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Operational feasibility of a hybrid roof insulation system with bamboo and vegetation: An experimental study in tropical climatic conditions

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ABSTRACT

A significant portion of the global energy is consumed for creating thermally comfortable building interiors. Insulating the roof has been identified as an effective measure in addressing the issue. Bamboo-transversed is a novel roof insulation material which has proven to yield significant energy saving. This paper presents the results of an experimental study conducted to compare the Life Cycle Operational Performance of polystyrene insulation, bamboo insulation, rooftop vegetation and hybridizing vegetation with polystyrene and bamboo. Results indicated that Polystyrene is a better thermal insulator than bamboo producing 12% reduction of annual energy consumption in comparison with that of 8% of bamboo. When hybridized with rooftop vegetation, both produce similar energy savings around 13–14%. However, polystyrene produced a reduction of 5% in the 50-year Life Cycle Cost analysis, in which bamboo produced 3% while the vegetated cases producing only 2% saving. Bamboo was proven to be paying back its initial investment in 0.9 years, while the same was 1 year for polystyrene. Hybridized insulated system was proven to take 2–4 years to pay back the initial investment. Hence, it was proven that hybridizing rooftop vegetation with bamboo does not boost the operational performance sufficiently to justify its investment.

1. Introduction

The world is gradually moving towards an energy crisis [1–4]. Reducing the energy demand and creating flexibility in energy demand in order to respond to fluctuations in renewable electricity generation need to go hand-in-hand to address the issue [5]. The main source of energy in the world to date is fossil fuel, which at the current state can assuredly be considered a scarce resource [6]. Besides, its adverse effects have accelerated the rate of Global Warming and climate change, escalating the issues.The increase of the electricity demand per degree of temperature increase is proven to vary between 0.5% and 8.5% [7]. The impacts of Global Warming have its shares in diverse fields. Liu et.al. state that the total production of rice in China will decrease by 11.4% under a temperature rise of 2.0 °C, which is proven to be likely in near future in the region [8]. Further, the same rise in temperature in the same region is predicted to result in an increase of toxic pollutant loads in stormwater by 50% [9]. Numerous studies including the few mentioned here prove that Global Warming has its impacts in a variety of fields. Reducing the energy consumption plays a key role in mitigating

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Global Warming.

In this setting, it is significant to study the possible approaches to reduce the domestic energy consumption. Presently, buildings consume 30–40% of global energy consumption and around one-third of global energy consumption which by itself is alarming [10].

The amount of energy consumed for thermal comfort contributes to a significant portion of the energy utilized worldwide. It has been discovered that heating and cooling in total building energy use is very diverse with this share varying between 18% and 73% across different regions in the globe [10]. Numerous studies have been carried out on the matter, among which insulating the building envelope has found to be effective as the envelope accounts for 50–60% of total heat gain/loss in a building [11,12]. A study in Greece has shown that the application of cool roofs results to 17% reduction in the annual cooling demand [13]. Another study in Florida, USA has resulted in finding that electrical savings in the buildings averaged 19% by applying a cool reflecting coating on the roof [14]. A cool roof application in Sicily has registered a 54% reduction of the cooling energy demand [15]. An Experimental study by Alvardo et al. based on laboratory-scale prototypes has shown that a hybrid system with an insulator and a reflector on top of the roof has led to reductions in heat conduction between 65% and 88% when compared to a control prototype [16]. Two similar studies (without the rooftop reflector) in Sri Lanka have proven to achieve a heat gain reduction of more than 75% [17,18]. A different approach has been adapted by Dimoudi et al. by experimenting with a ventilated roof. The addition of the barrier keeps the insulation at a temperature 5 K lower in comparison with a typical roof, but they have not quantified the cooling load reduction potential [19]. Another case study in Italy has obtained an energy saving potential of around 50% through a simulation by adding a low energy performing block to the facade of the building [20]. Those studies can be broadly categorized as studies involved in Temperate or Mediterranean climatic conditions where both heating and cooling are required, and arid or tropical climatic conditions where only cooling is required. It is evident by these studies that insulating the building envelope yields significant energy savings and most of these studies focus on reducing the heat gain through roof, as it is the element that contributes to the maximum thermal gain inside buildings [21].

There is also a trend in inventing eco-friendly insulation materials and some of these studies have gained success to a significant extent. Banana and Polypropylene fibre [22], sheep waste wool [23], corn cob [24,25], cotton stalks [26], date palm [27,28], cellulose [29], oil palm [30], durian [31], rice [32], pineapple leaves [33] and straw bale [34,35] have performed significantly well an insulators. In addition, Wang et al. have developed an inorganic insulation material from pitchstone, and Mandili et al, have experimented with waste paper as an insulation material, of which they claim to have succeded [36]. Megri et al. has tried plastic waste as an insulator, but proven to be less effective than traditional insulation materials. However, they conclude that the obtained results are 'interesting' and is feasible considering the environmental benefits [37,38] Their worth is enhanced considering the positive impact on the environment.

Rooftop vegetation is another alternative that is often used in the modern context instead of insulation. It has a vast spectrum of advantages from the perceptions of environmental, social and financial [39–41]. The energy saving potential is the key benefit on which most of the literature is available. A study in Japan has shown that Rooftop lawn reduced peak air temperature by 3–4 °C in summer [42]. A study in Greece has resulted an indoor temperature reduction of 0.6 °C [43]. In Singapore, a country with tropical climatic conditions, A maximum heat reduction of more than 60% has been obtained [44]. In Hong Kong, the Green roofs have yielded 75% lower heat storage than bare roofs [45]. A study in Taiwan presents a decrease in ambient air temperature by 0.3 °C in winter, 0.5 °C in spring, and 1.2 °C in summer [46].

Despite the advantages, such systems have not been gained the acclaim as intended due to their drawbacks such as the requirement of additional finances, durability concerns and probable structural enfeebling [47].

This study attempts to sort those issues out in tropical conditions. In this context, a system has been developed in Sri Lanka by Halwatura & Jayasinghe [48] with a significant degree of energy saving, but lacks on durability. Consequently, Nandapala & Halwatura have developed a new system which they claim have been proven durable [49].

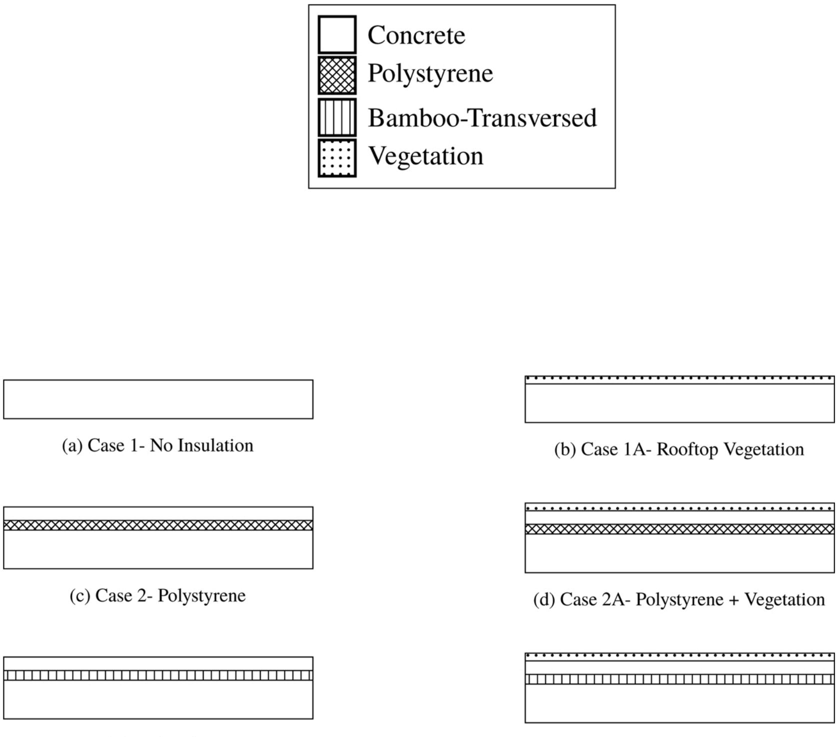
In the subsequent process of making the system 'Greener' another study has been carried out to replace the polystyrene layer which they had used as the insulator with a bamboo-transversed layer [50–52]. However, its thermal performance has not been proven substantial in comparison with traditional insulators. But they have concluded that it is worth considering based on an environmental standpoint.

Hybridizing bamboo with a rooftop vegetation layer has the potential of significant energy savings among other mentioned advantages. This paper presents a study on a comparison of the operational performance of standalone polystyrene (traditional insulation material), standalone bamboo and when those materials are hybridized with a layer of rooftop vegetation.

2. Objectives of the study

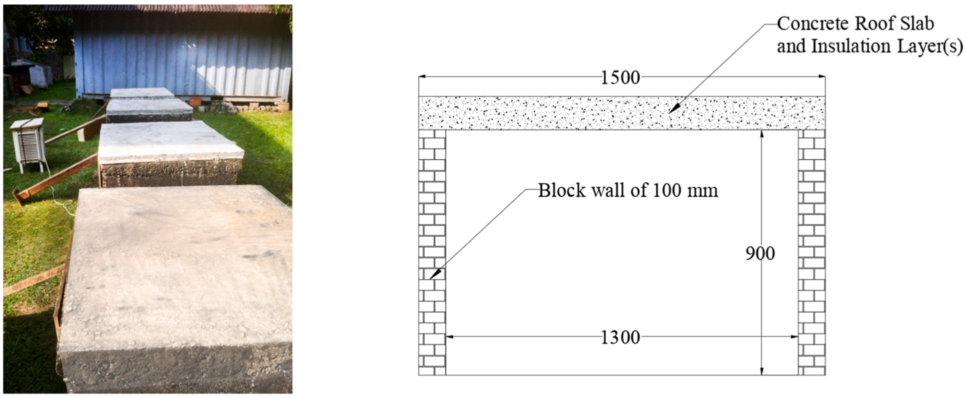
The objective of this study is to investigate the operational feasibility of bamboo-transversed insulation when hybridized with rooftop vegetation. Here, we compare the Life Cycle operational feasibility of standalone bamboo insulation with standalone traditional insulation in the form of polystyrene and those hybridized with a rooftop vegetation layer. We used an additional experimental setup without any form of insulation and another with a standalone vegetation layer to fortify the conclusions.

We calculated the annual energy consumption, Life Cycle Cost for a lifespan of 50 years and the discounted payback period of each of the cases and performed a comparison in the process of comparing the operational feasibility.



(a) Case 1- No Insulation
(b) Case 1A- Rooftop Vegetation
(c) Case 2- Polystyrene
(d) Case 2A- Polystyrene + Vegetation
(e) Case 3- Bamboo-transversed
(f) Case 3A- Bamboo + Vegetation

Fig. 1. Insulation cases that the experiments were conducted.



(a) A Photo of the Small Scale Physical Models Cast in Stage 1
(b) Cross-section of the Small Scale Physical Models Cast

Fig. 2. Small scale physical models.

3. Methodology

3.1. General

We used a three-step process in order to compare the six systems stated in Section 2: small scale physical model testing, calibrated computer simulations and a discounted cash flow analysis. GL820 midi data logger was used for recording temperatures and DesignBuilder v6 was used for computer simulations. Sri Lankan market rates, converted to United States Dollars (USD) at an exchange rate of 190/= Sri Lankan Rupees per dollar were used in discounted cash flow analysis.

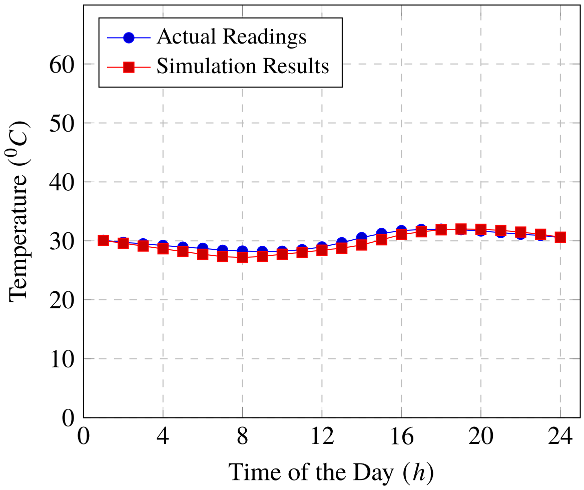


Fig. 3. Actual readings and the simulated results of slab soffit in the calibrated model for the experiments conducted in stage 1.

3.2. Small scale physical model testing

Six physical models were cast in April, which is one of the two months that Sri Lanka has extreme temperatures along with August/September, to obtain the optimum performance of insulators. Following are the insulation cases cast (refer Fig. 1);

- Case 1 – Uninsulated slab as the control experiment (Fig. 1a)
- Case 2 – Polystyrene Insulation layer of 25 mm in thickness and a screed concrete of 40 mm (Fig. 1c)
- Case 3 – Bamboo-transversed insulation layer of 25 mm in thickness and a screed concrete of 40 mm (Fig. 1e)
- Case 1A – Vegetation layer of 65 mm in thickness (Fig. 1b)
- Case 2A – Polystyrene layer of 25 mm in thickness, screed layer of 40 mm and a vegetation layer of 65 mm (Fig. 1d)
- Case 3A – Bamboo-transversed layer of 25 mm in thickness, screed layer of 40 mm and a vegetation layer of 65 mm (Fig. 1f)

The temperature measurements were taken in three stages, with each having an overlapping case to another. Fig. 2a shows a photograph of the small scale models cast in Stage 1 and Fig. 2b shows a cross section of the models. Slab-top and slab-soffit temperatures, inside air temperatures and outside ambient temperatures were measured in each of the cases. However, only the top and soffit surface temperatures were used in the calibration process as the effect of thermal mass had to be minimized since the results were to be comparable with real-scale applications. A minimum of two probes were used on a single surface to enhance the accuracy. Each stage was measured for a minimum of five days at ten-minute intervals and hourly average values were calculated after removing the outliers. The differences observed in ambient conditions between three stages were normalized by calibrated computer simulations.

3.3. Calibrated computer simulations

Computer simulations were performed with Design Builder v6 software package in two stages: Small scale physical models and a real scale model. The calibration of the small scale physical models were performed based on the experimental data obtained as mentioned in the previous section, and that of real scale model was performed by manual calculations as per the method prescribed in CLTD/SCL/CLF method for cooling load calculation.

First four cases of the small scale physical models stated in the Methodology (Case 1, Case 2, Case 3 and Case 1A) were modelled and compared with the observed results. The comparison was performed for slab-top and slab-soffit surface temperatures instead of internal air temperature to minimize the effect of thermal mass. The graph of the actual readings and the simulation results of the slab-soffit of the small scale physical model testing is shown in Fig. 3.

Two criteria were maintained for a satisfiable calibration;

1. The time of the peak temperature was maintained the same in both observed and simulated curves.
2. Each temperature value corresponding to a time in the simulated curve was maintained to be within 5% of the observed curve.

Having found the combined thermal conductivity values (U-values in W m^{-2} K^{-1}) by the procedure, layer thermal conductivity values (K-values in W m^{-1} K^{-1}) of all insulation layers were manually calculated. A sample calculation is given in Appendix A. Hence, the last two cases in Methodology (Case 2A and Case 3A) were used for validating the model maintaining the same calibration criteria. This iterative procedure was adapted until all models were sufficiently calibrated and validated.

A computer simulation was performed on a real-scale model with the characteristics provided in a previous study in similar

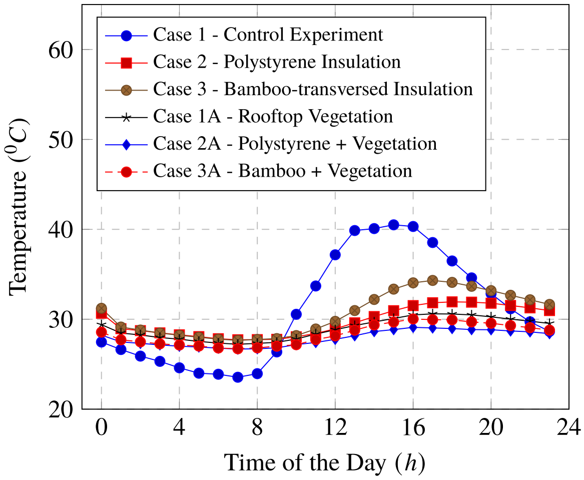


Fig. 4. Normalized average slab-soffit temperatures in a 24-h cycle.

Table 1
Air-to-air thermal conductivity values of the considered cases mentioned in Section 3.2.

Case	Type of insulation	Air-to-air U-value (W m^{-2} K^{-1})
1	No insulation	4.68
2	Polystyrene	1.03
3	Bamboo-transversed	2.48
1A	Rooftop Vegetation	0.98
2A	Polystyrene + Vegetation	0.56
3A	Bamboo-transversed + Vegetation	0.82

conditions [18] to analyze the energy saving potential of the insulation materials of interest in real-life conditions (the details of the real-scale model are given in Appendix). This was calibrated and validated by manual calculations as per the method prescribed in CLTD/SCL/CLF method for cooling load calculation [53]. A summary of the calculations for the calibration is presented in Appendix C. The deviation of the cooling load calculated manually and by the software was 3%, which was decided to be sufficient. Then the annual energy consumption to keep the operative temperature at 26 °C for each case was extracted from the model.

3.4. Discounted cash flow analysis

The Life Cycle Cost for a lifespan of 50 years and the discounted payback period of each case were calculated with a discounted cash flow analysis. Initial costs and annual maintenance costs were obtained by the market rates in Sri Lanka. The details of the assumed costs are presented in Appendix D. Annual energy consumption values were directly obtained by the calibrated model simulations, and the Life Cycle Costs (Present Values of all cost elements) were calculated by Eq. (1), and subsequent payback periods were calculated by Eq. (2) [54]. Finally, a sensitivity analysis was performed to study the effect of change in discounting factor on the results.

$$\text{Present value of costs across the lifespan (PV)} = \sum_{j=1}^{n} \frac{F_j}{(1+i)^j} \tag{1}$$

$$\text{Discounted payback period (T)} = \min\left\{k : \sum_{j=1}^{k} \frac{P_j}{(1+i)^j} \geq 0\right\} \tag{2}$$

Where, P_j = Present Value of the cost in j^{th} year, F = Future Value of Money in j^{th} year, i = Discounting Factor/Interest Rate, n = Project Life

4. Results

4.1. Results of the small scale physical model testing

The normalized slab-soffit temperatures of the systems are plotted in Fig. 4. It evidently indicates that there is an effect of vegetation on the thermal performance of the system in a 24-h cycle. Furthermore, it consolidates the observations made by Chandra et al. [55] that bamboo alone does not produce an equivalent thermal performance as polystyrene does. Unsurprisingly, Case 2A, the system

Table 2
Thermal conductivity values derived from the results of the computer models.

Insulation material	Thermal conductivity (W m^{-1} K^{-1})
Concrete	1.7 [48]
Polystyrene	0.034
Bamboo-transversed	0.15
Rooftop Vegetation	0.08

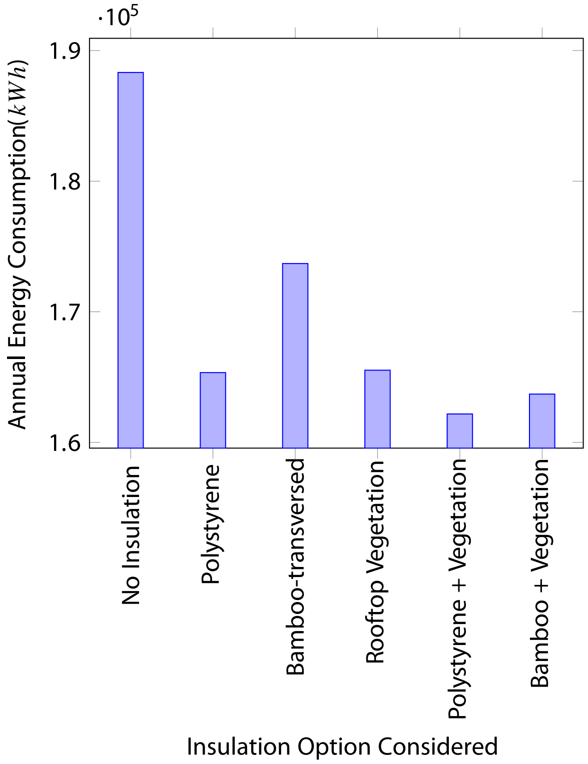


Fig. 5. Annual energy consumption obtained by calibrated computer simulations.

with vegetation coupled with polystyrene insulation, produced the best thermal performance of all cases tested, maintaining an almost constant temperature of 28 °C at the soffit of the slab.

4.2. Results of the calibrated computer simulations

The Air-to-air thermal conductivity (U) values with the roof slabs were picked out from the computer simulations of the small-scale models. The obtained *U*-values are as tabulated in Table 1. These values indicate that there should be significant energy savings for all insulation cases in comparison with a roof slab without any insulation. Furthermore, hybridizing with vegetation should yield some degree of enhancement in thermal aspects. Then each system was evaluated as a set of layers perpendicular to the direction of heat flow and the thermal conductivity (K) values were derived manually. A sample *U*-value calculation is presented in Appendix A.

The results of the subsequent compilation of literature details, model calibration, model validation, and reverse calculation of the thermal conductivity values are tabulated in Table 2. The values corresponding to concrete and polystyrene are consistent with the literature [18,49], and 0.15 W m^{-1} K^{-1} for bamboo-transversed and 0.08 W m^{-1} K^{-1} for rooftop vegetation were verified by the process of model validation.

The annual energy consumption of the real-scale model, of which the details are presented in B, were calculated by computer simulation and are presented in Fig. 5. Standalone polystyrene insulation and rooftop vegetation have produced a 12% annual energy saving, whereas the hybrid system with rooftop vegetation has increased the same to 14%. However, the 8% of the energy saving of bamboo insulation, which itself is significant in real-life conditions, has spiked to 13% when hybridized with rooftop vegetation.

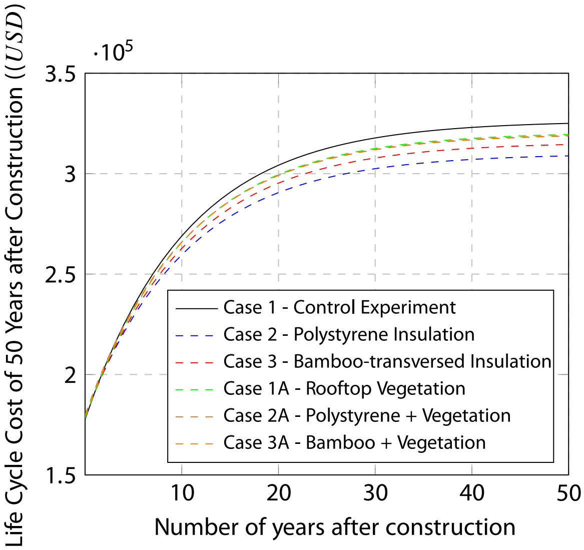


Fig. 6. Present value of costs across the lifespan of the compared systems for a period of 50 years and a discounting factor of 10%.

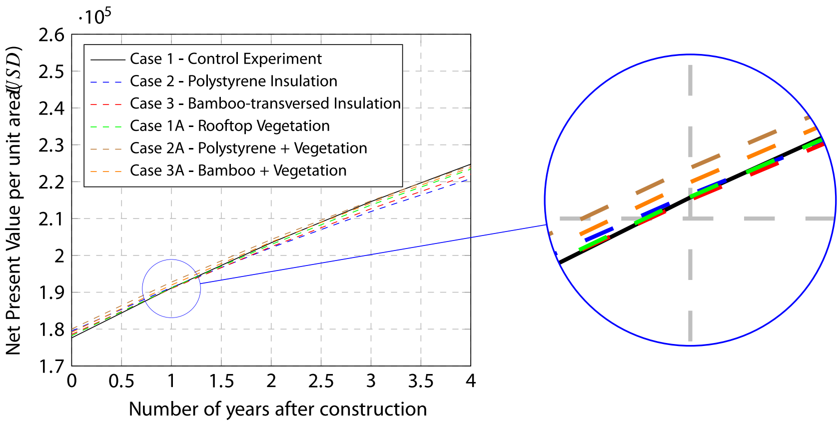


Fig. 7. Present value of the compared systems in the first four years for a discounting factor of 10% and a magnified around one-year mark.

Table 3
Calculated discounted payback periods of the insulation cases considered.

Case	Type of insulation	Discounted payback period (Years)
2	Polystyrene	1.0
3	Bamboo-transversed	0.9
1A	Rooftop Vegetation	1.1
2A	Polystyrene + Vegetation	3.4
3A	Bamboo-transversed + Vegetation	2.3

4.3. Results of the discounted cash flow analysis

Similar previous studies have compared the Life Cycle Cost values for different insulation cases for discrete values of lifespan [18, 56]. In this paper, we evaluate the variation of the Life Cycle Cost continuously up to 50 years from construction to study its behaviour with respect to time while comparing with previous findings. The calculated Present Values of costs across the lifespan of each of the insulation cases of interest corresponding to a discounting factor of 10% are depicted in Fig. 6.

At the outset, the figure indicates that Present Values of all the insulated cases fall below that of the control experiment, deducing that NPV is positive in all insulated options, and hence, all these options are financially viable in comparison with the control experiment which is the uninsulated slab.

Furthermore, it indicates that standalone polystyrene insulation is the best of all considered options in terms of Life Cycle Cost,

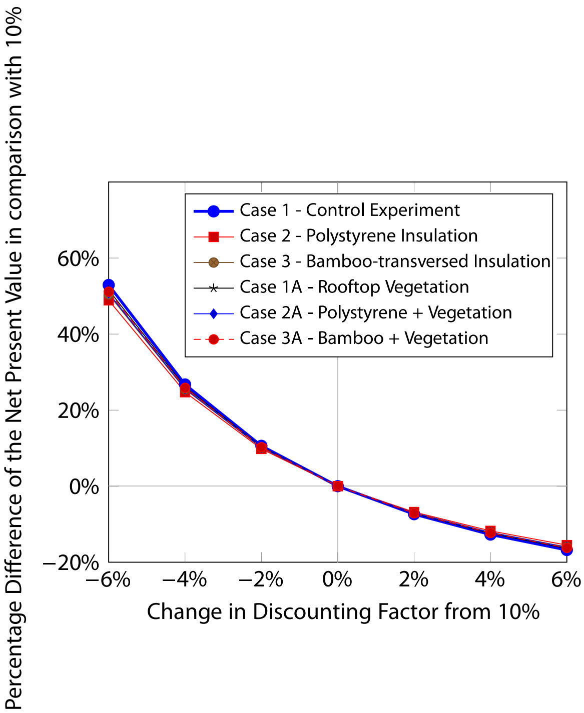


Fig. 8. Sensitivity of the discounting factor to the net present value in 50 years.

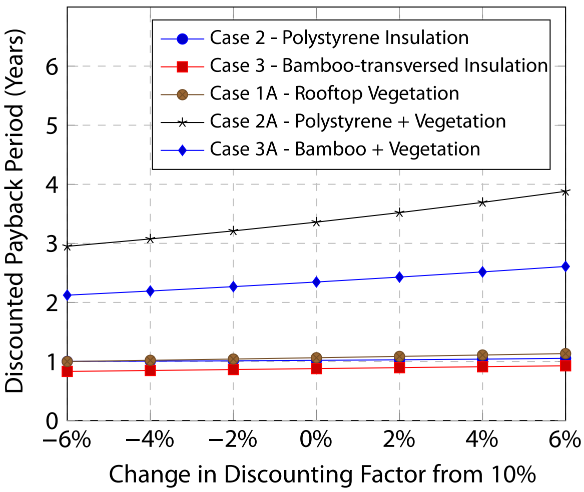


Fig. 9. Sensitivity of the discounting factor to the discounted payback period [57].

producing a 5% reduction at the end of the lifespan. Noteworthy, Bamboo-transversed insulation performs better than the systems with vegetation, resulting in deducing that the investment on hybridizing with vegetation is not operationally feasible in comparison in the long run. Even though it results in additional energy saving, the maintenance cost surpasses the financial gain of the energy cost saving.

Furthermore, all cases with rooftop vegetation have resulted in approximately 2% of Life Cycle Cost savings, indicating that whether it stays alone or hybridized with another insulation, it performs the same in financial aspects in the long run.

In addition, we performed a discounted payback period calculation to obtain another perception on the operational performance of the systems.

A zoomed graph of the Life Cycle Cost of the first four years of construction is shown in Fig. 7. It indicates at a glance that all insulation options have paid back their initial investment within the first four years of its construction. The calculated discounted payback periods of all considered cases are presented in Table 3.

The results suggest that Bamboo-transversed insulation performs the best in the considered cases in the discounted payback period.

Table 4
Summary of the results derived in the study.

Insulation case	*U*-value (W m^{-2} K^{-1})	Annual energy consumption reduction	Life Cycle Cost reduction	Discounted payback period (years)
No insulation	4.68	–	–	–
Polystyrene	1.03	12%	5%	1.0
Bamboo-transversed	2.48	8%	3%	0.9
Rooftop Vegetation	0.98	12%	2%	1.1
Polystyrene + Vegetation	0.56	14%	2%	3.4
Bamboo + Vegetation	0.82	13%	2%	2.3

However, the other two standalone insulation options, polystyrene and rooftop vegetation, closely follow the values, both hovering around the one-year mark. Case 2A and Case 3A, where the rooftop vegetation is hybridized with another insulation, understandably takes a significant amount of time to recover in comparison, but not as significant to deem the option to be operationally incompetent as a thermal insulator.

Finally, we performed a sensitivity analysis to study the effect of the variation in the discounting factor on the final results. Fig. 8 shows the effect at the end of 50 years. The graph deduces that the Life Cycle Cost is highly sensitive to the low values of the discounting factor, however, it can be concluded that the effect of which is insignificant in the context of this study since it affects all cases in an almost identical manner.

Similarly, the effect of the variation in the discounting factor on the discounted payback period is presented in Fig. 9. There is a positive correlation of the two variables in all considered cases, but can be considered insignificant in the macro level of this study as the intention of this study is to compare the insulation options.

5. Discussion and conclusion

The summary of the performed analyses are presented in Table 4. Comparing the annual energy consumption indicates that bamboo-transversed is a good enough insulator, but not as effective as polystyrene nor rooftop vegetation. However, hybridizing with rooftop vegetation spikes the reduction in energy consumption by an additional 5% from the original 8%. In contrast, polystyrene standing alone produces a 12% reduction in annual energy consumption, but the hybridizing process only adds 2% for the value. Hence, it is apparent that the effect of hybridizing is high in bamboo.

In contrast, the Life Cycle Cost reduction for a discounting factor of 10% and a lifespan of 50 years indicates that polystyrene insulation performs the best, and Bamboo-transversed lags behind but performs better than all cases with vegetation. The findings deduce that even though the initial investment on rooftop vegetation can be justified in comparison with a case with no insulation, its operational benefit is neither as significant as polystyrene nor bamboo-transversed in the long run.

Bamboo has been proven to payback its initial investment in the shortest time while rooftop vegetation and polystyrene insulation closely follow, all hovering around one-year mark. However, when insulation is coupled with rooftop vegetation, it takes longer to payback in comparison, but does within 2–4 years, which itself is a significant achievement. It should be noted that these values do not stand inline with the literature [58]. This is due to the higher degree of thermal performance in extremely hot and humid climate conditions, and the relatively low additional construction cost in the context of the experiment.

However, these observations should be noted with some remarks. The experiments were performed with a particular extensive rooftop vegetation, and therefore the effects of parameters such as the degree of saturation and leaf area index were not considered here. Changing the layer thickness and trying out a different type of vegetation layer could alter the findings, but with the results obtained in the study, the chances of which are marginal.

Another noteworthy remark is that this study focused only on the operational energy and financial aspects of insulation. Hence, polystyrene was proven to be the most effective of the considered options. A study on the embodied energy is needed to be carried on to make an overall final comment. Furthermore, the ecological aspects of the cases have not been studied in this paper, and a separate study on that is worthy to be considered.

In addition, it should be noted that the experimental measurements have been recorded for a few days, and the results were extrapolated over a period of an year for comparison purposes. Here, the weather file of the model has been inspected and periodic steady-state external temperatures calculated using maximum and minimum design summer weather conditions. It would be more accurate if the experiment itself were carried out over a year, however, the effect of which was considered negligible since the main intention of this study was to compare the operation feasibility and the same weather file has been used across all considered cases.

Finally, it can be concluded that hybridizing bamboo with rooftop vegetation boosts the thermal performance to a higher degree in comparison with the same of polystyrene. However, there was evidently poor performance of the systems with rooftop vegetation in Life Cycle Cost due to the continuous maintenance costs. Nevertheless, the initial investments of all systems were paid back plentifully within its lifespan, with standalone insulation cases performing exceptionally.

Hence, it can be concluded that even though any form of roof insulation is feasible in energy saving potential and financial feasibility. However, hybridizing rooftop vegetation with another insulation material does not boost the operational performance sufficiently to justify its investment.

Table A.5
Surface resistances of roof slab are shown in Table A.5.

Location	Symbol	Surface resistance
Top surface	R_T	0.04 [59]
Soffit	R_S	0.1 [59]
Insulation system	R_I	0.034 [49]

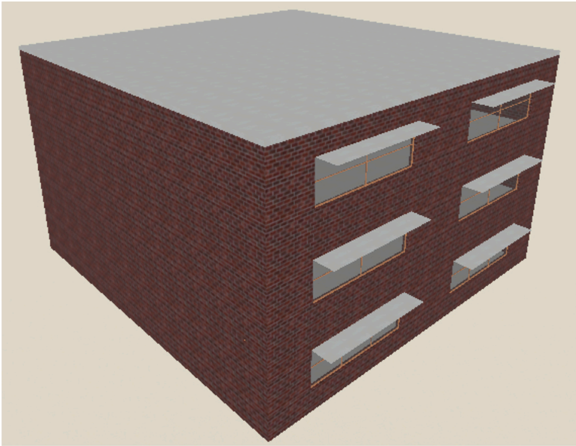


Fig. B.10. Simulated model of the actual scale model.

Declaration of interests

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.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Sample *U*-value calculation

$$\text{Thermal resistance of the system with polystyrene} = \frac{T_1}{K_1} + \frac{T_2}{K_2} + \frac{T_3}{K_3}; (T_i - \text{Thickness of the layer})$$
$$= \frac{0.04}{1.7} + \frac{0.025}{0.034} + \frac{0.125}{1.7}; \text{From Table A.5}$$
$$= 0.832\,\mathrm{m^2\,K\,W^{-1}}$$

$$\text{Air-to-air resistance of the new system} = R_T + R_I + R_S$$
$$= 0.04 + 0.832 + 0.1$$
$$= 0.972\,\mathrm{m^2\,K\,W^{-1}}$$
$$\text{Hence, the composite conductivity of the newly designed system} = \frac{1}{0.972}$$
$$= 1.028\,\mathrm{W\,m^{-2}\,K^{-1}}$$

Appendix B. Details of the computer model

The simulated model is shown in Fig. B.10.

Plan area	15 m × 15 m
Number of stories	03
Location	Moratuwa, Sri Lanka
Latitude	6.79^0N
Longitude	79.9^0E
Altitude	30 m
Exposure to wind	Normal
Average monthly mean temperature	28°C
Nearest weather station	Ratmalana, Sri Lanka
Type of the building	Office
Occupancy rate	$0.1/m^2$
Metabolic rate	Corresponds to light office work
Degree of clothing	Summer clothing
Target illuminance	400 lux
Energy generation by equipment	$10\,W/m^2$
Thickness of the roof slab	125 mm
Thickness of the intermediate slabs	125 mm
Walling material	Brick
Thickness of walls	225 mm
Percentage of openings in E-W direction	0%
Percentage of openings in N-S direction	30%
Type of openings	Glazed windows with 1m-overhang

Other than these basic details, following model conditions were used.

- Periodic steady-state external temperatures calculated using maximum and minimum design summer weather conditions.
- Wind effect has been neglected for cooling load comparison purposes.
- The external surfaces below the ground plane are considered adjacent to the ground and external surfaces above the ground plane are considered adjacent to outside conditions.
- Internal walls and floors were considered adiabatic.
- All layers (including the rooftop vegetation layer) were considered homogeneous.

Appendix C. Manual cooling load calculation by CLTD/SCL/CLF method for actual scale model calibration

Calculations are based on ASHRAE handbook 1997 [53]. The building was modelled without equipment nor appliances for calibration purposes. Calculations have been performed for the building with bamboo-transversed insulation for the roof slab.

Abbreviations used in the calculations;

$U-$	Thermal conductivity of the layer
$A-$	Area normal to the direction of the heat flow
CLTD−	Cooling load temperature difference
SC	Shading coefficient
SCL	Solar cooling load factor
t_b	Temperature outside
t_{rc}	Temperature inside
N	Number of people in space
CLF	Cooling load factor
W	Wattage of lights
F_{ul}	Lighting use factor
F_{sa}	Special allowance factor

Heat gain through roof and walls

$$\text{heat gain},\quad q = U \times A \times \text{CLTD} \tag{C.1}$$

Table D.6
Cost values considered for Life Cycle Cost analysis.

Cost element	Case 1	Case 2	Case 3	Case 1A	Case 2A	Case 3A
Initial cost (USD/m^2)	263	271	267	265	273	269
Maintenance cost (USD/m^2/year)	0	0	0	2	2	2
Cost for cooling (USD/m^2/year)	22.03	19.34	20.31	19.36	18.97	19.15

$$\begin{aligned}
&\text{Heat gain through roof} && = 2.477 \times 225 \times 47 \\
& && = 26,194.28\,W \\
&\text{similarly,} && \\
&\text{Heat gain through North wall} && = 2.3 \times 94.5 \times 11 \\
& && = 2390.85\,W \\
&\text{Heat gain through East wall} && = 2.3 \times 135 \times 18 \\
& && = 5589\,W \\
&\text{Heat gain through South wall} && = 2.3 \times 94.5 \times 16 \\
& && = 3477.6\,W \\
&\text{Heat gain through West wall} && = 2.3 \times 135 \times 22 \\
& && = 6831\,W \\
&\therefore\text{Total heat gain through roof and walls} && = 44,482.73\,\text{W}
\end{aligned}$$

Heat gain through windows

$$\text{heat gain,}\quad q = A \times (\text{SC}) \times (\text{SCL}) \tag{C.2}$$

$$\begin{aligned}
&\text{Heat gain through windows in the North wall} && = 40.5 \times 0.55 \times 110 \\
& && = 2450.25\,W \\
&\text{Heat gain through windows in the South wall} && = 40.5 \times 0.55 \times 274 \\
& && = 6103.35\,W \\
&\therefore\text{Total heat gain through windows} && = 8553.6\,\text{W}
\end{aligned}$$

Heat gain by the occupants

$$\text{Sensible heat gain,}\quad q = N \times \text{sensible heat gain per person} \times (\text{CLF}) \tag{C.3}$$

$$\text{Latent heat gain,}\quad q = N \times \text{latent heat gain per person} \tag{C.4}$$

$$\begin{aligned}
&\text{Total number of occupants} && = 0.1 \times 225 \times 3 \\
& && = 67.5 \\
&\therefore\text{Sensible heat gain} && = 67.5 \times 75 \times 1 \\
& && = 5062.5\,W \\
&\text{Latent heat gain} && = 67.5 \times 55 \\
& && = 3712.5\,W \\
&\therefore\text{Total heat gain by the occupants} && = 8775\,\text{W}
\end{aligned}$$

Heat gain by lighting

$$\text{Heat gain by lighting,}\quad q = W \times F_{\text{ul}} \times F_{\text{sa}} \times (\text{CLF}) \tag{C.5}$$

$$\begin{aligned}
&\text{Assumed power intensity of lighting} && = 20\,\text{W/m}^2 \\
&\therefore\text{Heat gain by lighting} && = (20 \times 2 \times 225) \times 1 \times 1 \times 1 \\
& && = 13,500\,\text{W}
\end{aligned}$$

$$\begin{aligned}
&\text{TotalManuallyCalculatedCoolingLoadRequirementoftheBuilding} && = 75.31\,\text{kW} \\
&\text{TheCorrespondingValueProducedbyComputerSimulation} && = 73\,\text{kW} \\
&\text{PercentageDifferenceinthesaidtwomethods} && = 3.1\%
\end{aligned}$$

Appendix D. Cost values considered for Life Cycle Cost analysis

Cost Values considered for Life Cycle Cost Analysis are given in Table D.6. Following remarks should be noted along with the table.

- All the calculations of the rates have been performed in Sri Lankan Rupees (LKR) and converted to USD with an exchange rate of LKR 190.00 for 1 USD.

- The initial costs and maintenance costs were calculated based on the Sri Lankan market rates before the pandemic as price fluctuations were too high during the pandemic.
- Following values were taken for calculating the values on table.
  –Superstructure cost is LKR 50,000 per m^2. (This value does not affect the final conclusions since it was taken as a constant in all cases)
  –Concreting cost is LKR 44,605 per cube. Hence, for the required thickness in this case, a value of LKR 630.46 per m^2 was deduced.
  –Polystyrene cost is LKR 900 per m^2.
  –Vegetation cost is LKR 300 per m^2.
  –Bamboo processing cost is LKR 150 m^2.
  –Electricity cost is LKR 15 per kWh (assuming the rate of a commercial building).

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