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D. P. P. Meddage
University of Moratuwa

M.T.R. Jayasinghe
University of Moratuwa

Upaka Rathnayake
Sri Lanka Institute of Information Technology

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D.P.P. Meddage [a,*], Aaron Chadee [b], M.T.R. Jayasinghe [a], Upaka Rathnayake [b]

[a] *Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka*
[b] *Department of Civil Engineering, Sri Lanka Institute of Information Technology, Sri Lanka*

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ABSTRACT

Heat transfer through roof slabs significantly increases the operational energy consumption of buildings. Therefore, passive implementations are necessary to improve the thermal performance of roof slabs in tropical climates. This paper presents a novel roof slab insulation using expanded polystyrene (EPS) based lightweight concrete panels. The workflow consists of field experiments and numerical simulations performed in Design Builder. Moreover, we offered a holistic life-cycle approach to investigate the economic and environmental feasibility of alternate forms. Accordingly, the roof slab with 75 mm EPS insulation and a white exposed surface performed satisfactorily. Corresponding decrease in life cycle cost, carbon emission (kgCO_2e), and operational energy consumption were 8.3%, 20%, and 41%, respectively. The overall eco-efficiency index (EEI) implies that the recommended insulation system is environmentally and economically feasible under tropical climatic conditions. Further, manufacturing EPS concrete is eco-friendly since it reduces EPS waste content which does not decay through natural means.

1. Introduction

Land scarcity and over-exploitation of natural energy sources are becoming more critical with population growth [1]. Massive demand in the energy sector will lead the world towards a crisis in the near future [2–5]. The world is further moving to construction to cater not only to development projects but also for day-to-day activities. Remarkably, the building sector accounts for around 40% of the world's energy demand [6]. Fossil fuel (still the primary energy source of the world) is becoming a scarce resource as a consequence of unstoppable demand [7], creating difficulties for the future construction industry. Reducing energy demand for buildings and constructions, therefore, will make a critical impact on these issues in near future.

On the other hand, because of land scarcity, vertical developments are promoted for residential buildings [8]. In consequence, low-rise apartment housing units are becoming prevalent in the local context (in Sri Lanka) compared to conventional housing units in urban areas. These apartments are often provided with typical roof slabs due to several reasons. On one hand, such roof configuration resists cyclonic wind damage with respect to conventional roofing systems (e.g: asbestos sheeting, roof cladding). Alternatively, it provides additional space to be utilized as a floor or a roof garden.

Despite the advantages mentioned earlier, concrete roof slabs have a major problem with their thermal performance [9]. Especially in tropical climates, direct exposure to sunlight can transmit solar radiation toward the intrinsic environment, making microclimate unfavorable. This effect is worse in the daytime [10]. Related studies have reported that roof component contributes up to 70% of total

* Corresponding author.
E-mail address: meddagedpp.20@uom.lk (D.P.P. Meddage).

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heat gain toward buildings [11–13]. Hence, conditioned spaces are preferred by the community to maintain required thermal comfort mostly during the daytime.

Air-conditioners heavily contribute to increasing operational energy demand and emit greenhouse gases [14,15]. For example, 20% of the energy demand of buildings is utilized to maintain intrinsic thermal comfort [16]. Ürge-Vorsatz et a.l [17] reported that heating and cooling accounts for (18–73%) of total building energy usage around the globe [17]. Therefore, alternative approaches are encouraged to decrease operational energy usage.

Kolokotsa et. al. [18] investigated that cool roofs contribute to a 17% decrease in annual cooling energy demand. Cool roofs are designed to reflect more solar radiation compared to a traditional roof. Generally, cool roofs are provided with white or light colors to increase thermal emittance. In addition, Parker et. al [19] confirmed that cool reflective coating on a roof can save electricity by an average of 19%. Cool roofs have been explored under different climate conditions due to their superior performance over traditional roofs [20–25]. Akbari et al. [25] conducted a study on the effect of cool roofs in California, USA. They obtained an energy-saving between 22% and 54% as a result of a cool roof. A similar study was conducted in Italy which showcased an energy-saving of 15–44% due to cool roofs [26]. Lapisa et al. [27] introduced a cool roof system in Singapore (tropical climate) and claimed a 51% energy saving compared to conventional roofs. Alvarado et. al [28] have developed a hybrid roof slab insulation that consists of insulators and reflectors. The combined slab system exhibited a decrease in heat conductance from 65% to 88% in contrast to the prototype without insulation. Rawat and Singh [12] concluded that the highest energy saving due to cool roofs is observed in tropical climates.

Providing a green cover (e.g. grass) over the roof slab is another method of utilizing roof space as a thermal barrier. For instance, grass acts as a capacitive insulator, consequently, reducing the peak thermal load [29]. Even in highly populated cities, a green roof is a pragmatic alternative [30–34]. Lower layers of a green roof provide additional benefits in stormwater such as delaying the peak runoff during precipitation. Nevertheless, its highly sensitive nature (e.g to different climates) makes its performance more complicated [35].

In tropical zones, few studies have been conducted to improve the thermal performance of roof slabs [8,36–42]. Such countries receive a large amount of solar radiation during the daytime. Zingre et al., [43] proposed a cool roof slab in tropical climates. It achieved a 53% reduction in peak heat gain, decreasing the peak indoor temperature by 2.4 °C. Zingre et al. [44] conducted a similar study by using cool roof and green roof concepts for concrete slabs in the tropics. The roof slab with a cool coating showcased an early net heat reduction of 90% which was then gradually reduced up to 59–63% with its age. The proposed green roof (with 0.1 m soil layer) acquired a net heat reduction of 32–41% whereas the roof slab with extruded polystyrene (50 mm) resulted in 62–72% of net heat reduction. Halwatura and Jayasinghe [34,35] developed an insulated slab system using polystyrene insulation. However, the long-term performance of the slab system was not up to an adequate level as water patches were observed. Nandapala and Halwatura [38] extended the experiment by providing discontinuous strip support to reduce the fraction of concrete in the insulation layer. Results showed a decrease in thermal conductivity and a trivial impact on structural integrity. Though, both these systems require pure polystyrene insulation whereas the process of manufacturing polystyrene is associated with crude oil extraction, leading to greenhouse emissions [39]. Recently, Nandapala et. al [41] examined the performance of hybrid insulation systems using bamboo, polystyrene, and vegetation. Interestingly, the system with bamboo and vegetation has shown good performance compared to the remaining models. However, involving vegetation in the insulation system has a major drawback because of regular maintenance.

Considering the drawbacks of previous insulation slab systems, we intended to develop an insulated roof slab system using expanded polystyrene (EPS) lightweight concrete panels. Polystyrene beads are locally available as waste material. Many industrial products are packed inside polystyrene and it absorbs the shocks and has a lower thermal conductivity. These packing wastes can be collected and used to produce EPS-based concrete panels. It is an effective way to dispose of a non-biodegradable EPS, avoiding open dumping [8]. Section 02 provides an overview of EPS concrete panels.

Furthermore, previous studies failed to assess the performance of insulated slabs considering both economic and environmental feasibility. The life cycle concept can be applied for such cases when lifetime impact is considered [45]. This approach is widely used by the research community to explore energy consumption, performance, and impacts of a product or service during its lifespan [46]. According to the authors' best knowledge, the present study is significant as it engages both economic and environmental aspects to examine the feasibility of roof slab insulation. Also, we studied a cool-roof combined with insulation for the first time in Sri Lanka. Further, it is timely important to recommend a suitable roof slab insulation for tropical climates. This paper interprets the eco-efficiency index that combines both life cycle cost and assessment in order to compare the overall feasibility of proposed insulation.

The main objective of this research is to investigate the performance of EPS-based concrete panels as roof slab insulation in tropical climates. The main objective can be further divided into the following sub-objectives: (a) to investigate the thermal performance of roof slabs combined with EPS concrete panels as insulation in tropical climatic conditions (experimental program); (b) to enhance the performance of the proposed insulated slab system in order to reduce the operational energy demand (energy modeling); (c) to assess economic and environmental feasibility of novel insulation system (life cycle approach); and (d) to evaluate the generic structural performance of the novel system.

Hence, the authors strongly believe that this work is greatly important for tropical countries to improve cost-effectiveness, environmental feasibility, and performance of insulated roof slabs throughout the life span with minimized adverse impacts. Moreover, the study assists the research community in decision making whereas appropriate insulation must be selected based on a holistic approach. On the other hand, the proposed work is highly relatable for federal and municipal decision-makers to develop a framework related to the energy efficiency of the residential housing sector considering the life cycle view.

In order to showcase the outcome of the research work, the paper is structured as follows. Sections 2 and 3 describe the materials and life cycle approach engaged in this study, respectively. Section 4 explains the proposed workflow of this research. Subsequently, results have been interpreted in Section 5. Finally, Section 6 concludes the paper.

2. EPS concrete panels

EPS concrete panels are manufactured by replacing coarse aggregate of conventional concrete using EPS beads [47] (refer to Fig. 1). Many researchers have reported the advantages of EPS concrete over traditional materials [44–49]. Lightweight, low chloride permeability, and non-absorbant and hydrophobic nature hold a relative significance among such characteristics [50–58]. Properties of EPS concrete reported in the literature are summarized in Table 1.

Besides, cement fiber sheets provide a better-finished surface as well. Cement fiber boards are available in 6 mm and 8 mm thicknesses. It consists of ordinary portland cement, fine silica, quartz, fly-ash, and mineral additives. These sheets are manufactured according to IS 14682 specifications [63]. EPS concrete panels are locally available at 75 mm, 100 mm, and 150 mm thicknesses. The standard height and width of a full panel are 2400 mm and 600 mm thick respectively. Lightweight nature was achieved using the mixed proportion stated in Table 2.

Nonetheless, cement-fiber sheets govern the cost of EPS concrete panels. Therefore, we suggest EPS panels without cement fiber sheets (Type II) as insulation material.

3. Life cycle approach

The life cycle approach can be defined as cradle to grave analysis of a service or product [45]. It consists of different stages (e.g. production, construction, utilization, end-of-life, and re-using /recycling) as system boundaries. This approach is separated in terms of economic and environmental aspects that are described in the latter subsections.

3.1. Life cycle cost (LCC)

Life cycle cost (LCC) is an appraisal that evaluates economic performance at several stages of a building [64]. Instead, LCC can be used to compare distinct alternatives based on their respective investments [65–69]. Therefore, this approach is more reliable than comparing the costs of each material or product. LCC considers a specific period to carry out the economic assessment. For the analysis, depreciation was considered to be taken place in terms of inflation rate, design life, discount rate, analysis period, and cost incurred at different stages. Eq. (1) expresses the formulae to evaluate LCC.

$$\text{LCC} = \text{Capital cost} + \text{Cost for usage} + \text{Cost at End-of-life} - \text{Salvage value} \tag{1}$$

The 1st term includes costs of production, transportation, and construction [70] whereas the 2nd term consists of costs of maintenance and operations. Compared to the remaining terms, the 2nd term is dominant since it claims a considerable proportion from LCC. The 3rd term evaluates demolition and disposing costs [69], and the last term of the equation represents the recoverable amount after the design life of the building [71,72]. Several indices are available to interpret LCC. Those are net present value (NPV), net saving (NS), payback period, internal rate of return (IRR), and equivalent annual cost (EAC). Related work confirms that NPV is more often used for LCC analysis [73].

3.2. Life cycle assessment (LCA)

Life cycle assessment (LCA) measures the potential impacts of a product/process on the environment. LCA considers a system throughout its life span. The life span consists of (a) construction stage (material extraction, transportation, handling, and processing), (b) operational stage (intended usage), and (c) disposal stage (end-of-life). LCA needs several major components. First, the goal and scopes of the analysis should be defined. Next, the function unit and system boundaries shall be emphasized. Subsequently, the

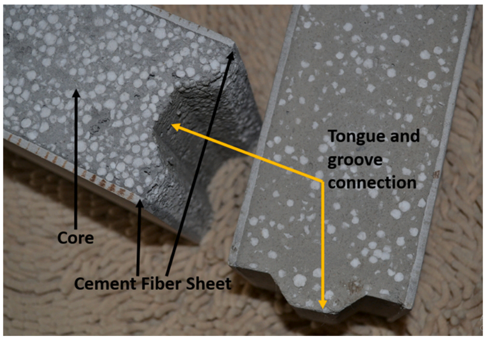


Fig. 1. EPS concrete panels (with cement fiber sheet).
Source: Google images

Table 1
Summary of related work on EPS concrete.

Study on:	*Remarks*	*Reference*
Thermal conductivity	Concrete with 28% and 82% EPS content retained a thermal conductivity of 0.212 and 0.0848 W/mK, respectively	[52,54]
Density	(550 – 2200) kg/m^3	[55]
	(1200–2300) kg/m^3	[54–56]
Compressive strength	10.2–21.4 MPa	[48]
	11–50 Mpa	[54–56]
Density and Compressive strength	The size of EPS particles strongly influences the characteristics of EPS concrete such as density, and compressive strength	[59]
Effect of fly-ash	Improves the workability of the mixture	[60]
Effect of fly-ash	Fly-ash can lower the embodied energy of EPS concrete from 4.5 MJ/kg to 0.1 MJ/kg	[61]
Compressive strength	2.89 Mpa for panels with cement fiber sheets (Type I)	[47]
	1.69 Mpa for panels without cement fiber sheets (Type II)	
Flexural strength	1.64 Mpa for panels with cement fiber sheets (Type I)	[47]
	0.31 Mpa for panels without cement fiber sheets (Type II)	
Fire performance	Mix design with 400 kgm^{-3} density can withstand a fire for three hours	[62]

Table 2
Mix proportion of EPS based light-weight concrete;.

Materials	*Content (kg/m^3)*	*By weight (%)*
Cement	380	42
Sand	136	15
Water	282	31
EPS	22	2
Fly ash	98	11

Source: [47]

inventory analysis can reflect all data related to inputs, processes, emissions, etc, considering the entire life cycle. Next, the inputs and environmental impacts are estimated in terms of inventory analysis. Finally, the results can be interpreted which highlights the impact on the end-point indicator.

3.2.1. Goal and scope

The research aims to perform an LCA for the NERD roof slab system of housing sectors with and without the novel insulation in tropical climates.

3.2.2. Functional unit

The scope of LCA shall emphasize the performance characteristics of the research. ISO standards are often followed when conducting an LCA. Certain tools are available to assist in conducting LCA [45,74]. According to ISO 14044 [70], the functional unit shall be consistent with the objective of the system. Therefore, we considered the roof area (plan area of the building) as the functional unit that highlights the effect of insulation. The assumed lifetime of 50 years is consistent with many related studies [75].

3.2.3. System boundaries

The research accounts for the following boundaries. **Initial stage**: material acquisition, transportation of materials, **Construction stage**: transportation to site, handling and assembling, and the energy used during the construction work. For this, the study done by Dissanayake et al. [76] mostly used in which they conducted an embodied energy analysis of a house constructed using EPS concrete panels. **Operation stage**: building operation related to cooling, and **End-of-life stage**: demolishing and disposal.

3.2.4. Inventory analysis

In this component, the quantification of inputs and outputs of the product was carried out by considering the life span. Useful data can be extracted from existing inventories according to the scope of the study. For this study, a broader LCA is expected as we consider both initial, construction, end-of-life, and operational stages. For the interpretations, the amount and the type of energy source we used are also crucial.

It should be noteworthy that our LCA is input-output based which considers a wider system boundary compared to a process-based LCA.

As highlighted in the introduction, the consequences of building energy consumption have noticeably affected the environment. In such cases, LCA provides impacts of possible alternatives and strategies to minimize the harm. $LCCO_2A$ which is a subset of LCA has become more popular in this decision-making process which considered only CO_2 emissions of a product [77,78]. The same approach is referred to as "carbon footprint analysis". $LCCO_2A$ is particularly employed in the building sector to assess the effect on the environment over the lifespan. However, Fenner et al. [77] pointed out it's often difficult to compare related work as those consider distinct scopes, boundaries, and methodologies. The increasing trend of global warming stresses the importance of life cycle assessment in terms of CO_2. Therefore, the authors followed the same approach in order to conduct our LCA by considering CO_2 emissions.

3.3. Eco-efficiency (EE)

Eco-efficiency (EE) combines LCC and LCA [73]. The maximum EE can be obtained when both costs and impacts are inferior [74]. The insulation system is proposed to be ranked in terms of eco-efficiency defined by Eq. (2). Thus, the unit-less eco-efficiency index (EEI) interprets environmentally and economically feasible alternatives.

$$EEI = \frac{LCC}{LCA} \tag{2}$$

4. Methodology

The workflow of the study is depicted in Fig. 2. The workflow was divided into four main phases.

4.1. Small-scale physical modeling of novel roof slab with EPS insulation

Foremost, the traditional roof slab system was altered using the (National Engineering Research and Development) NERD slab system. The NERD slab consists of a 60 mm reinforced concrete slab which was supported by precast pre-stressed NERD beams at (0.4–0.6) m spacing. Sanjaya et. al [79] stated the benefits of NERD slab over conventional reinforced slab system. For instance, it is 35% more cost-effective than a conventional slab system and reduces vertical stresses at the base level. Furthermore, it allows fast construction. Nevertheless, thin concretes fail to provide occupant thermal comfort as a result of higher thermal conductivity. Therefore, we advocated providing EPS panels on the NERD slab as insulation. It was used upon the existing slab with a protective screed to enhance thermal performance (refer to Fig. 3b). Three physical models were constructed (refer to Fig. 3a) by changing the insulation thickness (75 mm, 100 mm, and 150 mm).

A cement block of 0.6 m, was cast up to the beam soffit level and the gap between beam soffit and slab soffit was closed, leaving a sufficient gap to facilitate air movement. The NERD slab (60 mm) was placed on top of NERD beams. Later, insulation panels and the protective screed (60 mm) were laid, respectively. Insulation panels should be split to have at least 50 mm void between each panel (refer to Fig. 3c). The reason is to provide good support between the protective screed and the NERD slab. However, the effect of concrete strips will cause a decrease in thermal conductivity. Progelhof et al. [80] introduced a relationship to compensate for the effect of concrete fraction inside the insulation layer as shown in Eq. (3).

$$\frac{1}{\lambda_I} = \frac{(1-\alpha)}{\lambda_P} + \frac{\alpha}{\lambda_C} \tag{3}$$

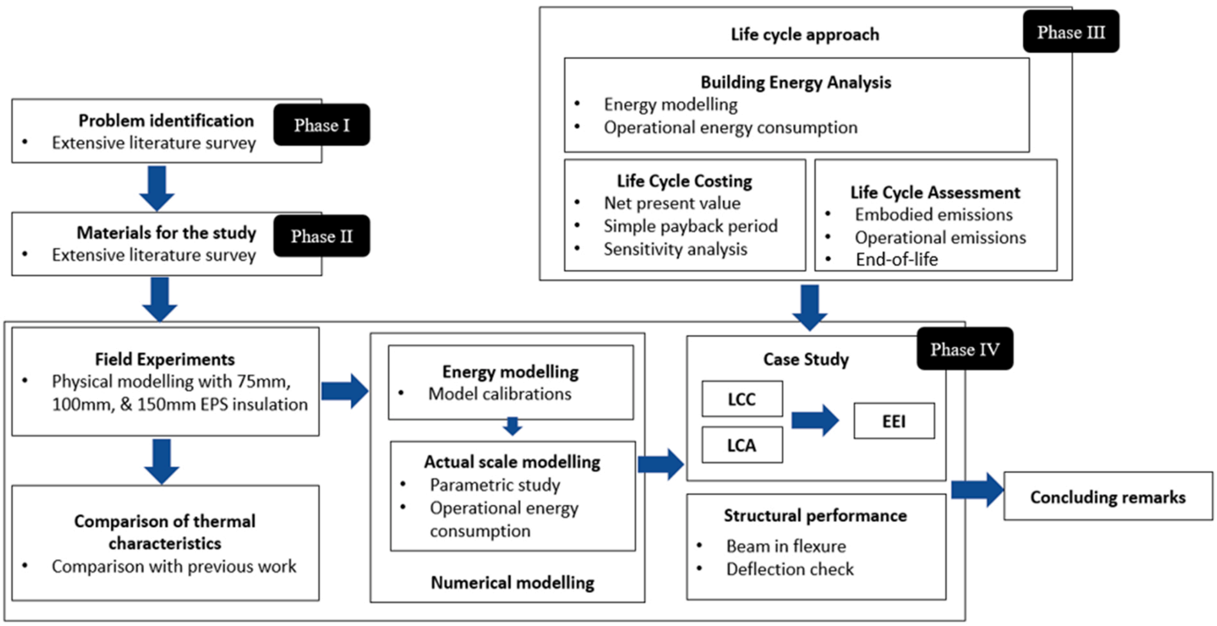
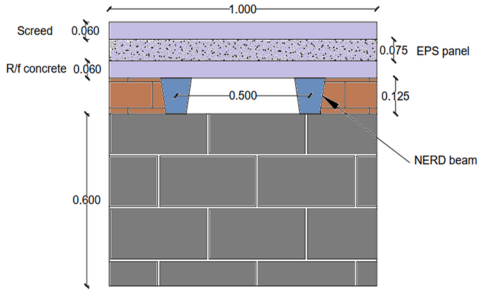


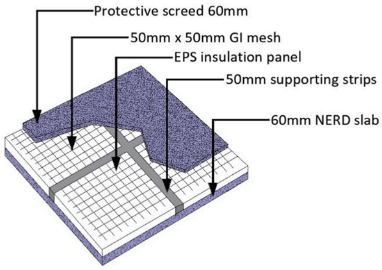
Fig. 2. Proposed work-flow of the study.

(a) Constructred physical models



(b) Section diagram of the model with 75 mm insulation

(c) 50 mm gap between insulation panels



(d) Schematic diagram of insulated slab system

Fig. 3. Proposed insulated slab system and its components.

Where λ_P, λ_I, λ_C, and α denote the thermal conductivity of insulation, the modified thermal conductivity of insulation, the thermal conductivity of concrete, and the fraction of concrete in the insulating layer, respectively.

Later, the effect of the insulated slab was investigated using type K thermocouples. These thermocouples are commercially available, having a wide range (−200 °C to + 1200 °C) of temperature recording with a 41 $\mu V°C^{-1}$ sensitivity. Thermocouples were connected to the top of the screed and the bottom of the NERD slab. Temperature readings were directly fed into a data logger. Data acquisition was taken place continuously for a week to obtain a stable variation. A typical summer week was used for experiments. During the experiment, a proper connection should be ensured between each surface and thermocouples.

4.2. Comparison of thermal characteristics

The thermal characteristics of the novel slab system can be estimated as follows. Generally, thermal resistance (R) and thermal conductivity (U) are two of the major performance indices of an insulation system. Thermal resistance values are combined with surface resistance to obtain air-to-air resistance. Composite thermal conductivity (U_C) and air-to-air resistance (R_a) can be computed using Eqs. 4–6. Surface resistance values were obtained from Halwatura and Jayasinghe [36]. The modified thermal conductivity of the insulation layer due to the concrete fraction was calculated using Eq. (3). The calculation has been attached in Appendix D.

$$R_B = \sum\left(\frac{t_i}{\lambda_i}\right) \tag{4}$$

$$R_a = R_I + R_B + R_O \tag{5}$$

$$U_C = \frac{1}{R_a} \tag{6}$$

where t_i, λ_i, R_O, R_I, and R_B denote the thickness of i^{th} layer, the thermal conductivity of i^{th} layer, surface (roof) resistance, surface (ceiling downward) resistance, and thermal resistance of the body, respectively.

4.3. Numerical simulations

All numerical simulations were performed using Design Builder: Version 4.5.0.148. This software is widely used for energy simulations and to compare the function and performance of buildings. It consists of sophisticated design options at each stage of construction.

Foremost, field models were simulated in the software to calibrate design parameters. Subsequently, the model calibration was performed and calibrated parameters (refer to Appendix A) were used for the actual-scale office building. All simulations were performed for 48 h on the same summer week in which experiments were carried out. Exact site conditions are required for modeling to reproduce reliable results. Climate data were obtained from the Rathmalana weather station.

An actual scale office building, having a floor area of 225 m^2 was selected for this work. The same configuration had been selected by Nandapala et. al [41] to perform energy modeling. Hence, we explicitly intend to extend the comparison of results. The three-story office building model is depicted in Fig. 4. External walls were modeled using conventional cement-sand blocks with plaster. Windows were provided only in the north-south direction since the east-west direction can have adverse effects, especially in day time due to direct solar radiation.

4.4. Life cycle approach

4.4.1. Life cycle cost (LCC)

The financial feasibility of the novel slab was assessed using discounted cash flow method. Capital costs and maintenance costs are in accordance with current Sri Lankan rates (refer to Appendix B). Here, Eqs. (7) and (8) were used to calculate the net present value of cost over the life span and corresponding payback period, respectively. F represents the future value of the payment and r is the discounted rate. The letter 'n' denotes the number of years. For the LCC analysis, energy consumption (cooling load) was obtained from energy simulations. The authors highlight that salvage values were not considered and the demolition will be carried out free of charge.

$$Net \quad Present \quad Value \quad (NPV) = \sum_{i=1}^{n} \frac{F_i}{(1+r)^i} \tag{7}$$

$$Simple \quad Payback \quad Period = \frac{Change \quad in \quad capital \quad cost}{Change \quad in \quad cost \quad for \quad operational \quad energy} \tag{8}$$

4.4.2. Life cycle assessment

For LCA, data from the inventory of carbon and energy (ICE) [81] were used. In addition, several values were obtained from related work from Dissanayake et al. [76], Huang and Chen [82], and Nadeeshani et al. [83]. Dissanayaka et. al [76] reported that embodied energy can be presented in terms of equivalent CO_2 emission. Similarly, grid electricity emissions can be denoted in terms of $kgCO_2$ per kWh (0.71 $kgCO_2e$ per 1 kWh) [73]. Emissions that occur during maintenance and end-of-life must be considered too.

It is noteworthy that the study did not use the entire building as a model in order to perform LCA. Instead, we considered the effect of having /not having an insulated slab system. Since this is a comparative study, it's rational to assume that the impact of the whole building is comparable for each case (with or without insulation). Ultimately, we estimate the eco-efficiency of the insulated slab system with respect to the conventional slab system. Table 3 shows the carbon coefficients of raw materials which were reported in previous work.

4.5. General structural performance

The general structural performance was computed using changes in system recommendations. For example, for a given beam spacing, the corresponding maximum allowed span of the NERD beam has been already specified. Because loads are increased for the novel system, the maximum span of the beam will be reduced. Therefore, the reduction in nominal span was calculated with respect to the original spacing.

Since the beam is a pre-stressed precast trapezoidal beam (refer to Appendix C for design parameters), BS 8110 [85] specifications were followed for calculations, assuming it as a Class 2 section. For the pre-stress NERD beam, the weight of the structural (NERD) slab,

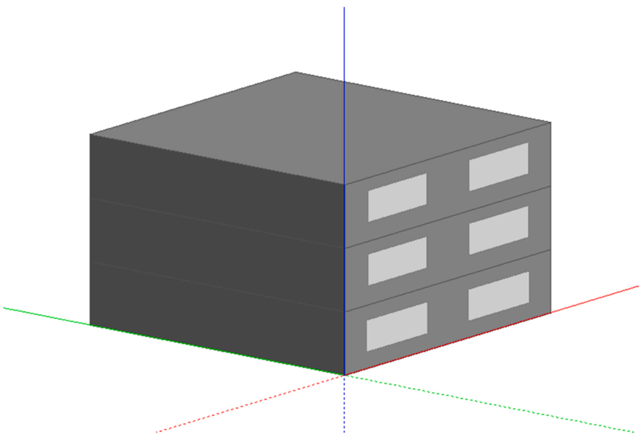


Fig. 4. Three storey office building (15 m × 15 m).

Table 3
Carbon coefficients reported in related work.

Material	*kgCO₂/ kg*	*Reference*
Cement	0.73	[76]
Sand	0.0048	
Fly ash	0.004	[84]
EPS (virgin)	2.55	[76]
Steel	1.37	
Paints	2.42	

the weight of EPS insulation, and the weight of the protective screed were considered uniformly distributed loads. Besides, the self-weight of the beam was also considered. A live load of 2.5 kN/m^2 was assumed for the roof slab, considering the possibility of utilizing it as an additional floor.

Moreover, the long-term deflection of the beam was compared, assuming an allowable deflection of L/360 (L = span of the beam). For the calculation, simply supported conditions are valid.

5. Results and discussion

5.1. Performance of insulated NERD slab

Fig. 5 depicts diurnal temperature fluctuations for the novel insulated slab system. The maximum slab soffit temperature reached 38.4 °C whereas the topmost surface recorded a maximum of 55 °C. Respectively, 100 mm and 150 mm EPS insulation shows a maximum soffit temperature of 36.4 °C and 33.1 °C. However, the reduction in soffit temperature was not as anticipated for 100 mm and 150 mm insulation. For example, after providing 150 mm insulation instead of 75 mm, the maximum soffit temperature reduction was 14%. On the other hand, due to excess weight, 100 mm and 150 mm EPS panels couldn't be handled easily compared to 75 mm thick panels. Therefore, the experiment was focused on 75 mm thick panels to proceed with energy modeling and remaining analysis. Even if 75 mm insulation is provided, the slab soffit is fairly warm, especially in the daytime. Thereby, this system demanded an improvement to be effectively utilized in warm climates. During the field experiment, a model without insulation was not constructed, whereas it was performed during energy modeling on a real scale.

5.2. Comparison of thermal characteristics

Table 4 shows the thermal conductance of roof systems with and without insulation. Evidently, vegetation provides better characteristics for tropical climates. However, Nandapala and Halwatura [41] stated the maintenance cost of insulation with vegetation. Accordingly, the novel system appeared the most appropriate under tropical climatic conditions. Interestingly, the thermal conductance of conventional NERD slab has decreased by 62% just from insulation. Moreover, the thermal conductance of EPS insulation is 29% lower than the corresponding value of the bamboo insulation system.

5.3. Energy simulations

Heretofore, the slab did not operate adequately in the tropical environment. Therefore, modifications were expected to enhance the thermal performance of the novel system. The authors proposed to investigate the modification of the novel insulated slab system on a real scale using energy modeling. However, proper calibration is important prior to parametric modeling.

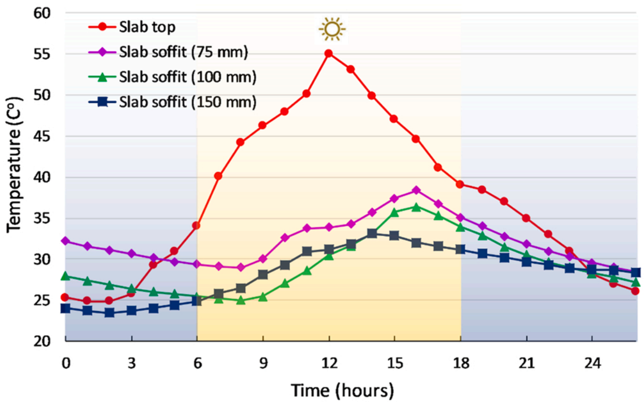


Fig. 5. Diurnal temperature variation of insulated slab.

Table 4
Thermal conductance values obtained from research carried out in a local context for roof slabs.

Reference	*Insulation*	*U_C value ($Wm^{-2}K^{-1}$)*
Halwatura and Jayasinghe [34]	Polystyrene	1.1
Nandapala and Halwatura [38]	Polystyrene	1.0
Nandapala and Halwatura [41]	No insulation	4.68
	Polystyrene	1.03
	Bamboo	2.48
	Vegetation	0.98
	Vegetation + Polystyrene	0.56
	Vegetation + Bamboo	0.82
Present study	No insulation	4.65
	EPS concrete panel	1.75

Fig. 6 shows simulated results extracted from 48 consecutive hours. Since the slab soffit was fairly warm with 75 mm insulation, low-absorptive color was applied on the exposed surface, involving a cool-roofing concept. Low-absorptive colors provide a phase to reflect solar radiation while maintaining the exposed surface at a lower temperature [82–84]. However, using the roof slab during the daytime would be difficult due to reflected heat.

For modeling the purpose, we specified the following test cases.

- Case A: NERD slab without any insulation
- Case B: NERD slab with EPS 75 mm insulation
- Case C: NERD slab with EPS insulation + white color on the exposed roof surface

Table 5 summarizes the proposed modeling scenarios. It elucidates that on a real scale, Case A will attain a decrement factor of 0.94. The decrement factor is defined as the maximum temperature of the slab-soffit divided by the maximum temperature of the exposed surface. Therefore, such a higher value (0.94) should be reduced particularly in tropical climates due to the potential of absorbing excessive solar radiation. Plausibly, EPS insulation alone could decrease the soffit temperature up to 37.6 °C and it is comparable with observed results in the field experiment (38.4 °C).

Later, the appropriate modification was to reduce absorbed solar radiation by reflecting. The applied white paint on the surface would result in an absorptance coefficient between 0.2 and 0.35. Surprisingly, the maximum temperature of the exposed surface of the slab has reduced to 42.6 °C, showing a 22% reduction in contrast to Case A. Accordingly, the corresponding maximum value of slab soffit has decreased from 37.6 °C to 35.4 °C. From evening (18.00–08.00 h), the soffit temperature was lower than the exposed surface, where it is prudent to assume that heat transmittance direction is reversed.

Table 5 showcases a substantial effect on this slab system after providing EPS insulation. For instance, Case A transfers a massive amount of solar radiation toward occupants, making microclimatic conditions unfavorable. Moreover, it will be a major reason to accelerate the utilization of operational energy during the daytime. With only 75 mm insulation, the maximum temperature of slab-soffit decreased from 51.6 °C to 37.6 °C, providing a time lag of 6 h. Later it could be brought down to 35.4 °C as a result of the passive modification (cool roof). Overall, this provides a valuable insight to reconsider the potential of thin concretes to form heated envelopes. In urban environmental conditions, these heated envelopes can form urban heat islands. Such heat islands are capable of increasing the surrounding temperature drastically, despite the energy consumption.

The use of passive modifications can be rationalized by thermal conductivity values of pure polystyrene (0.038 $Wm^{-1}K^{-1}$) [89] and EPS concrete (0.214 $Wm^{-1}K^{-1}$). For instance, the concrete fraction of EPS concrete has a considerable effect on the overall thermal conductivity value. Together with passive modification (Case C), the insulated slab performs well under tropical climatic conditions. The maximum soffit temperature is now lower than the human body temperature. Therefore, it is rational to assume heat transfer occurs from occupants toward the slab [36]. Thereafter, it acquires a decrement factor of 0.63 and a time lag of 6 h. Fig. 7 depicts the

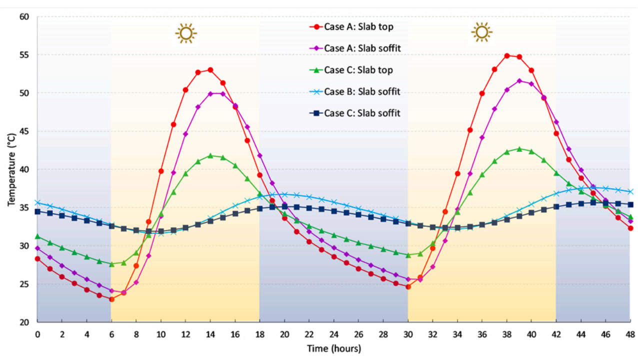


Fig. 6. Diurnal temperature variation obtained from energy modeling.

Table 5
Summary of energy simulations.

Case	*Maximum soffit temperature (°C)*	*Lag time of peak (hours)*	*Decrement factor*
A	51.6	0.5	0.94
B	37.6	6	0.69
C	35.4	6	0.63

annual energy consumption in (kWh). Accordingly, Case C has reduced annual energy consumption by 41%. In contrast, it is 27% compared to Case B.

5.4. Life cycle analysis

5.4.1. Life cycle cost

LCC was calculated for 50 years considering capital investment and cost for operational energy requirements for cooling (see Fig. 8). Evidently, Cases B and C initially show a greater capital cost due to insulation in contrast to Case A. However, as a result of the energy-saving, Cases B and C decrease their rate of increase. From year 4, the highest LCC was observed for the uninsulated NERD slab. Therefore, the effect of insulation is a long-term investment despite its capital cost. Table 6 exhibits, Case B reduces LCC by 3% and the corresponding energy saving is 20%. Likewise, Case C claims an 8.3% reduction in LCC is observed while obtaining 41% energy saving. The calculated payback period was based on the ratio of change in capital to energy savings. Thus, Case C has obtained a payback period of 2 whereas it was 3.8 years for Case B. All calculations were performed under a discount rate of 10%.

5.4.1.1. Sensitivity analysis. The authors suggested a separate analysis to examine the sensitivity of three different systems. For example, the discount rate was changed from the initial value (10%) to observe the change in NPV. Case C was less sensitive to variation in discount rate in contrast to the remaining cases. An increase in the discount rate (up to 16%) can affect a maximum of 10% change in NPV whereas a decrease in the discount rate can cause a 30% change in NPV for Case A. At a discount rate of 4%, the corresponding change in NPV is 30% for Case A, 24% for Case B, and 18% for Case C (See Fig. 9).

5.4.2. Life cycle assessment

The magnitude at end-of-life is comparatively low such that it had a negligible effect on the LCA of slab system which agreed with the latest study done by Gurupatham et al. [73]. Fenner et al. [78] also report that the operational phase is the largest share of total carbon emissions over the lifespan whereas embodies emissions hold the second-largest share. The end-of-life stage holds a considerably lower fraction, therefore, it's not considered in many studies [78]. Therefore, the total calculation mainly highlighted the operational energy consumption and the embodied emissions (during the initial and construction stage). Even the CO_2 emission during initial and construction stages is considerably lower (< 4%) than the corresponding value at the operational stage. Table 7 shows embodied energy values for each case and corresponding LCA values. Thus, it emphasizes the importance of utilizing both insulation and cool roof to improve the performance of roof slabs in tropical climates. Unsurprisingly, the maximum embodied energy emission was obtained for Case C. However, that becomes the lowest in magnitude when operational energy is considered.

5.4.3. Eco-efficiency index

EEI was calculated by the following values stated in Table 8. Since LCA and LCC values consist of different units, those were normalized to obtain unitless indices. Normalization was done by dividing all values from the corresponding Case A value. Considering the holistic life cycle approach, Case C is the feasible alternative for tropical climates. Despite its capital investment of insulated slab system, it has a payback period of approximately 2 years (refer to Table 6). Obtained EEI values are illustrated in Fig. 10. Case C and Case B provide EEI values which are respectively 52% and 18% greater than Case A, implying sustainability of passive alternatives compared to heated roof slabs in tropical climates.

5.5. General structural performance

Fig. 11 shows the reduction in span and corresponding deflection of the beam. Deflection criteria were satisfied with a considerable margin as a result of pre-stressing. The maximum deflection was obtained when beam spacing was 350 mm. Span is a governing term in deflection criteria. Therefore, when spacing reduces, the maximum allowable span increases, thus, allowing more load on the beam. However, the maximum allowable span of NERD beams has been reduced by 11% due to the excess weight of the insulation system. Given the system is now robust and heavy, bearing stresses under beams should be investigated in a separate study.

6. Conclusions

This study has addressed the importance of improving the thermal performance of roof slabs in tropical climates. We have employed EPS concrete panels without cement fiber sheets as roof insulation material for the NERD slab system.

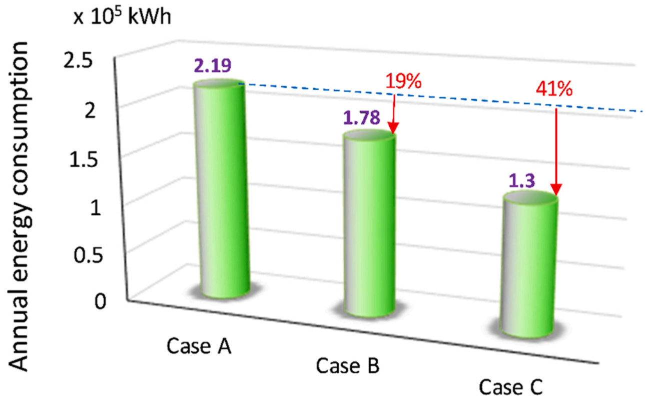


Fig. 7. Annual energy consumption of office building for cooling (kWh).

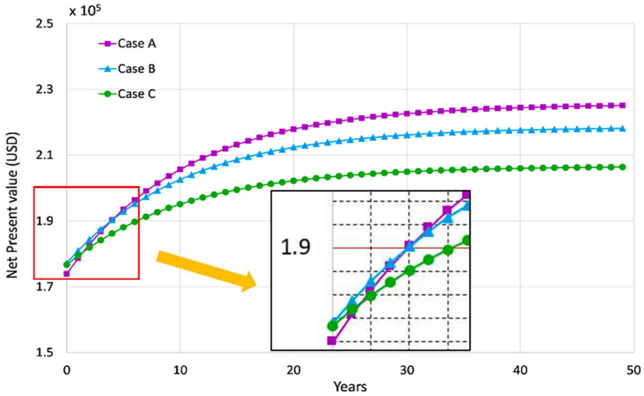


Fig. 8. Evaluated LCC (for 50 years) for three distinct cases.

Table 6
Casewise comparison of LCC indices.

Case	*Annual energy saving*	*Change in life cycle cost*	*Simple payback period (Years)*
A	N/A	N/A	N/A
B	20%	3%	3.8
C	41%	8.3%	2

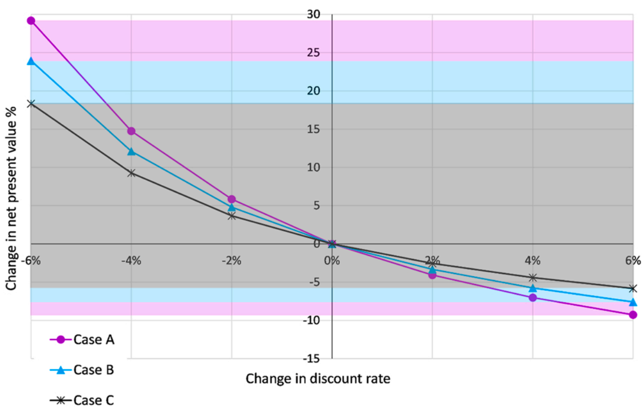


Fig. 9. Summary of sensitivity analysis for NPV.

Table 7
Summary of LCA of three cases.

	Case A	*Case B*	*Case C*
Embodied emission of slab system in $kgCO_2$ e	163,489	171,277	172,877
Energy consumption for 50 years in kWh	10,950,000	8,900,000	6,500,000
Embodied energy due to operational energy in $kgCO_2$ e	7,774,500	6,319,000	4,615,000
LCA (Total $kgCO_2$ e)	7,937,989	6,490,277	4,787,877

Table 8
Eco-efficiency index for each case.

	Case A	*Case B*	*Case C*
LCA (Total $kgCO_2$ e)	7,937,989	6,490,277	4,787,877
Normalized LCA (Using Case A)	1	0.82	0.6
LCC for 50 years (USD)	225,079	219,584	207,831
Normalized LCC	1	0.97	0.91
EEI (LCC/LCA)	1	1.18	1.52

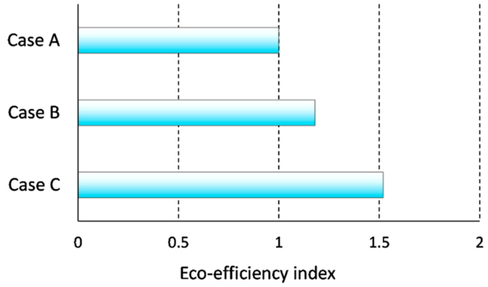


Fig. 10. Overall comparison of eco-efficiency index.

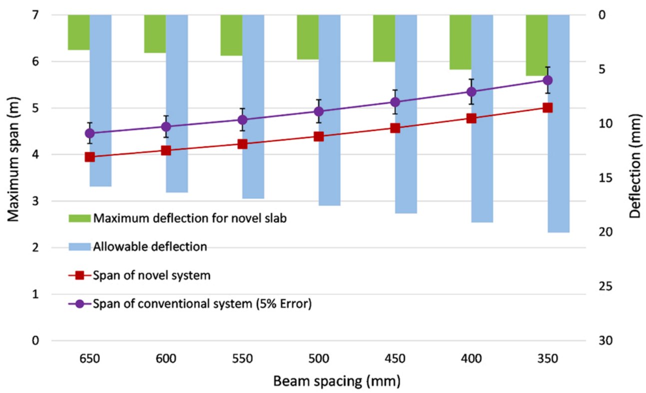


Fig. 11. Change in structural performance due to insulation system.

- The analysis emphasized that a 75 mm EPS panel can be used as insulation for the NERD slab. However, with only EPS insulation, observed thermal performance was unacceptable for tropical climates. However, the system resulted in a 3% decrease in life cycle cost and a 20% reduction in operational energy consumption. In addition, it is 18% eco-efficient compared to the un-insulated NERD slab.
- The roof slab with EPS (75 mm) insulation and a white exposed surface obtained the lowest life cycle cost. For example, it resulted in an 8.3% decrease in life cycle cost and a 41% reduction in operational energy consumption. The eco-efficiency of the recommended system is 52% higher than the conventional NERD slab.
- The novel system requires an 11% reduction in maximum span to withstand excess loading. Finally, the authors suggest EPS concrete panels as alternative insulation for the NERD slab system considering environmental and economic feasibility. For tropical climates, the insulated slab requires a low-absorptive exposed surface to improve energy performance. However, the authors

recommend a detailed structural assessment for this system. Furthermore, the reflected heat (cool roof) can increase the temperature of immediate surroundings which needs to be investigated in a future study.

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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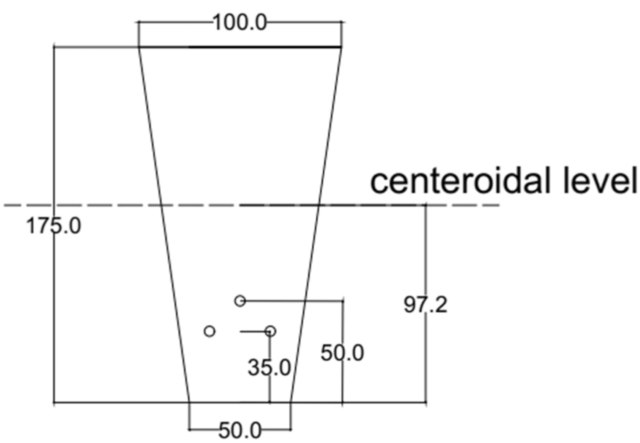
Appendix A. parameters for energy modeling

Floor area: 225 m^2 (15×15).
3 storey office building.
Location: Rathmalana, Colombo, Sri Lanka.
Latitude: 6.79°N.
Longitude: 79.9°E.
Altitude: 30 m.
Monthly average temperature: 28 °C.
Nearest weather station: Rathmalana.
Rate of occupancy: 0.1 per m^2.
Equipment energy generation: 10 Wm^{-2}.
Walls: cement sand blocks (with plaster).
Openings in E-W direction: 0%.
Openings in N-S direction: 30%.
Neutrality temperature: 26 °C.
Coefficient of performance: 2.
Humidity ratio (supply): 0.008.
Insulation layers were assumed as homogeneous and the effect of wind has been neglected for analysis.

Appendix B. Costs considered for Life cycle approach

All calculations were based on Sri Lankan Rupees and, subsequently, converted to US dollars using the current rate (LKR 200 for 1 USD).
Cost for superstructure: 250 USD per m^2.
EPS insulation cost (75 mm): 13 USD per m^2.
For a commercial building, electricity cost is 0.075 USD per 1kWh [39].
All other rates were extracted from BSR 2021 document.

Appendix C. Design parameters of pre-stressed precast NERD beam



Section view of NERD beam.
Pre-stressed concrete: Grade 40.
Design class 2 [85].
Permissible tensile stress: 2.9 Nmm^{-2} at serviceability state.
In-situ concrete: Grade 30.
The density of concrete – 24 kNm^{-3}.
The density of EPS concrete – 7.35 kNm^{-3}.
Tendon size - 5 mm.
Jacking force per tendon 20 kN.
Effective prestress force after losses (assume) = 75% (jacking force).
I_C = 3,255,504.17 mm^4.

Appendix D

Thermal conductivity of concrete = 1.7 $Wm^{-1}K^{-1}$.
Thermal conductivity of EPS concrete = 0.221 $Wm^{-1}K^{-1}$ (From laboratory experiment).
From Eq. (3), modified thermal conductivity of EPS = 0.234 $Wm^{-1}K^{-1}$.
From Eq. (4), R (Body) value of composite slab.
= 2 x (0.06/1.7) + (0.075/0.234) = 0.39 m^2KW^{-1}.
R_O = 0.04 m^2KW^{-1}.
R_I = 0.14 m^2KW^{-1}.
R_B = Thermal resistance of body.
From Eq. (5), R_a of insulated slab = 0.57 m^2KW^{-1}.
From Eq. (6), U_C of insulated slab = 1.75 $Wm^{-2}K^{-1}$.

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