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A study on the feasibility of a new roof slab insulation system in tropical climatic conditions

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ABSTRACT

A roof slab provides an extra robustness and a cyclonic resistance to the structures due to its self-weight. However, its performance in warm humid conditions is unsatisfactory because of the thermal discomfort in the immediate space beneath. Insulation has been recognized as an effective passive approach to address this issue. Thus, numerous insulation systems have been developed throughout the world. In this study, a system proven to be fruitful in tropical conditions was chosen and its negative aspects were recognized. Then, a new insulation system (a system with discontinuous supporting strips) was developed addressing the key drawbacks, and its thermal performance was compared with the prevailing systems. Prototype testing indicated that the negative effect of the supporting strips on the thermal performance of the system is negligible. Further, it was proven that this system achieves a heat gain reduction of more than 75%. An actual scale physical model proved that the system performs even better than a Calicut-tiled roof with a timber ceiling in thermal aspects. Computer simulations deduced that on a sunny day in tropical conditions, about 20% of the peak cooling load reduction can be achieved by the system. In addition, it was found out that about 5% reduction of life cycle cost was achieved by this technique for a lifespan of 10–50 years. And also, it was proven that the insulated slab performs better than an insulated Calicut tiled roof in terms of Life Cycle Costing.

1. Introduction

It is forecasted by the research community that the intensity and the severity of the natural disasters will be increased due to the drastic climatic changes [1–3]. One of the vital natural disasters common in tropical countries is cyclones. Hence, it has made the designers in tropical countries to develop disaster-resistant structures [4,5].

Thus, a number of research works have been carried out to increase the robustness of the structures. It has been scientifically proven that flat roof slabs cater this demand due to its large self-weight [6]. Further, it provides some additional benefits like the possibility of future vertical extension, ability to use as an extra working space, and having vegetation on top. And also, it adds a significant economic value by regaining the land as well [7].

Despite these benefits, the use of flat concrete slabs is not very popular in tropical countries due to the lack of thermal comfort [8]. When a concrete slab gets heated due to the direct exposure to the sunlight, the longwave radiation makes the immediate space beneath thermally uncomfortable. The effect is worse at the day time with a significant effect during the night as well [7]. Air conditioning the affected area is the most common remedy, which is unfavourable in both economic and environmental aspects.

Nonetheless, a significantly higher portion of commercial buildings is air-conditioned. Consequently, around 20% of total energy demand of tropical countries is for making thermally comfortable building interiors [8]. This high consumption of energy must be discouraged as it directly contributes to the energy crisis [4,6–11].

Subsequently, the research community has come up with some feasible solutions in the form of passive techniques. They are a set of techniques that the designers incorporate during the design phase itself so that the buildings operate with minimum operational energy [12–15]. Insulating the building envelope is one such popular technique. Even though this incorporates an additional initial investment, that cost is proven to be paid back by

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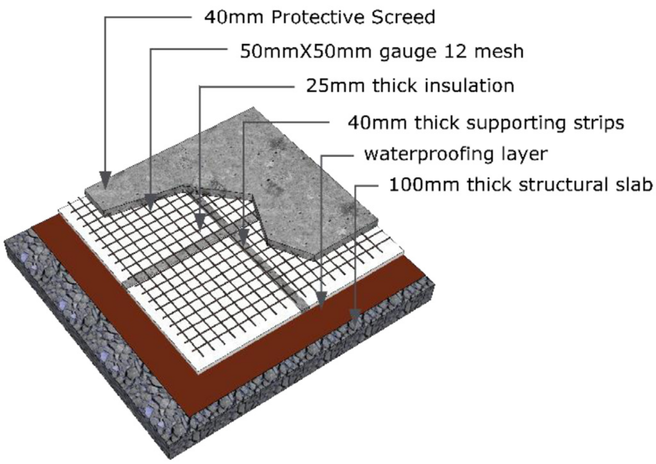

Fig. 1. Halwatura and Jayasinghe slab insulation system with a continuous strip arrangement [41.].

the reduction in operational cost within a reasonable span of time [16–20].

Thermal insulation of the roof is in the focus of the research community as it contributes to about 70% of the total heat gain of buildings [21]. There are several techniques used in roof thermal insulation, such as applying a cool paint [15,22–26], using a variety of insulation materials in roofing [27–35], and using rooftop vegetation [36–40]. All the above systems have been proven to perform well with regard to thermal aspects. But, when it comes to roof slabs, both thermal performance and structural integrity of the system have to be concerned.

A study by Halwatura and Jayasinghe has presented the structural integrity of a thermally insulated roof slab in addition to thermal performance. Details of the system are as shown in Fig. 1 [41].

After several years, another study by Nandapala and Halwatura has optimized the system in terms of structural aspects and has come up with a discontinuous strip arrangement to enhance the structural integrity of the system. Details of the novel system are as shown in Fig. 2 [42]. This study states that it has addressed a durability issue associated with the previous system by providing a set of drainage paths within the insulation. Newly introduced drainage paths are as shown in Fig. 3. It has further proven that this system has the capacity of withstanding any practical load on a roof [42,43].

However, the thermal performance of the system by Nandapala and Halwatura has not been studied comprehensively. This paper

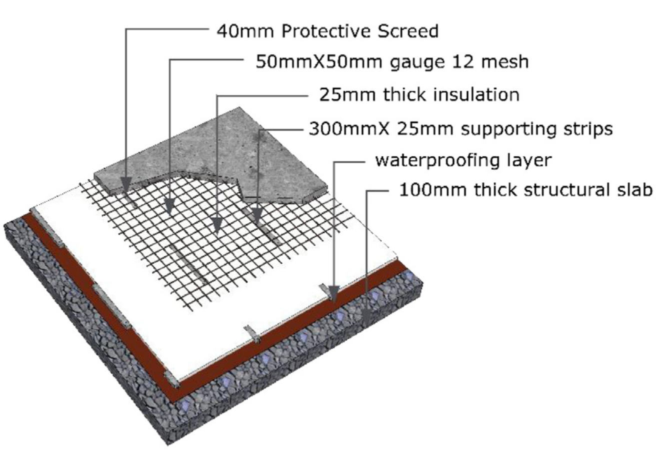

Fig. 2. The newly designed system with discontinuous supporting strips [42].

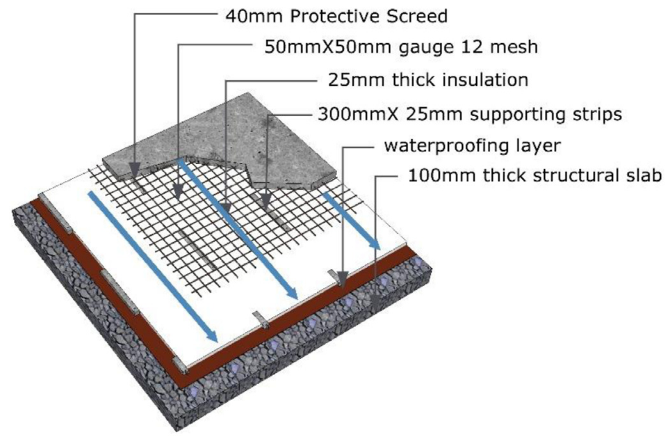

Fig. 3. Drainage paths of the newly designed system.

is intended to address that gap. Further, the peak cooling reduction and the financial feasibility of the system are presented here.

2. Objectives

2.1. Overall objective

The main objective of the article is to access the effectiveness and feasibility of the newly designed roof slab insulation system in tropical conditions.

2.2. Specific objectives

The specific objectives of this study are as listed below;

- To compare the thermal performance of the newly designed roof slab insulation system with similar existing techniques
- To compare the thermal performance of the system with an insulated Calicut-tiled roof
- To investigate the peak cooling load reduction that can be achieved by the novel system
- To check the financial feasibility of the system in comparison with a traditional Calicut-tiled roof

3. Materials and experimental methods

3.1. Thermal performance comparison of the novel roof slab insulation system with prevailing techniques

Physical model testings which were done in 2018 were used to achieve this objective. Four prototype models, as shown in Fig. 4, were constructed to study the thermal performance of the newly developed discontinuously supported insulation system.

The specific details of four prototype models are as listed below

- A control experiment (a model without any insulation)
- A model with a continuous-strip supporting arrangement (Fig. 1) [41]
- A model with the discontinuous supporting arrangement (novel system) (Fig. 2) [42]
- A model without any supporting arrangement (continuous insulation layer)

Plan area of each prototype model was 1.2 m × 1.2 m and each was 1.0 m high. Since the scope was limited in roof slab insulation, each wall was kept uninsulated. There, the walls were constructed using half brick thick walls made of un-plastered engineering bricks (0.51 W/mK). And reinforced concrete (1.7 W/mK) was used in roof slabs.

Fig. 4. Prototype models constructed to compare the thermal performance.

125 mm thick uninsulated reinforced concrete slab was used in the control experiment. It was used to study the effect of insulation in general. The system by Halwatura and Jayasinghe was to compare the two insulation systems, and the continuously insulated system was used to study the reduction in effectiveness due to the concrete layers present in the insulation. A detailed description of strip arrangement is available in a previous publication of authors [42].

Temperature readings were taken at ten-minute intervals during five continuous typical sunny days until a consistent ambient temperature variation was obtained. Then the average temperature of each hour was calculated after removing the outliers. Later consistent temperature values for each hour were obtained. To have enhanced reliable outcomes, one common set of readings representing the thermal readings of five days was obtained using the figures with minimum standard deviations.

Slab top and slab soffit temperatures were used for comparison purpose to obtain the real effect of insulation, minimizing the effects of any local variations within the systems. The 'GL820 Midi Data Logger' was used to obtain temperatures for an uninterrupted set of readings. The recordings were graphically represented, and the time lags and the decrement factors of each system were calculated and the thermal performances of the systems were evaluated based on them.

3.2. Thermal performance comparison with an insulated Calicut tiled roof

Section 3.1 comprised a thermal performance comparison of the discontinuous stripped roof slab insulation system with a set of slab insulation systems. As discussed in Section 1, despite many advantages of the roof slabs, they are not much popular in the community. This is mainly due to thermal discomfort [8]. Hence, it is worthwhile to compare the degree of insulation with an insulated Calicut-tiled roof, which is the most popular in tropical conditions.

The physical model made to the actual scale used for testing is shown in Fig. 5a. The Calicut-tiled roof in the model was insulated with a 3 mm foil layer, an air gap between its timber ceiling and the roof covering. The uninsulated slab in the physical model was with 125 mm uninsulated RCC slab while the insulated slab was that of shown in Fig. 2. Here also GL820 Midi Data Logger was used to obtain temperature readings of rooftop and soffit surfaces.

Those temperature readings were logged with respect to an uninsulated slab, an insulated slab and a Calicut-tiled roof on the same side of the building to negate the different impacts in solar radiation with the time of the day. The top and soffit temperature readings were obtained in the same way described in Section 3.1, and the rooftop and soffit temperature variations were compared.

3.3. Accessing the peak cooling load reduction of the slab insulation system

A typical 15 m × 15 m office building was selected to assess the performance since previous literature is available for such a building. Since the objective was to analyse the effect of heat gain through the roof, other housing elements were included with as many passive features as possible. The external walls were taken to be 225 mm thick brick walls. No windows were placed in East and West walls, and the provided windows in North-South directions were coupled with 1 m overhangs to prevent direct solar radiation being penetrated in. The simulated model is shown in Fig. 6.

Calibrating the model is significant before extending it to predict the performance through simulation. In this case, the model shown in Fig. 5b was used as the basic model, of which the top surface and soffit temperatures had been logged over a period of 24 h. Then, a computer simulation was performed with the software package "Design Builder v4" and the internal and external variables such as thermal properties of materials, energy generation by equipment etc. were adjusted until the simulated model behaves similarly to the actual conditions. The top surface temperatures of the actual model and the simulation of the finally calibrated model is shown in Figs. 7 and 8 shows those results in the

Fig. 5. (a) The actual scale model used to compare the thermal performances of the Calicut-tiled roof and the insulated slab, (b) the virtual model developed for the actual scale model.

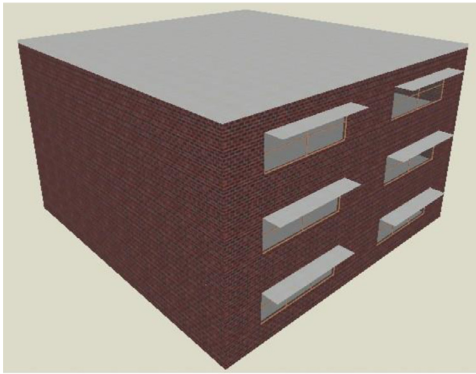

Fig. 6. The model used to perform computer simulations.

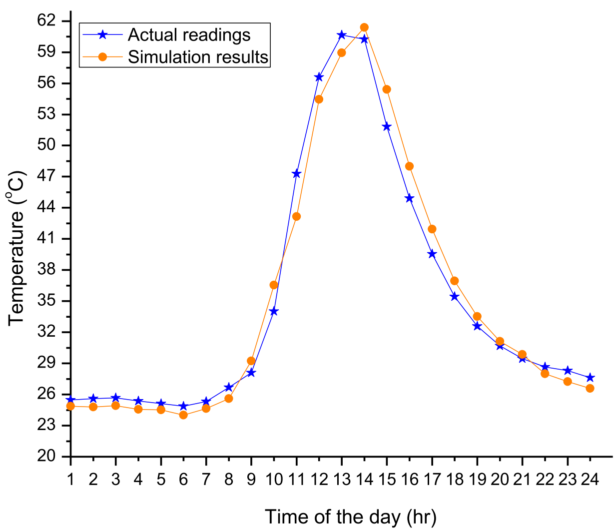

Fig. 7. Actual readings and the simulated results of the slab top in the calibrated model.

soffit. Figs. 7 and 8 clearly indicated that the actual readings behave very similar to the simulation outcomes.

Typically, it is sufficient to match the actual indoor temperatures to them of the simulated model to obtain sufficiently accurate results. However, in this case, it was decided to use the surface temperatures of the slab to increase the accuracy of the model since it is the element under consideration. The other relevant details of the virtual model were as listed in Appendix A.

3.4. Accessing the financial feasibility of the slab insulation system

Finally, the results obtained by computer simulation were extended to perform a life cycle cost analysis. There, the additional initial cost incurred for insulation was compared with the cumulative net present values of long-term economic benefit achieved in the form of the operational energy saving.

$$P = A\left\{\frac{(1+i)^n - 1}{i(1+i)^n}\right\} \tag{1}$$

where,

P = Present Value of Money
i = Discounting Factor/ Interest Rate
n = Project Life
A = Annual Worth

Eq. (1) was used to calculate the present value of progressive energy savings over the lifespan of the building [45].

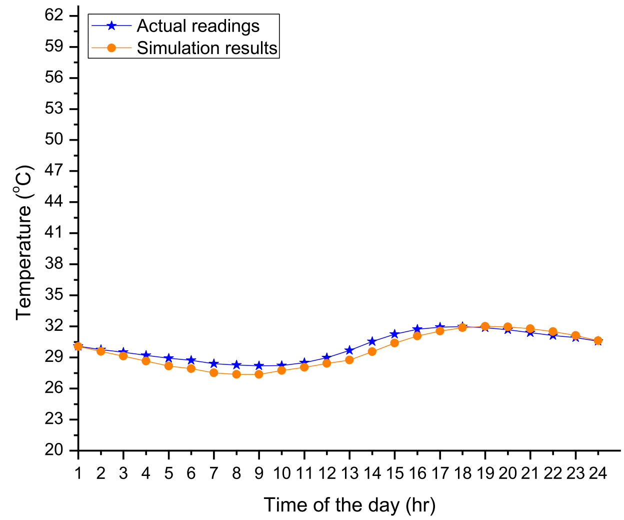

Fig. 8. Actual readings and the simulated results of slab soffit in the calibrated model.

The building life itself is an arguable topic among the research community. Some of the studies have taken it to be as small as 10–20 years [6,8–10,13–17,21], while some others recommend it to be 50 years [46]. 10% was taken to be the discounting factor, which was proven to be a typical value in Sri Lankan context [7]. Hence, three cases: 10 years, 20 years and 50 years, were considered based on 10% discounting factor in the analysis.

There are other factors that would have been ideally considered the life cycle cost analysis. The required load of the air conditioning equipment would inevitably become lesser after insulation and it marks a considerable reduction of the initial cost. However, it was not considered in the analysis, since it significantly affects the sensitivity of the heat gain to the cost figures.

The degree of land recovery and the maintenance costs are the other factors which were neglected in the analysis. The insulation system was proven to provide an unrestricted access [42], these parameters were considered to be cancelled out over the flat-slab options considered.

Each material related cost calculation was done with respect to standard BSR values and the electricity cost incurred by air conditioners was calculated according to the rates of Ceylon Electricity Board, Sri Lanka. Since the considered aspect was an ordinary office building, operational period which directly affects the cooling energy demand was taken as 0800–1700 h. (Other essential details related to cost calculation were listed in Appendix A)

In addition, the Life Cycle Cost Analysis was used to compare the performance in comparison with a traditional clay tiled roof with a timber ceiling and a 3 mm foil insulation. In this case, the land recovery poses a significant difference in the cost figures to be considered. Since this study mainly focuses on the thermal performance of the systems, it was not considered in the analysis. (The other relevant details of the virtual model were as listed in Appendix A).

4. Results and discussion

4.1. Thermal performance comparison of the novel roof slab insulation system with prevailing techniques

As described in Section 3.1, the thermal performance comparison between the novel roof slab insulation system and existing techniques was done using the temperature readings obtained from prototype model testings. Here, both top and bottom surface

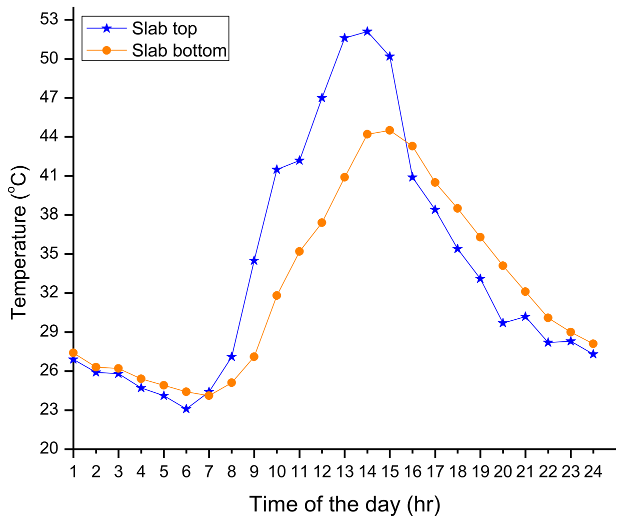

Fig. 9. Slab top and slab soffit temperatures of the control experiment over a period of 24 h.

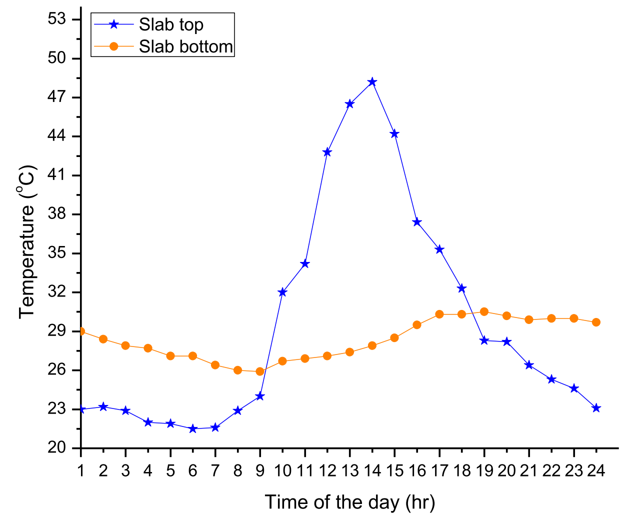

Fig. 11. Slab top and slab soffit temperatures of the intermittent-stripped system (newly designed system) over a period of 24 h.

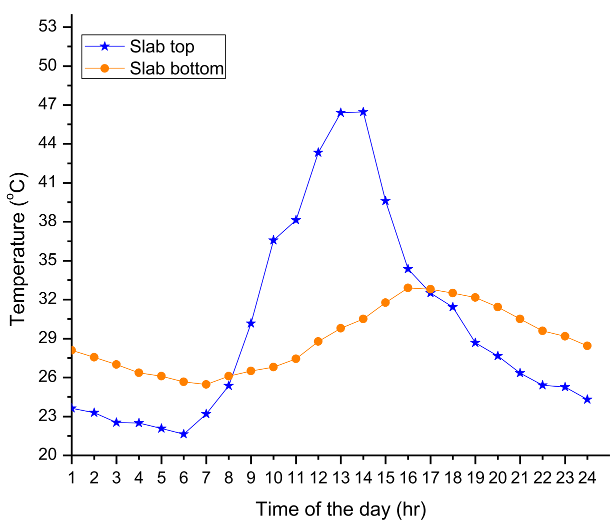

Fig. 10. Slab top and slab soffit temperatures of the system with continuous-strip supports over a period of 24 h.

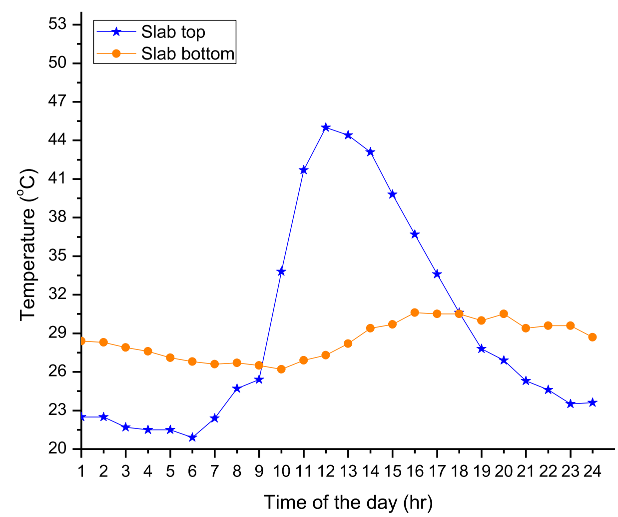

Fig. 12. Slab top and slab soffit temperatures of the system without any supports over a period of 24 h.

temperatures of each roof slab system were obtained using the data logger. Slab top and slab soffit temperature readings of each system mentioned in Section 3.1 are as shown in Figs. 9 –12 respectively.

Fig. 9 shows the slab top and slab soffit temperatures of the control experiment over a period of 24 h. It shows insulation characteristics to a certain extent due to the thermal mass effect of the roof slab. However, the soffit temperature has reached 46 °C, which is a significantly higher value in comparison with the other three cases tested. The results produced by the model with supports of continuous strips are indicated in Fig. 10. Predictably, it reveals a significant reduction in soffit temperature in comparison with the uninsulated (control) system. Figs. 11 and 12 elaborate the temperature variations of the discontinuously supported system (the novel system) and the system with continuous insulation respectively. They indicate that the behaviours of those two systems are nearly the same. It indicates that the new system is optimized in way of not accumulating a significant effect on thermal performance from the discontinuous concrete strips.

These results further emphasise that the concrete supporting strips of the discontinuously supported system do not have any notable impact on its thermal performance.

The absolute heat gain reduction by this system has to be found by a separate study by comparing the ambient temperatures and the temperature inside the room. It could not be found out with these set of temperatures as the thermal mass is small in this case. However, it has been proven through a previous study that the system by Halwatura and Jayasinghe has a heat gain reduction of 75% [41]. According to the above figures, it is evident that the new system performs better than the Halwatura and Jayasinghe system in thermal aspects. Hence, it can be deduced that the novel roof slab insulation system has a heat gain reduction of more than 75%.

4.2. Thermal performance comparison with an insulated Calicut tiled roof

As described in Section 3.2 the thermal performance with ordinary Calicut tilled roof was performed using an actual scale model testing. Temperature readings were obtained with the aid of the Data Logger correspondent to the experimental methodology described in Section 3.1.

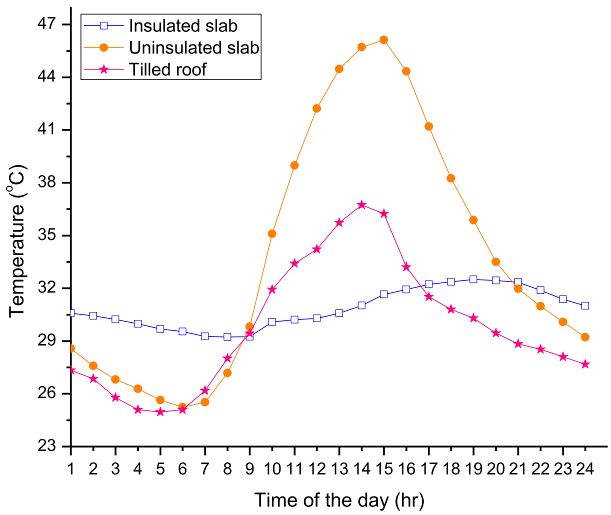

Fig. 13. Bottom surface temperatures of the insulated slab, uninsulated slab and Calicut tiled roof over a period of 24 h.

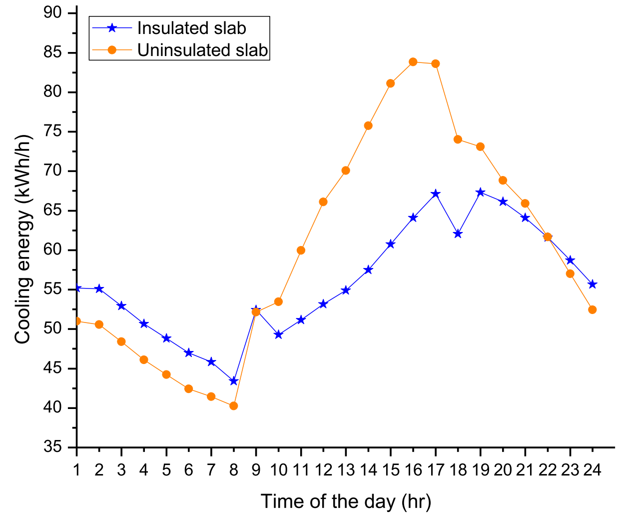

Fig. 14. Cooling energy required for insulated and uninsulated slabs over a period of 24 h.

Table 1
Slab top and soffit temperature readings, time lags and decrement factors of each roof systems.

Type of the roof	Slab top maximum temperature (°C)	Slab soffit maximum temperature (°C)	Time lag (hours)	Decrement factor
Uninsulated roof slab	54.0	46.1	2.0	0.85
Roof slab insulation system	56.0	32.5	5.0	0.58
Ordinary Calicut tilled roof	58.8	36.7	1.0	0.62

Fig. 13 shows the results obtained by the actual scale model testing. Here, a comparison between an uninsulated roof slab, an insulated roof slab which is the newly designed slab insulation system and a clay-tiled roof was obtained. According to the obtained results, the top surface temperatures were almost the same, with a slight edge to Calicut tiled roof. It was due to the lower Albedo value of Calicut tiles due to its relatively darker colour.

But there were considerable differences among the slab soffit temperature readings of considered scenarios as shown in Fig. 13. Corresponding slab top and soffit temperature readings, time lags and decrement factors of each case are as listed in Table 1.

Examining the soffit temperature readings, it can be clearly concluded that the insulated slab performs even better than a Calicut-tiled roof, which is proven to be the most popular roofing material due to the thermal comfort it provides [6]. That scenario is further verified by the least decrement factor of 0.58 correspondent to the new roof slab insulation system.

4.3. Peak cooling load reduction of the slab insulation system

As described in Section 3.3, the office building of 15 m × 15 m was used to access the peak cooling load reduction through the novel roof slab insulation system. The virtual model was simulated using "Design Builder v4" software package to find out the cooling load required to achieve neutral operating conditions on a typical sunny day. The neutrality temperature was taken to be 26 °C which was proven to be a reasonable value for tropical climatic conditions [44]. In Section 4.2 it is clearly shown that the concrete strips of discontinuously supported system do not impose and significant effect on the thermal performance of the slab system. Hence, the insulation layer was added using design Builder software neglecting the concrete strips.

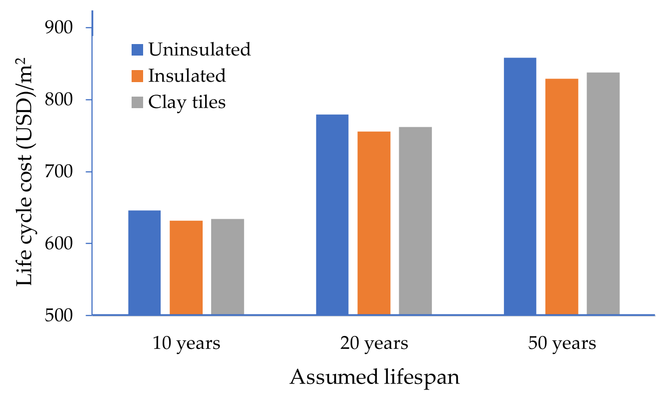

Fig. 15. Life cycle cost assessment for different lifespans assumed.

The cooling energy requirements obtained for this particular building under the conditions mentioned are shown in Fig. 14. (Further details of the virtual model were listed in Appendix A). The displayed results are for discontinuously supported insulation system (novel slab insulation system) and 125 mm thick uninsulated RCC roof slab. Even though the simulations were carried out for all the four options specified in the methodology, only the graph obtained for the discontinuously supported system was presented here since the energy requirements for each insulated systems differ by less than 1% of each other.

It is clearly evident in Fig. 14 that the peak energy requirement on a typical sunny day can be reduced by about 20% by thermal insulating. (The corresponding calculation was available in Appendix A). This clearly reduces the intensity of the working rate of air conditioning equipment required, thus the initial investment itself too.

4.4. Financial feasibility of the slab insulation system

The calculated life cycle costs under the parameters mentioned in Section 3.4, for the 125 mm thick uninsulated RCC slab, the roof slab insulation system and the clay-tiled roof with a timber ceiling and 3 mm foil insulation are depicted in Fig. 15. Here also, only the analysis performed for the discontinuous-stripped system is presented here since the three insulated systems do not differ significantly from each other.

According to the results, it is apparent that both the other options possess a less life cycle cost than the uninsulated slab for all the options of lifespans considered. Quantitatively, it is apparent that about 5% life cycle cost saving can be achieved by insulating the slab. This, in fact, is the lower bound of the saving since the reduction in initial cost by insulation was not considered in the analysis.

The insulated slab performed even better than the clay-tiled roof, even without taking the land recovery into account. Hence, it is obvious that the system is economically feasible for a lifespan of more than 10 years, which is the practically the lower bound to be considered for a building.

5. Conclusions

It had been proven in the literature that a system developed by laying an insulation layer on top of a roof slab and covered by a thin protective screed provides a significant heat gain reduction through the roof. Further, a discontinuous supporting arrangement had provided a performance boost in terms of structural and durability aspects. This study focused on the thermal aspects of this insulation system.

Small-scale physical model testing proved that the effect of the supporting concrete strips to its thermal performance is negligible. Further, a comparison with literature derived that this system achieves a heat gain reduction of more than 75%.

Then, the experimental setup was extended to an actual scale model to assess the performance under real conditions. There, the system performed well and resulted in a better thermal performance than even a Calicut-tiled roof with a timber ceiling with a 3 mm-foil insulation.

A computer simulation was used to find out the energy-saving potential by this insulation technique. A 20% of peak cooling load reduction was observed on a typical sunny day in tropical climatic conditions.

Finally, a life cycle cost analysis resulted that it is possible to achieve about 5% reduction in life cycle cost through insulation in comparison with an uninsulated roof slab, even without taking the reduction of cooling equipment load requirement into account. Further, the insulated system performs better than an insulated Calicut tiled roof with a timber ceiling, even without taking the land recovery into consideration. Hence, this system was proven to be economically feasible for any practical lifespan of a building. Based on the results of the study, the ultimatum is the proposed slab insulation system can be effectively used in tropical climates as a passive cooling remedy to the existing adverse temperature effects.

And also, the contemporary roof slab insulation system "heat insulation system for flat 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: 17803.

Declaration of Competing Interest

All the authors thereby state that there is no conflict of interest.

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Appendix A

A.1. Details of the virtual model used for computer simulation performed using Design Builder v4

Basic details of the model	
Plan area of the building	15 m × 15 m
Number of stories	Three
Basic location	Moratuwa, Sri Lanka
Latitude	6.79° N
Longitude	79.9° E
Altitude	30 m
Wind exposure	Normal
Nearest weather station	Ratmalana, Sri Lanka
Activity details of the model	
Type of the building	Office 24/7
Occupation rate	0.1/m^2
Metabolic rate	Corresponds to light office work
Energy generation by equipment	10 W/m^2
Construction details	
The thickness of the walls	225 mm
Walling material	Engineering bricks
Structural slab thickness (insulation system)	100 mm
Protective screed thickness (insulation system)	40 mm
Structural slab thickness (uninsulated slab)	125 mm
Percentage of openings in E-W direction	0%
Percentage of openings in N-S direction	30%
Thermal properties of construction materials	
"U" value of concrete blocks	0.51 W/mK
"U" value of concrete	1.70 W/mK
HVAC details of the model	
Neutrality temperature	26 °C
Coefficient of performance (COP)	2.0
Supply humidity ratio	0.008

A.2. Peak cooling load reduction calculation

Peak cooling load from roof slab insulation system = 67.32 W

Peak cooling load from uninsulated RCC slab = 83.82 W

Peak cooling load reduction of the roof slab insulation system $= \{1 - (\frac{67.3199}{83.8256})\} \times 100\% \ = 19.69\% \approx 20\%$

A.3. Essential details related to cost calculation

It was considered that 1 USD = 160 LKR (Sri Lankan Rupees)

The rates were reasonable market rates by 2018

Initial cost

In general, the construction cost of Rs. 45,000/ per m^2 was considered in the analysis per the expert judgements related to the field of building construction.

The cost of 40 mm protective screed and discontinuous strips of the insulated slab was separately calculated considering the cost of Rs. 4050/ per m^2

The uncommon cost values (although there was a sloping roof in one model, it was not common for the other two models) for considered three scenarios were calculated according to the standard BSR values.

Cost of insulation

The rate of polystyrene was taken to be Rs. 900/ per m^2

The rate of 3 mm thick foil insulation (used in clay tiled roof) was taken to be Rs. 130/ per m^2.

Cost of electricity

Electricity cost was calculated according to the 2018 CEB rates (Ceylon Electricity Board). They are as listed in Table A1.

Table A1
Electricity charges in Sri Lanka (source; www.ceb.lk/commercial-tarif).

Monthly electricity consumption (kWh)	Unit Charge (Rs/Kwh)	Fixed service charge (Rs)
61–90	10.00	90.00
91–120	27.25	450.00
121–180	32.00	450.00
> 180	45.00	540.00

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