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ORIGINAL RESEARCH

Developing a durable thermally insulated roof slab system using bamboo insulation panels

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Abstract

Traditional roofs can be effectively substituted by reinforced concrete roof slabs while gaining multiple advantages such as cyclonic resistance, possibility of future vertical extension and possibility of utilizing as an extra working space or a rooftop garden. Further, it adds a significant economic benefit from land regaining. However, the immediate space beneath the roof slab results in thermal discomfort and hence the inventions related to insulated roof slab systems have been increased recently. Although the expected thermal comfort could be achieved, most of the inventions use artificial thermal insulation materials such as polystyrene. This paper introduces a novel roof slab insulation system which uses the natural material of transversely cut bamboo layer as the thermal insulator. The proposed system minimizes the negative environmental impacts induced by the use of artificial insulation materials. The optimum insulation layer thickness is found to be 25 mm, which has acquired a 53% peak heat gain reduction with a decrement factor of 0.61 and a 3-h time lag.

Keywords Slab insulation · Natural thermal insulation · Bamboo insulation · Heat gain reduction · Global warming

Introduction

Countries like Sri Lanka, located close to the equator, experience tropical climatic conditions having a higher humidity level with low seasonal temperature variations. Most of the Asian countries with such climatic conditions are rapidly developing countries with challenges such as energy crisis and scarcity of usable land for construction [1]. As a result of the damages caused by this development, global warming increases at an alarming rate and has become one of the major issues in the planet [2]. Although scientists and researchers attempt to find measures against global warming, its effects do continue to affect. The world is on its path of facing far worse consequences of global warming such as ice melting and rapid rising of sea level, abnormal precipitation, hurricanes and storms, floods and droughts [3]. According to the recent studies, failure to take necessary actions against global warming would result in a 1.1–6.4 °C rise of earth surface temperature by the end of the twenty-first century [4]. Consequently, countries like Germany have determined to reduce the emission of CO_2 by 80% by 2050 [5].

Subsequently, people seek active cooling solutions such as Air Conditioning to overcome the thermal discomfort inside the buildings induced by global warming. Improved economic standards and availability have made the utilization of Air Conditioners popular among the people [1, 6]. But this should never be encouraged due to the higher energy demand and thereby the higher emission of Greenhouse gases [1, 7, 8]. The usage of Air Conditioning equipment in buildings has increased over the years; hence, a proper mechanism of minimizing the need of active cooling measures would reduce both household and national electricity demand [9–11]. Such systems can be replaced by passive

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techniques to improve the indoor thermal comfort while reducing the energy consumption [12, 13].

On the other hand, frequent natural disasters have occurred recently highlighting the significance of disaster resistant structures. Recent findings predict that the severity and the intensity of the natural disasters would be increased in the near future [14]. Disaster resistant structures serve the community saving their lives in the events of natural disasters by preventing sudden collapses. Saving the structures indirectly assists in mitigation of the emission of greenhouse gases by minimizing the repeated usage of embodied energy through preventing the rebuilding [1, 15]. Cyclones are a common scenario in tropical countries. Having conventional roofs made of clay tiles and roofing sheets makes the buildings vulnerable. The effect of the cyclones can be mitigated by increasing the robustness of the structures, which can be achieved by concrete roof slabs through its self-weight [1, 16, 17]. Further, it provides additional benefits such as the possibility of future vertical extension, the possibility of using as an extra working space and the possibility of having vegetation on the top. And also it adds a significant economic value by regaining the land [17–19]. However, the main drawback of roof slabs is the thermal discomfort in the immediate underneath space [1].

This issue can be effectively mitigated by insulating the roof slab. Although it requires an additional capital that can be paid back within a reasonable period of time by the reduction in operational cost [20–23]. Since about 70% of the total heat gain of a building occurs through roofs [24], a considerable amount of heat gain reduction could be achieved through the roof insulation. That has enhanced the enthusiasm of the researching community towards the investigation of effective roof insulation techniques [24]. Several of such tested across the world are listed in Table 1.

Halwatura and Jayasinghe have developed an insulated roof slab system suitable for tropical countries using a polystyrene layer as the thermal insulator [1, 16]. In that system, a 25-mm-thick polystyrene (thermal conductivity of 0.035 W/mK) layer has been used between a 40-mm protective screed layer and a 100-mm-thick structural slab [1]. It has been calculated that the air-to-air thermal resistance and the composite thermal conductivity of the system to be 0.9 m^2 K/W and 1.1 W/m^2 K, respectively [17].

Although the invention of Halwatura and Jayasinghe has been proven to be effective in terms of thermally and structurally, the system has been found to have issues related to durability since some water patches were observed on slab soffit in the long run [1]. Moreover, the concrete ratio of insulation layer was 16% [17]. Addressing this and the durability issue without harming the structural integrity, Halwatura and Jayasinghe system was further optimized by Nandapala and Halwatura [17].

In the system of Nandapala and Halwatura, the continuous strips of Halwatura and Jayasinghe system were converted into a discontinuous strip setup and thereby, the drain paths were added and the concrete ratio of the insulation layer was reduced to 3.3% [17] resulting a further decrement of composite thermal conductivity (corresponding calculation is as performed in "Appendix A"). Although the strip arrangement has been altered, it has not compromised the structural performance of the system [17].

Although the system of Nandapala and Halwatura is found to be sound in thermal and structural performance, the thermal insulation material used was polystyrene, (0.033 W/m K thermal conductivity) a product of crude oil extraction that contributes the most to the Greenhouse gas emission [29, 30]. Since it is unfavourable in terms of global warming, it was decided to prepare a suitable natural thermal insulation method to achieve the desired comfort levels. This paper describes a detailed study performed to invent a durable and thermally insulated roof slab system using bamboo insulation panels made of transversely cut bamboo. This system intends to achieve the domestic energy conservation which is highly conferential [31–33] as well

Table 1 Roof thermal insulation techniques tested across the world

Country	Insulation technique	Remarks
Florida, USA	Applying a cool paint	19% of energy saved on average, saved up to 38% on peak [25]
Italy	Applying a cool paint	Indoor temperature is reduced by 2.5 °C in comparison with outdoor [26]
Greece	6 cm of ventilated air gap	Daily heat gain is reduced by 56% [27]
Sri Lanka	25-mm-thick polystyrene insulation on a concrete roof	9 °C reduction in slab soffit temperature, about 75% reduction of heat flow [1]
A laboratory experiment	Combined application of aluminium reflector and polyurethane insulation	Heat flux reduction of 88% [28]
A laboratory experiment	10-cm plastic waste thermal insulation	About 70% effective insulation in comparison with ordinary insulation materials. However, considering the economic aspects, this is viable [29]

as the energy conservation of other commercial buildings by mitigating the need for air conditioners. And also, the novel insulation system "bamboo heat insulation panels for roof slabs" obtained a patent under Sri Lankan intellectual property act No. 36 of 2003 and under the international patent classification (IPC: E0C 1/100, B28B, B28C) with the patent number: 18880.

Objectives

Overall objectives

The main objectives of the study are to develop a roof slab insulation system using a natural thermal insulation material and assess the effectiveness of the slab insulation system in tropical climatic conditions.

Specific objectives

The specific objectives are as listed below:

- Investigation of natural thermal insulation solutions.
- Accessing the possibility of using an air gap as a thermal insulator.
- Studying the effect of air confinement through bamboo cut in the transverse direction.
- Studying the effect of thickness and number of bamboo layers and optimization.
- Calculating the peak heat gain reduction by the bamboo insulation system.

Materials and experimental methods

Investigation on potential natural thermal insulation materials that can be used in local conditions in Sri Lanka

The most important factor in any thermal insulation system is its insulation material. Hence, it is better to select a feasible thermal insulation material to achieve the desired comfort levels. Here, the necessary data of locally available natural materials that can be used as thermal insulators were gathered from the available literature.

Using an air gap as the thermal insulator

Small-scale physical model tests were conducted under typical summer days in the 1st week of September 2018 at the University of Moratuwa, Sri Lanka. Plan area of each model was 1.2 m × 1.2 m and height was 1.0 m. Thermal readings were recorded over five consecutive days using GL820 Midi Data Logger and a set of average hourly uninterrupted readings of 24 h were obtained considering the temperature readings with minimum deviations. The sample views of small-scale physical models are as shown in Fig. 1. Each physical model was constructed using half brick thick walls made of ordinary un-plastered bricks (0.51 W/m K) and reinforced concrete (1.7 W/m K) was used in roof slabs.

Models were prepared using the structural arrangement of Nandapala and Halwatura system [17]. Details of the slab insulation system with a 25-mm-thick air insulation layer are as shown in Fig. 2.

Fig. 1 Small-scale physical models used to assess the thermal performance

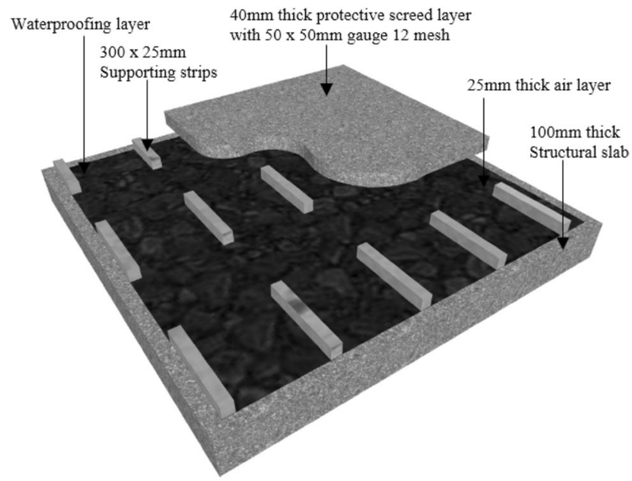

Fig. 2 Details of the slab insulation system with an air insulation layer

Using a bamboo cut in the transverse direction as a thermal insulation material

The experiment described in "Using an air gap as the thermal insulator" was corresponding to an insulation layer of unconfined air. Even in insulation materials such as expanded polystyrene, air confinement is used as a thermal insulator. Hence, it was decided to create an air confinement in such a way that the additional cost for the confinement is minimized and the system is conveniently constructible. Desired air confinement was achieved using bamboo cut in the transverse direction. Since bamboo is a rapidly growing plant which holds the Guinness record for the fastest growing plant in the world [34] the adverse effect imposed using bamboo for construction purposes is negated in a shorter span of time. In addition, it has been proven that bamboo is a good thermal insulator [35].

In a nutshell, the intention was to create an air confinement using a locally available, stiff natural material. And also, the impact to the environment due to the utilization of such material had to be minimized since the study focuses on sustainability. Satisfying all those requirements, bamboo cut in transverse direction does possess the qualities to be the ideal material. The planned structural arrangement with bamboo is shown in Fig. 3.

As shown in Fig. 3, the structural arrangement by Nandapala and Halwatura, which was experimentally verified to be capable of withstanding any practical load [17] was used here. Panel units are as shown in Fig. 4. They were pre-cast units and were placed as the thermal insulation layer in such a way that the air confinement is achieved. The bamboo layer was prepared using the same age and approximately the same size bamboo creating an approximate uniform distribution. One of the small-scale physical models which were constructed using the bamboo insulation system is as shown in Fig. 5. In this experiment, the thermal performance of the model with a 25-mm-thick bamboo insulation layer was compared with the one with

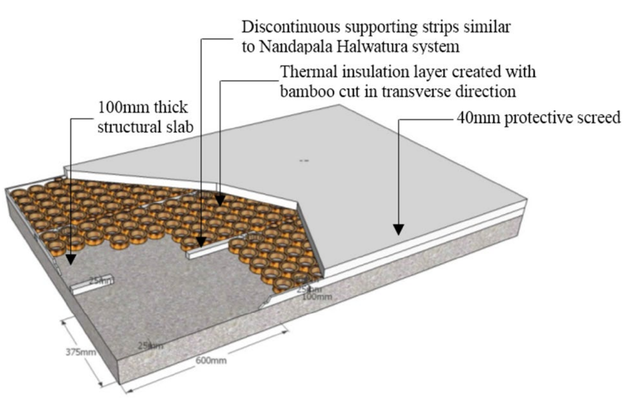

Fig. 3 Planned arrangement of the bamboo insulation layer

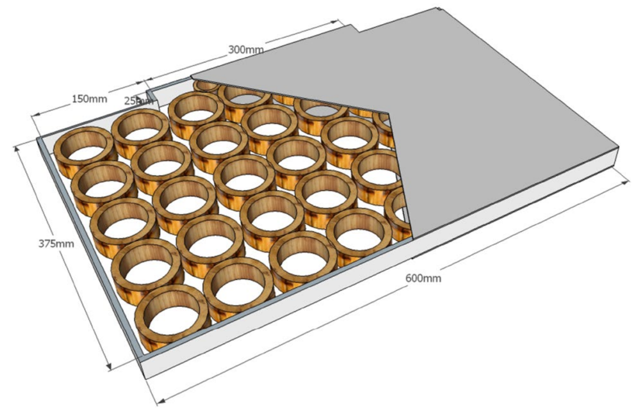

Fig. 4 Panel units used in the construction of bamboo insulation layer

a 25-mm polystyrene layer with respect to the temperature readings which were recorded during the same period of time.

Initially, the insulation layer was prepared using a set of 25-mm-thick bamboo panels. Since better thermal performance can be achieved by optimizing the insulation layer thickness and the number of layers, the optimization was done. The objective was achieved using a set of small-scale physical model testings containing the models with the dimensions mentioned in "Using an air gap as the thermal insulator". The thermal performance of the slab systems of 25 mm (1.0″), 50 mm (2.0″) and 75 mm (3.0″) bamboo insulation thickness was observed and the effect of the number of layers was investigated using two layers of 37.5 mm bamboo (1.5″). Here also, GL820 Midi Data Logger was used to measure the slab top and slab soffit temperatures of each model.

Fig. 5 Construction of the system with bamboo insulation

Calculation of peak heat gain reduction by bamboo insulation slab system

The heat gain reduction due to the bamboo insulation system was calculated with respect to a 125-mm-thick uninsulated reinforced roof slab. Heat flow calculation was performed using the temperature difference between slab soffit and slab top temperatures and corresponding air-to-air resistivity values (the calculations and material properties are given in "Appendix A").

Since there was an air trapping in the bamboo insulation system, a computer simulation which was performed using "Design Builder V5" software package was used to obtain the air-to-air resistivity value. The virtual model was prepared similar to the actual model described in "Using an air gap as the thermal insulator" (details of the simulation model used in the experiment are as listed in "Appendix A"). Since the objective was to obtain the experimental air-to-air resistivity and corresponding "U" values (composite thermal conductivity), the virtual model was calibrated with respect to the inputs of measured outdoor temperature values. The slab top and slab soffit temperature readings of the actual model and computer simulation are as shown in Fig. 6.

Figure 6 shows that the simulation results are much similar to the results obtained through the physical model testing. Hence, air-to-air resistivity and corresponding "U" values of bamboo-insulated slab obtained through the computer simulation were used in heat flow calculations.

Results and discussion

Prevailing locally available natural thermal insulation materials

As mentioned in "Investigation on potential natural thermal insulation materials that can be used in local conditions in Sri Lanka", details regarding locally available thermal

Table 2 Properties of locally available natural thermal insulation materials

Natural thermal insulation material	Thermal conductivity (W/m K)
Banana and polypropylene (PP) fibre [36]	0.157–0.182
Bagasse [37, 38]	0.046–0.055
Corn cob [39, 40]	0.101
Cotton (stalks) [41]	0.058–0.081
Date palm [42, 43]	0.072–0.085
Durian [44]	0.064–0.185
Oil palm [45]	0.055–0.091
Pecan [46]	0.088–0.103
Pineapple leaves [47]	0.03–0.04
Rice [46]	0.046–0.056
Sunflower (cake from bio refinery) [37, 38, 45]	0.046–0.055
Sunflower (pitch) [48]	0.038–0.050
Straw bale [49, 50]	0.038–0.067

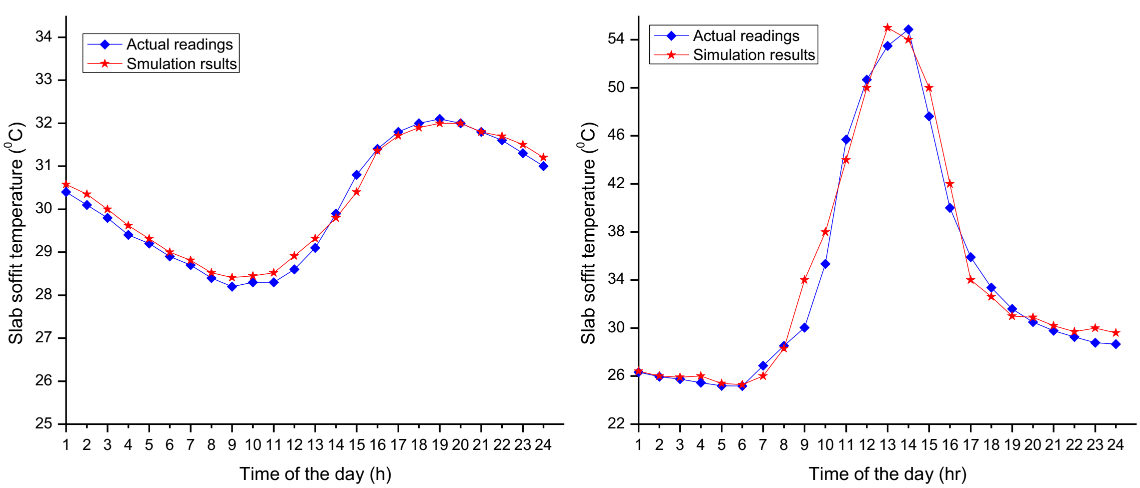

Fig. 6 Slab top and slab soffit temperature readings of the actual model and computer simulation

insulation materials were collected via a literature review. The summary of the literature data is listed in Table 2.

The thermal conductivity values of considered natural thermal insulation materials were in between 0.03 and 0.182 W/m K, and the thermal conductivity of polystyrene which was used in Nandapala and Halwatura system is in the lower bound of Table 2. Hence, it is clear that there is a possibility of substituting polystyrene by a natural thermal insulator and obtaining a reasonable degree of insulation.

An efficient thermal insulator needs to be a material with high porosity as it disturbs the heat conduction. The pores in the material absorb heat disturbing the conductive heat flow and reduce the composite conductivity of the system [4, 51]. According to this process, increasing the void ratio in the insulation layer should theoretically increase the effectiveness of the insulation system. Therefore, the extreme condition, a system with a 100% void ratio, a layer of air, was selected for a trial analysis.

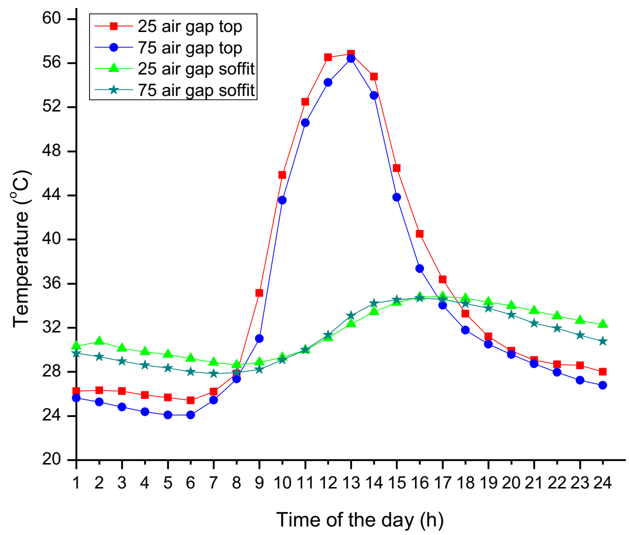

Fig. 8 Observed slab top and slab soffit temperatures of the systems with 25-mm and 75-mm air gaps

Natural air gap as a thermal insulator

Temperature readings were obtained using the Data Logger mentioned in "Using an air gap as the thermal insulator". Initially, the polystyrene insulation layer of Nandapala and Halwatura system was replaced by a 25-mm-thick unconfined air layer. The temperature readings observed on slab top and slab soffit of the model with 25-mm-thick air gap insulation are as shown in Fig. 7.

The peak slab top temperature of the model was observed to be 56.8 °C at 1300 h. The peak had transferred to the soffit within 3 h at 1600 h with a decrement factor of 0.62. These outcomes are significant figures for an insulation system as it considerably reduces the heat flow.

Then the study was extended to find out the effect of the thickness of the air gap to the thermal performance of the system. Figure 8 depicts the slab top and slab soffit temperature variations of two models with air gap thicknesses set at 25 mm and 75 mm. The result obtained for the 75-mm air gap was having a time lag of 3 h with a decrement factor of 0.62. Since the outcomes were similar to the 25-mm air gap, it was concluded that there is no effect due to the increment of the thickness of the air layer on the thermal performance.

The next attempt was made to compare the effectiveness of the 25-mm air gap with the 25-mm polystyrene (PS) insulation layer. The previously used experimental methodology

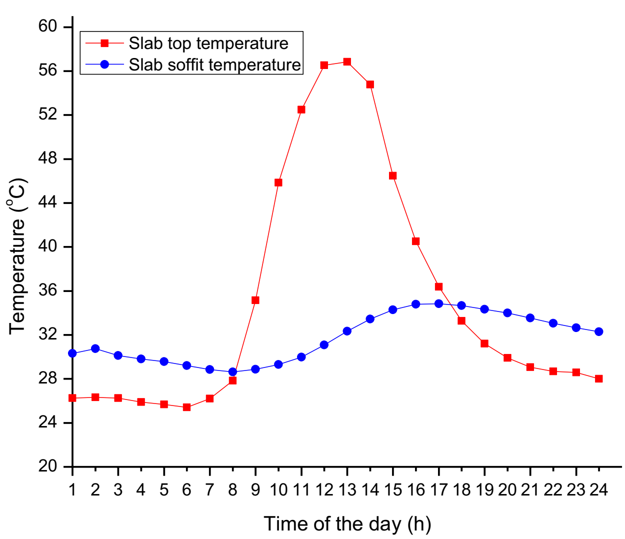

Fig. 7 Observed slab top and slab soffit temperatures of the system with 25-mm air gap

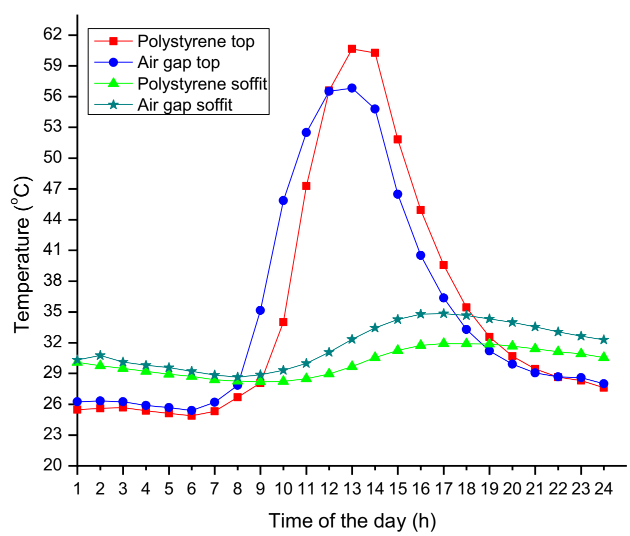

Fig. 9 Observed slab top and slab soffit temperatures of the systems with 25-mm polystyrene layer and 25-mm air gap

described in "Using an air gap as the thermal insulator" was adapted and slab soffit and top temperature readings of the models were obtained on the same day. The observations are as shown in Fig. 9.

The peak slab top temperature of the system with an air gap was observed to be less than that of polystyrene but found to have reached earlier than polystyrene. This means that the convective heat transfer is quicker in the case of the air gap. However, the heat barrier created by polystyrene was stronger than that of the air gap; hence, polystyrene was concluded to be the better insulator. The soffit temperatures shown in the same figure emphasized this fact. Anyhow, the system with the air gap has shown considerable insulation properties. Assuming that the better performance of polystyrene is due to the air confinement increasing the porosity of the insulation material, it was decided to confine the air gap to check whether there is any improvement in thermal performance.

Replacing the air gap with a transversely cut bamboo layer making an air confinement

As described in "Using a bamboo cut in the transverse direction as a thermal insulation material", a 25-mm-thick bamboo insulation panel made of transversely cut bamboo was used to substitute the 25-mm-thick air insulation layer providing an air confinement. Figure 10 shows the slab top and soffit temperature variations observed in the model constructed with a 25-mm-thick bamboo insulation layer.

The peak slab top and slab soffit temperatures of the bamboo-insulated model were observed to be 54.9 °C and 33.3 °C, respectively, with a 3-h time lag. Hence, the corresponding decrement factor was calculated to be 0.61.

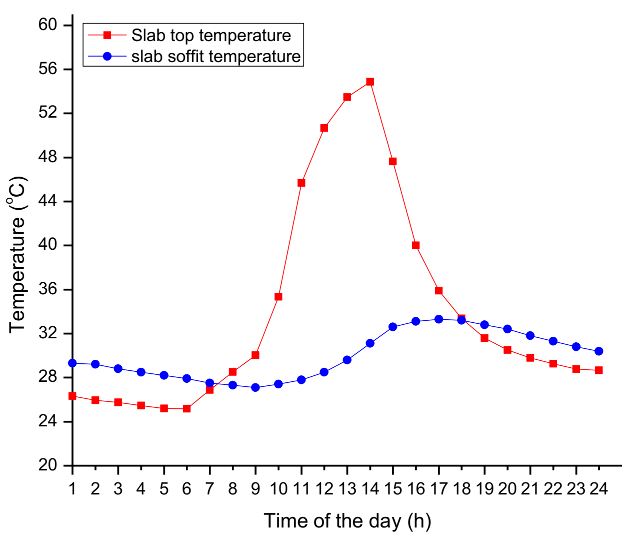

Fig. 10 Slab top and slab soffit temperature readings of the system with a 25-mm bamboo insulation layer

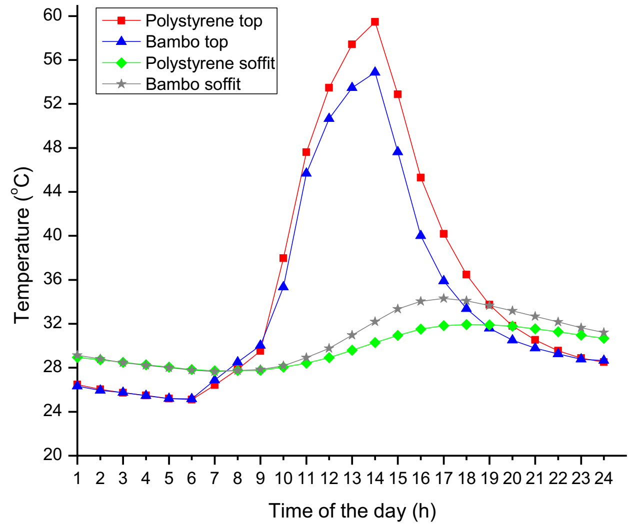

Fig. 11 Slab top and soffit temperatures of the system with a 25-mm polystyrene layer and a 25-mm bamboo layer

Nevertheless, it was necessary to analyse the thermal performance of the 25-mm bamboo insulation layer quantitatively in comparison with a 25-mm polystyrene (PS) layer. The comparison of the slab top and slab soffit temperatures between the two systems is as shown in Fig. 11.

Although the slab top temperature of the system with bamboo was lower than that of the system with polystyrene, the soffit temperatures behave conversely, similar to the case of the ventilated air gap. Considering the outcomes illustrated in Fig. 11, it is evident that polystyrene has marginally better insulation properties than bamboo. However, considering the environmental aspects, the achievement of bamboo insulation panels can be concluded to be significant.

Then the study was extended to investigate the effect of bamboo insulation layer thickness and the number of layers towards the thermal performance of the system.

Optimization of bamboo layer thickness and number of layers

Four small-scale models were constructed. Models with 25-mm-, 50-mm-, 75-mm- and two 37.5-mm-thick bamboo layers were used in the experiment. Slab top and soffit temperature readings were obtained using the experimental method mentioned in "Using an air gap as the thermal insulator".

Figures 12, 13, 14 and 15 show the slab top and soffit temperature variations observed in the models constructed with 25-mm-, 50-mm-, 75-mm- and two 37.5-mm-thick bamboo insulation layers, respectively.

Any significant difference among the slab top temperature readings of the four corresponding models was not observed.

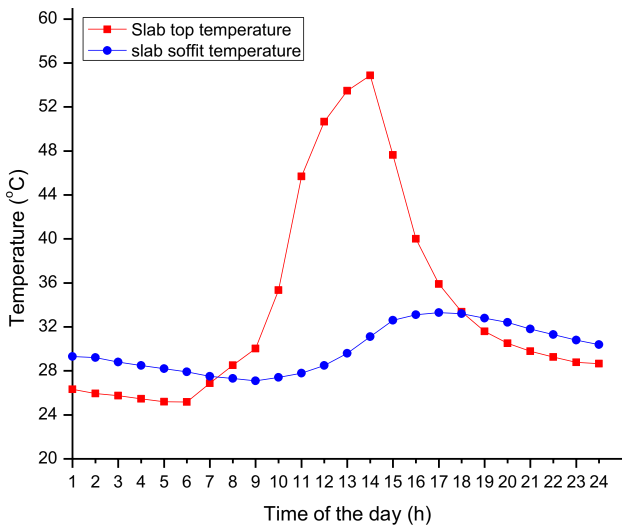

Fig. 12 Slab top and slab soffit temperature readings of the system with a 25-mm bamboo insulation layer

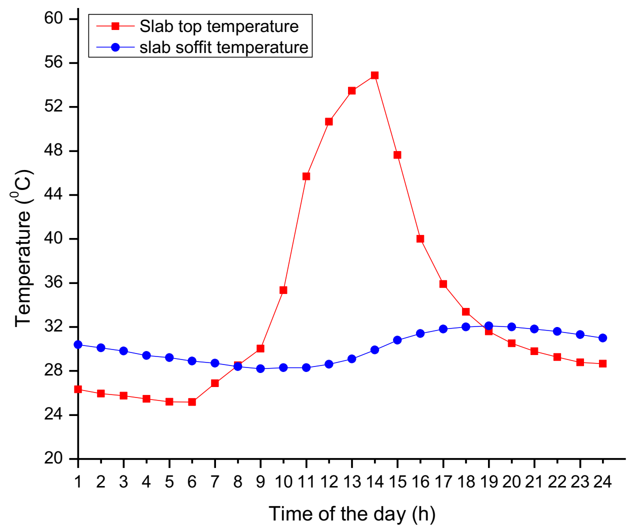

Fig. 14 Slab top and slab soffit temperature readings of the system with a 75-mm bamboo insulation layer

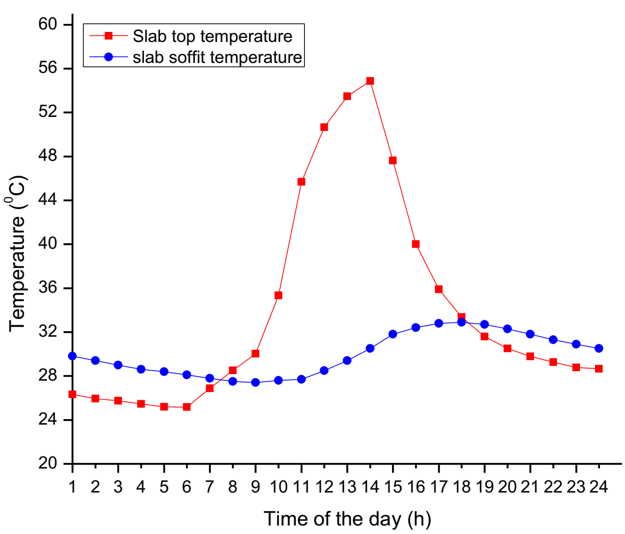

Fig. 13 Slab top and slab soffit temperature readings of the system with a 50-mm bamboo insulation layer

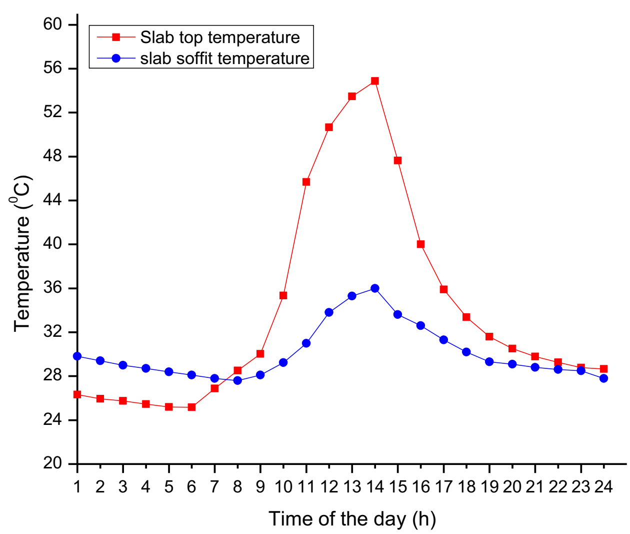

Fig. 15 Slab top and slab soffit temperature readings of the system with two 37.5-mm bamboo insulation layers

But the slab soffit temperature readings have varied in a consistent manner. They are as depicted in Fig. 16.

The peak slab top and slab soffit temperature readings, corresponding time lags and the calculated decrement factors of four tested scenarios are as listed in Table 3.

During the day of the experiment carried out, the maximum outdoor temperature was recorded as 34.6 °C. Table 3 and Fig. 16 clearly indicate that the minimum slab soffit temperature and the maximum time lag between two top temperature readings were corresponding to the model with 75-mm-thick bamboo layer. Hence, it was concluded that the increment of the height of the confined air layer improves the thermal insulation properties. Although higher thicknesses give higher thermal insulation properties, the heat transfer by convection within confined sections are prevented by own viscosity [52]. Because of that, the layer thickness cannot be increased infinitely and convective heat transfer occurs when the layer thickness becomes greater than 75 mm [52]. The slab soffit temperature difference between bamboo insulation panels of 75-mm and 25-mm-thick bamboo layers was 1.2 °C and the difference between decrement factors was 0.02. Although the least slab soffit temperature and the decrement factor was corresponding to the 75-mm-thick bamboo layer, it has consumed a three-time greater insulator thickness compared to the 25-mm bamboo layer. Because

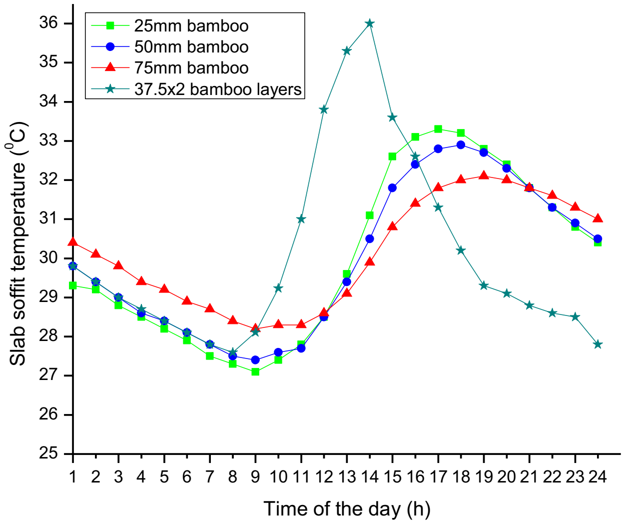

Fig. 16 Slab soffit temperature readings of the system with 25-mm-, 50-mm-, 75-mm- and two 37.5-mm-thick bamboo insulation layers

of that, 25 mm was selected as the optimum bamboo layer thickness.

When it comes to the effect of the number of layers, 37.5-mm-thick two bamboo layers were considered representing 75 mm layer thickness. Figure 16 clearly indicates that the line of the graph which represents the slab soffit temperature variation of the two 37.5-mm bamboo layer model behaves significantly different to others. In there, the maximum slab soffit temperature was 36 °C creating a decrement factor of 0.66 without any time lag. Hence, it was concluded that increment of the number of bamboo insulation layers does not significantly contribute to the enhancement of thermal performance of the system. Ultimately, it was concluded that a layer of a 25-mm-thick transversely cut bamboo insulation panel can be effectively used as the optimum insulation layer thickness of the system.

Peak heat gain reduction by bamboo insulation slab system

The ultimate objective of any thermal insulation method is lowering the heat gain/loss through the corresponding building element. Since the study is limited to tropical climatic conditions, only the heat gain reduction was considered. Heat gain reduction was calculated using the novel slab insulation system with a 25-mm-thick bamboo insulation layer and a 125-mm-thick uninsulated reinforced concrete roof slab. All the temperature readings were obtained adhering to the experimental setups described in "Using an air gap as the thermal insulator". The calculated "*U*" value (composite thermal conductivity) of the uninsulated slab was 3.944 W/m^2 K and the "*U*" value of bamboo-insulated system obtained from the computer simulation was 1.097 W/m^2 K. Graphical representation of calculated heat gain/loss values of two scenarios are as shown in Fig. 17 (corresponding calculations are given in "Appendix A").

The peak heat gain through bamboo-insulated and uninsulated slab systems was 38.51 W and 81.67 W, respectively. Figure 17 clearly indicates a significant drop in heat flow with 25-mm-thick bamboo insulation system. According to the ultimate calculation, the peak heat gain reduction due to 25-mm-thick bamboo insulation system with respect to the 125-mm-thick uninsulated slab was 53% (the calculation is given in "Appendix A"). Hence, it is evident that the novel thermally insulated roof slab

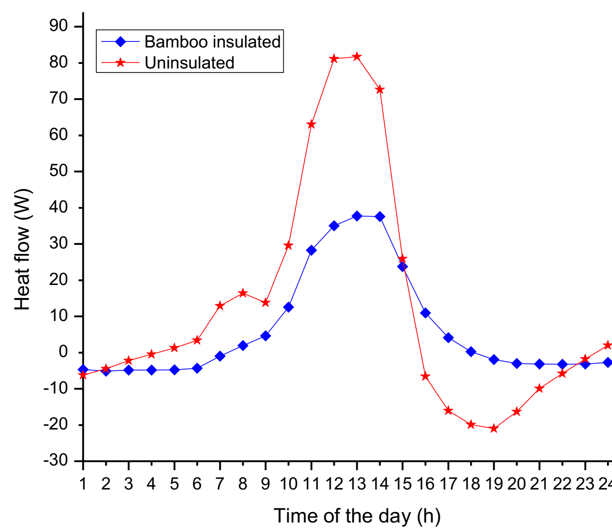

Fig. 17 Heat flow values for the two considered scenarios

Table 3 Decrement factors of tested models

Layer thickness (mm)	Slab top maximum temperature (°C)	Slab soffit maximum temperature (°C)	Time lag (h)	Decrement factor
25	54.9	33.3	3.0	0.61
50	54.9	32.9	4.0	0.60
75	54.9	32.1	5.0	0.59
2×37.5	54.9	36.0	0.0	0.66

system with 25-mm-thick bamboo layers can be used as an effective way of achieving the indoor thermal comfort.

Conclusions

Following the necessity of developing an eco-friendly insulation system, a number of experiments have been conducted with different materials and system configurations. Since the increment of void ratio of the insulator is directly proportional to the effectiveness of the thermal insulation system, the extreme condition, an air layer with 100% void ratio was tested initially. Tests on the thermal performance of an air gap as the thermal insulator indicated that no thermal performance enhancement can be obtained by increasing the air gap thickness. Since the results proved that polystyrene acts as a better thermal barrier than the unconfined air layer, an air confinement was introduced using transversely cut bamboo sections. These experiments revealed that the optimum thermal performance can be achieved through a 25-mm-thick bamboo insulation layer and there is no significant effect from the multiple bamboo layers towards the ultimate thermal performance. Since the bamboo is a highly available low-cost natural material with a rapid growth rate, it can be consumed without any risk of scarcity. Utilization of bamboo insulation system to fulfil the thermal insulation aspects assist in achieving the desired comfort levels in a much environmental friendly manner. Due to the structural arrangement with the ability to withstand any practical load on roof, the bamboo-insulated roof slab insulation system is considered as a structural sound as well as a thermally insulated eco-friendly slab insulation solution which can provide a peak heat gain reduction of 53% % under tropical climatic conditions with a decrement factor of 0.61, followed by a 3-h time lag.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author; Madujith Sagara Chandra states that there is no conflict of interest.

Appendix A

Calculating composite thermal conductivity of Nandapala Halwatura system [53]

$$\frac{1}{K_1} = \frac{1-\emptyset}{K_{ps}} + \frac{\emptyset}{K_{con}},$$

where K_1 is the thermal conductivity of the insulation layer, $\emptyset$ is the volume fraction of concrete (3.3% in the case [17]), K_{ps} is the thermal conductivity of polystyrene (taken as 0.033 W/m K), and K_{con} is the thermal conductivity of reinforced concrete (taken as 1.7 W/m K),

$$\frac{1}{K_1} = \frac{1-3.3\%}{0.033} + \frac{3.3\%}{1.7},$$

where $K_1 = 0.034$ W/m K

Thermal resistance of the system $(R_1) = \frac{d_1}{K_1} + \frac{d_2}{K_2} + \frac{d_3}{K_3}$ ("d" is the layer thickness),

$$= \frac{0.04}{1.7} + \frac{0.025}{0.034} + \frac{0.1}{1.7} = 0.82\ \mathrm{m^2\ K/W}$$

Air-to-air resistance of the slab insulation system = $R_{top} + R_1 + R_{soffit}$

R_{top} and $R_{soffit} = 0.04\ \mathrm{m^2\ K/W}$ and $0.14\ \mathrm{m^2\ K/W}$

Air-to-air resistance of the slab insulation system = $0.04 + 0.82 + 0.14 = 1.0\ \mathrm{m^2\ K/W}$

Hence, composite thermal conductivity of the slab insulation system $= \frac{1}{1.0} = 1.0\ \mathrm{W/m^2\ K}$

Calculating thermal conductivity of uninsulated slab system

Thermal resistance of the system $\left(R_1\right) = \frac{d_1}{K_1}$ ("d" is the layer thickness),

$$= \frac{0.125}{1.7} = 0.0735\ \mathrm{m^2\ K/W}$$

Air-to-air resistance of the slab insulation system = $R_{top} + R_1 + R_{soffit}$

R_{top} and $R_{soffit} = 0.04\ \mathrm{m^2\ K/W}$ and $0.14\ \mathrm{m^2\ K/W}$

Air-to-air resistance of the slab insulation system = $0.04 + 0.0735 + 0.14 = 0.2535\ \mathrm{m^2\ K/W}$

Hence, composite thermal conductivity of uninsulated roof slab $= \frac{1}{0.2535} = 3.94\ \mathrm{W/m^2K}$

Details of the simulation model used obtain composite thermal conductivity and air-to-air resistivity of bamboo insulation system

Basic details

Plan area	1.2 m × 1.2 m
Number of stories	01
Location	Moratuwa, Sri Lanka
Latitude and longitude	6.79°N, 79.9°E
Altitude	30 m
Exposure to wind	Normal
Average monthly mean temperature	28 °C
Nearest weather station	Ratmalana, Sri Lanka

Activity details

Type of the building	Dwelling, 24/7
Occupation rate	0.00/m^2
Metabolic rate	Corresponds to dwellings
Household equipment	None

Construction details

Thickness of the walls	102.5 mm (half brick thick wall)
Walling material	Brick (0.51 W/m K)
Structural slab thickness	100 mm (1.7 W/m K)
Protective screed thickness	40 mm (1.7 W/m K)
Percentage of openings in E–W direction	0%
Percentage of openings in N–S direction	0%

Specimen heat flow calculation

Heat gain/loss $(W) = A \times U \times \Delta T$,where A is the area subjected to heat flow, U is the composite thermal conductivity of the system and ΔT is the temperature gradient.

Heat flow calculation of bamboo insulation system: $A = 1.2 \times 1.2 = 1.44$ m^2, $U = 1.097$ W/m^2 K, and $\Delta T = 53.48$ °C–29.1 °C = 24.38 temperature units

Peak heat gain of bamboo insulation system = $1.44 \times 1.097 \times 24.38 = 38.51$ W

Heat flow calculation of uninsulated slab system: $A = 1.2 \times 1.2 = 1.44$ m^2, $U = 3.944$ W/m^2 K, $\Delta T = 55.45$ °C–41.07 °C = 14.38 temperature units

Peak heat gain of uninsulated slab system = $1.44 \times 3.944 \times 14.38 = 81.67$ W

Heat gain reduction calculation

Peak heat gain of bamboo insulation system = 38.51 W

Peak heat gain of uninsulated slab system = 81.67 W

Peak heat gain reduction through bamboo insulation system with respect to uninsulated slab system = $\left\{1 - \left(\frac{38.5126}{81.6692}\right)\right\} \times 100\% = 52.84 \approx 53\%$

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