective thermal conductivity (0.04376 W/mK). For the case of green façade the inside wall temperature of the cubicle below 28 °C starts from 8:00 pm onwards. Till then, the temperature is higher than the ambient and is not desirable for tropical climates. When green façade is included, evapotranspiration plays a vital role in blocking the solar radiation. For the case of a green façade with coir mat, the time for

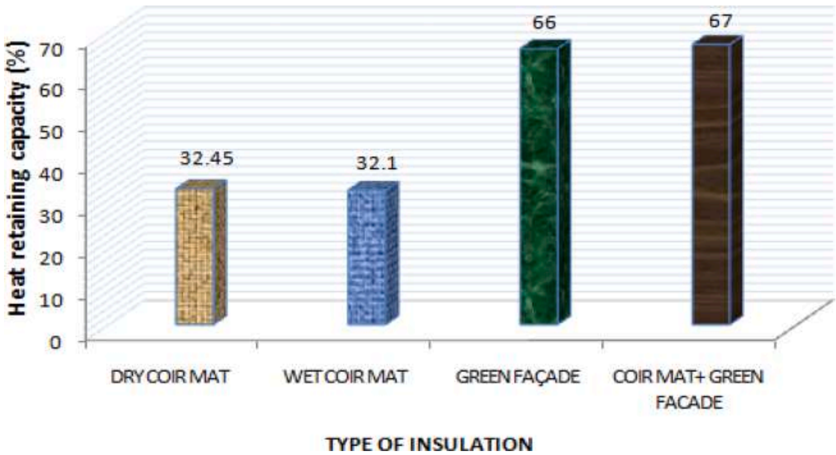

Fig. 10. Heat retaining capacity of insulations during wee hours.

the cubicle's temperature being maintained below 28 °C is extended to 8 h, compared to 6 h in the case of green façade alone.

Heat retaining capability of insulations during non-solar hours

Fig. 10 depicts the heat-retaining capabilities of different insulations that are studied in accordance with their ability to reject heat to the ambient air (in the negative direction). This phenomenon occurs during the late-night and early morning hours, i.e. from, 10.00 pm to 10.00 am on an average. It is evident that, the heat rejection capability (negative heat flux) will be more for bare wall and it is compared with different insulated cases using Eq. (6).

$$Heat\ retaining\ capability = \frac{(Total\ negative\ heat\ flux\ through\ the\ bare\ wall - Total\ negative\ heat\ flux\ through\ the\ Insulated\ wall)}{Total\ negative\ heat\ flux\ through\ the\ bare\ wall} \times 100 \quad (9)$$

During non-solar hours, the heat release from the wall is hindered by the long wave radiation from the vegetative parts in the case of green façade [24,25]. For the green facade alone and coir mat with the green facade, vegetation acts as a blanket to trap heat in the wall.

Summary at a glance

The heat-retaining capacity of the green facade during non-solar hours minimizes its cooling potential during nighttime. However, it is effectively blocking solar radiation during solar hours. This adverse effect during the wee hours can be overcome by the coir mat insulation on the walls by its ability to reject heat. Experiments related to environmental factors sincerely rely on dynamic climatic conditions, which cannot be reproduced. For all four cases, the experiments are conducted in a summer climate with a clear sky for 72 h. Since the study was conducted in a hot and humid climate, the experiments need to be extended to other climatic zones to know about the behaviour of the set of insulation studied here.

Conclusions

Experimental investigations are conducted to determine the insulation performance of dry coir mat, wet coir mat, green facade alone, and coir mat with green facade. The study eventually investigated the efficacy of using a coir mat as a heat insulation material compared to the green facade.

The experiment is conducted for 72 h for each case of insulation, and the cooling capacity for an average of 24 h is analyzed in two phases, ie. during solar hours and non-solar hours. It is found that dry coir mat has appreciable heat blocking ability during solar hours with a time lag of 7 h and remarkable heat rejection capacity during non-solar hours owing to its porosity (24.47%). The time duration of heat transfer to the cubicle side was 13 h for dry coir mat insulation, which clearly indicates that the inside temperature of the cubicle could be successfully maintained lower than ambient for a longer duration. The green facade showed appreciable heat mitigation during solar hours but less heat rejection during wee hours. On integrating the heat flux through the wall for 24 h, the dry coir mat showed a high heat mitigation capacity of 41.45% compared to the green facade (6.15%). It was also found that the heat mitigation capacity of the green facade (6.15%) has increased to a greater extent by combining the coir mat with the green facade (40.3%) since the blocking ability of double-layer insulation is more prominent than the trapping effect. The dry coir mat insulated wall sustained a temperature below 28 °C for seven hours, but the duration was from 6:00 am to 1:00 pm. By coupling the coir mat with the green facade, the period below 28 °C for the inside wall was extended from 8:00 am to 4:00 pm, the overloaded time slot for air conditioners during the daytime. Considering the less care and easy fixing on walls, the dry coir mat can undoubtedly be selected as the most convenient thermal insulation for the walls of the building.

CRediT authorship contribution statement

T.S. Sigi Kumar: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **K.A. Shafi:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Supervision. **Rijo Jacob Thomas:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Supervision. **Jesna Mohammed:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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