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\*Corresponding author: Kasun Nandapala, Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka  
E-mails: [mpkcnandapala@gmail.com](mailto:mpkcnandapala@gmail.com), [kasuncn@uom.lk](mailto:kasuncn@uom.lk)

Reviewing editor:  
Raja Rizwan Hussain, King Saud University, Saudi Arabia

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## CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

# Design of a durable roof slab insulation system for tropical climatic conditions

Kasun Nandapala<sup>1\*</sup> and Rangika Halwatura<sup>1</sup>

**Abstract:** Flat roof slabs become popular day-by-day due to the advantages like cyclonic resistance, the possibility of future vertical extension, and the possibility of utilizing as an additional working space. However, a serious matter of concern is its thermal discomfort, for which air conditioning is used as the most common remedy. This has led to extensive use of energy, increasing the operational cost of the buildings, and contributing to global warming. Hence, the current trend is to go for passive techniques. Insulating roof slabs is identified as a better passive way to make buildings thermally comfortable. In this study, several existing roof slab insulation systems and their performances were investigated, and the most effective system for tropical climates was identified. Since that system had an issue in durability, a new system was developed with a discontinued-stripped supporting arrangement, which withstood a 4MT-point load. Further, it was proven by comparing literature that the newly designed system has a heat gain reduction of more than 75%.

**Subjects:** Built Environment; Engineering & Technology; Sustainable Development

**Keywords:** roof slabs; insulation; thermal performance; structural performance; durability

### 1. Introduction

It is evident that deforestation in the world has reached an intolerable level and has become the primary cause for the imbalance that the world is facing today. This phenomenon has aggravated mainly because of the unplanned construction and the extensive land consumption caused due to the

### ABOUT THE AUTHORS

Kasun Nandapala is a full-time PhD candidate at the Department of Civil Engineering in University of Moratuwa, who is carrying out his core research on thermal insulation in roof slabs. Rangika Halwatura is a senior lecturer at the Department of Civil Engineering in University of Moratuwa. The research interests of this team include but not limited to thermal optimization of buildings, development of sustainable construction materials, invention of techniques to promote sustainable built environment.

### PUBLIC INTEREST STATEMENT

Global warming and the associated climate change are the biggest issues that the current world is facing. Consequently, the natural disasters have increased in intensity and severity. Therefore, structures need to be made robust, for which the use of flat concrete roof slabs is a good strategy. It provides some additional advantages like possibility of future vertical extension and possibility of using as a working space. However, the thermal discomfort in the immediate underneath floor is its major drawback. Even though air conditioning solves the problem, it is at a higher cost in the form of energy consumption. Insulating slabs is a better strategy to prevent this. In this study, a roof slab insulation has been developed which is structurally sound and durable. It was proven that this system reduces more than 75% heat gain into a building, which eventually will either eliminate the necessity of air conditioning or will reduce the necessary capacity.

increased population. Consequently, due to the scarcity created, “land” has become one of the most expensive commodities, particularly in urban areas. In this context, multi-storey construction has become popular, as it produces a higher floor-area ratio (Dareeju, Meegahage, & Halwatura, 2011).

Consequently, use of flat concrete roof slabs has begun to be popular as it provides the flexibility of using either as a working space, as a rooftop garden or as a temporary shelter till a future vertical extension is taken place (Banting, 2005; Berardi, GhaffarianHoseini, & GhaffarianHoseini, 2014; Halwatura & Jayasinghe, 2007). Further, roof slabs increase the robustness of the structures and provide an additional cyclonic resistance which is very handy against the climate change taking place in the world (Halwatura, 2013).

However, the use of roof slabs has not been sufficiently penetrated to the middle-class population due to a variety of reasons. Thermal discomfort in the immediate underneath floor has been found to be the primary reason for that (Nandapala & Halwatura, 2014). The concrete roof slabs get heated in the daytime and emit long-wave radiation to the underneath space, causing the discomfort (Halwatura & Jayasinghe, 2008).

Air conditioning is the most common remedy to overcome this issue. Even though air conditioning resolves this issue, a higher operational cost has to be incurred. Further, this increases the energy usage which leads to the biggest problem in the world, Global Warming (Halawa et al., 2014; Lean & Rind, 2001; Macilwain, 2000).

Elaborating the impact of this in quantitative terms, in Singapore, buildings use up to 57% of the total energy usage of the country (Kwong, Adam, & Sahari, 2014). In Malaysia, a country with similar tropical climatic conditions, more than 30% of the total energy in buildings is used for making them thermally comfortable (Dong, Lee, & Sapar, 2005). Those findings sum up that around 15–20% of the total energy usage in tropical countries is used for enhancing thermal comfort in buildings. It is evident that the amount of energy used for comfort is much more than what the world can afford.

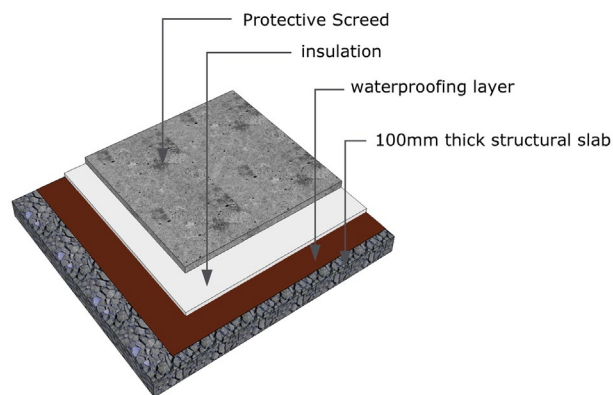
Hence, active cooling (in the form of Air Conditioning) is not a preferred remedy to achieve thermal comfort. Therefore, passive cooling techniques have emerged (Al-Obaidi, Ismail, & Abdul Rahman, 2014; Alvarado, Terrell, & Johnson, 2009; Sadineni, Madala, & Boehm, 2011), insulation in particular (Al-Homoud, 2005; Brito Filho & Santos, 2014; Dylewski & Adamczyk, 2014). Insulating the roof has been identified to be the best option as it is the element that contributes to about 70% of the total heat gain inside buildings (Halwatura, 2014; Vijaykumar, Srinivasan, & Dhandapani, 2007).

There are several roof slab insulation techniques tried out in the world. A research work carried out in Florida, USA, has obtained a 38% energy saving by applying a cool paint (Parker & Barkaszi, 1997), and another study in Italy, with the same technique, has achieved a 54% energy saving (Romeo & Zinzi, 2013). A daily heat gain reduction of 56% has been observed in Greece, using a 60 mm ventilated air gap as an insulator (Dimoudi, Androutsopoulos, & Lykoudis, 2006). A system developed in Sri Lanka, a tropical country, has achieved a heat reduction of 75% using a 25 mm polystyrene layer (Halwatura & Jayasinghe, 2008). Some laboratory experiments have obtained similar results as well (Alvarado & Martínez, 2008; Megri, Achard, & Haghighat, 1998).

Above figures incontrovertibly suggest that insulation can be effective in any climatic condition. Since this study focuses on tropics, the system developed in Sri Lanka was identified to be the most recent and the most effective to suit the conditions.

A further study on the system suggested that this particular system has been developed as an alternative to one of the most common insulation systems used in tropical countries, shown in Figure 1. It has an insulation layer on the structural slab and a protective screed on top of it.

**Figure 1. The most common roof insulation system used in tropical countries.**



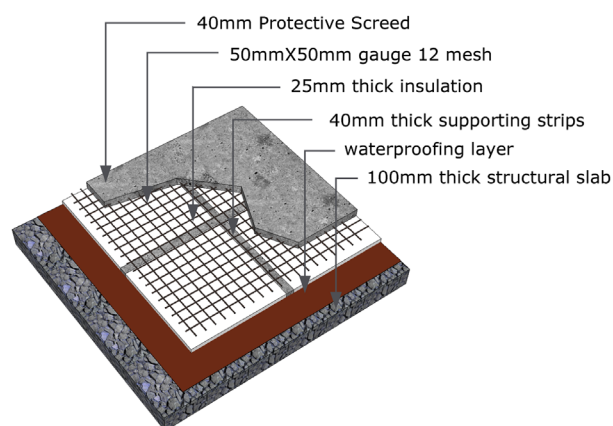
This system had been tested under practical conditions and its thermal performance is emphasized. However, this has imposed a restriction on loading, since a layer of weak material (insulation material) is placed between two layers of concrete, and the load path from the slab passes through it.

The system by Halwatura and Jayasinghe (shown in Figure 2) has been developed as a remedy for this. It has a set of concrete strips within the insulation layer to support the top screed. Hence, the load path passes through those strips, without transferring the load to the insulation layer. Further, a 50 mm × 50 mm steel mesh has been introduced to distribute the load.

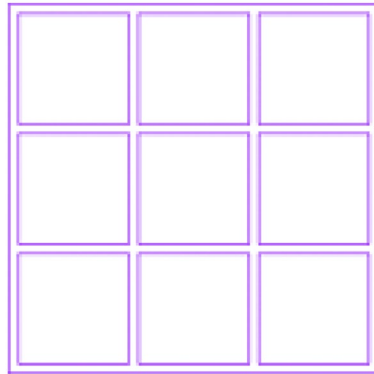
However, a field study suggested that there is a concern about the durability of the system as some water patches were observed in slab soffits in the long run. A thorough study resulted in finding that water was stagnant in the polystyrene layer. This phenomenon can further be elaborated as follows:

The arrangement of supporting strips in plan view is shown in Figure 3. It is apparent that there is no drainage path for the penetrated water to flow out, as the insulation material is enclosed by a set of continuous concrete strips. Hence, a water head is developed in the system, resulting in a reduction in the lifespan of the waterproofing layer.

**Figure 2. The insulation system with continuous concrete strips by Halwatura and Jayasinghe (2008).**



**Figure 3. Plan view of the supporting arrangement of the system with continuous concrete strips.**



## 2. Objectives

The primary goal of this study is to develop a new system that is structurally sound with a proper drainage path. The objectives of this study are as enlisted below:

- To investigate the importance of roof slab insulation and performance of existing techniques It was expected to study the importance of roof slab insulation in general, importance of it in tropical climates, existing techniques, their advantages and disadvantages by means of a literature survey. (This was presented in Section 1).
- To develop a new system that is structurally sound with an optimum structural arrangement The structural arrangement was optimized in such a way that it has no restriction for loading. Further, a proper drainage path was provided for the penetrated water to flow out. Most importantly, the thermal performance of the system was studied as well.

## 3. Methodology

### 3.1. Overall methodology

A literature survey was carried out to figure out the significance of roof slab insulation in tropical climates, the existing techniques, and their strengths and weaknesses.

A field study was carried out to check and verify the data in literature and to find out the practical issues of those techniques in the operational stage.

Finite element modeling by SAP 2000 software (verified by manual calculations) was used to optimize the structural arrangement. The procedure followed in this optimization process is described in Section 3.2.

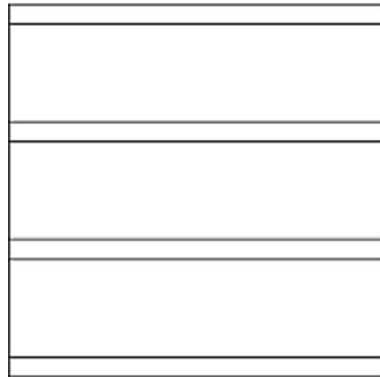
Then, actual scale testing was performed to verify the data obtained by computer simulations.

Finally, the possible thermal gain reduction is predicted based on the results of a similar technique in literature.

### 3.2. The method followed to optimize the strip arrangement

It was decided to provide a proper drainage path along the insulation layer, as it was the major drawback identified in the system with continuous concrete strips. First of the options considered was to remove the supporting concrete strips in one direction, of which a typical plan view is shown in Figure 4. The objective of providing a support was to eliminate the restriction for loading. Hence, the system had to be designed in such a way that it can withstand any practical load applied on that. Therefore, a structural analysis was carried out assuming that the imposed load applied on the system is  $5 \text{ kN/m}^2$ , which is the maximum specified in BS 6399-1: 1996 (British Standards Institution, 1996).

**Figure 4. Plan view of the supporting arrangement after removing strips in one direction.**



In this context, there were four variables to be considered:

- (1) Spacing between strips
- (2) Size of the strips
- (3) Strength and the mix proportion of the concrete to be used
- (4) Reinforcing arrangement in the protective screedAn optimum spacing for the system was to be found out. Because the system would have structurally failed if the strips are placed too far apart to each other, and the thermal performance of the system would have depleted, if they were placed too closer to each other as it increases the concrete area within the insulation layer.

It was intended to optimize the system by minimizing the concrete area within the insulation. Hence, a minimum size of the strips that would bear the load applied on that had to be determined.

The concrete used had to be strong enough to carry the load, and had to be able to be compacted in an area of a width of 40 mm. Hence, concrete with a lower maximum aggregate size (chip concrete) was used. A suitable proportioning was found out by laboratory experiments.

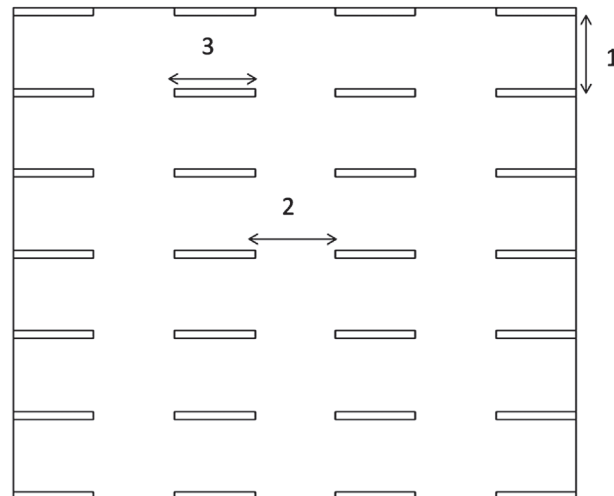
The protective screed had to be designed as a load bearing slab itself. Since concrete is a material which is weak in tension, some arrangement of reinforcement had to be incorporated into the system (Min, Yao, & Jiang, 2014). The bottom reinforcement was fixed to be a 50 mm × 50 mm gauge 12 mesh, due to the convenience of construction. Four options were considered for the top reinforcing arrangement: no reinforcement, 6 mm mild steel bars near supports, 10 mm tor steel bars near supports, and a similar continuous 50 mm × 50 mm mesh (double nets). Then the optimum arrangement was found by computer simulations.

Thereafter, the system was further optimized by varying the spacing between strips while discontinuing them. A typical arrangement of this case is shown in Figure 5. In this case, three more variables were added;

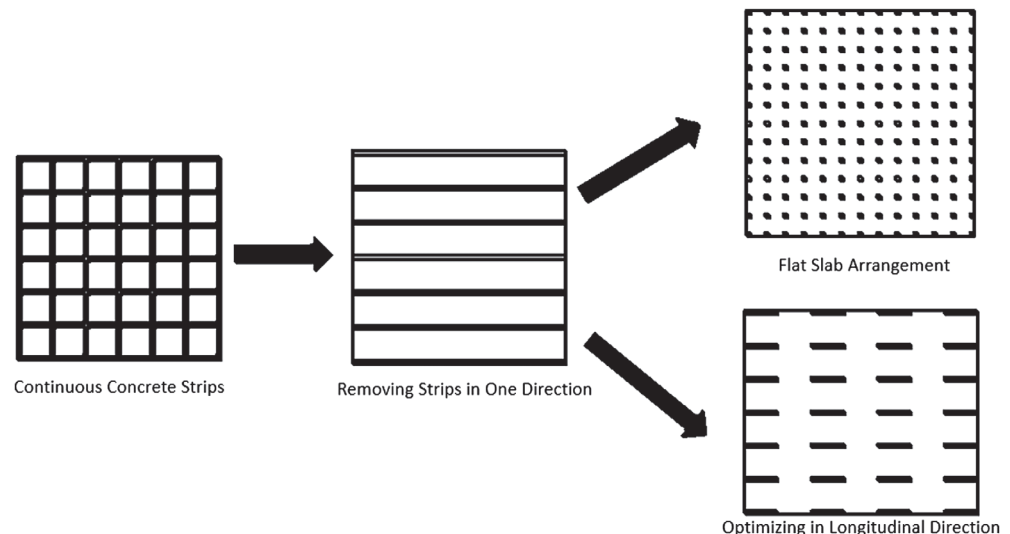
- (1) Spacing between strips (Number 1 in Figure 5)
- (2) Longitudinal spacing between supports (Number 2 in Figure 5)
- (3) Length of the supports (Number 3 in Figure 5)

Different finite element models were developed by varying the spacing of strips, and the optimum arrangement for each value of spacing was found out. This process went on until the top screed becomes a flat slab with a set of blocks as supports.

**Figure 5. Variables to be considered in optimizing the strips in longitudinal direction.**



**Figure 6. The process followed to optimize the system.**



Then the system with a minimum concrete area within the insulation layer was selected as the best arrangement.

A graphical elaboration on the process followed to optimize the system is depicted in Figure 6.

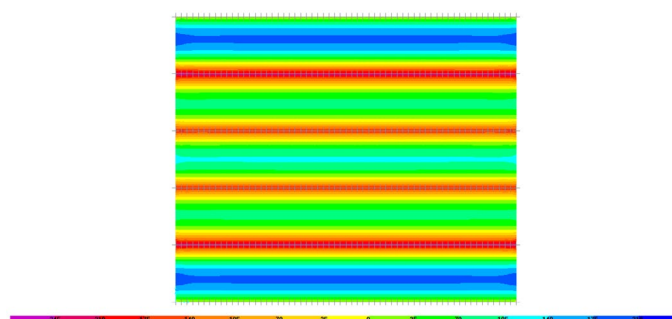
## 4. Results

### 4.1. Step 1: Removing strips in one direction

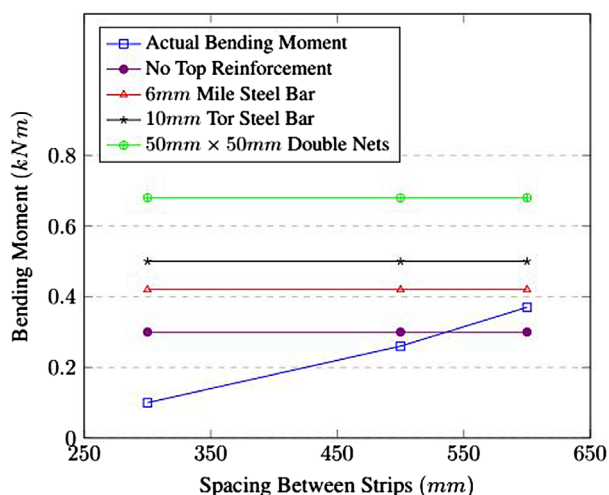
Initially, the size of strips was fixed to 50 mm, and a concrete strength of 15 N/mm<sup>2</sup> was assumed for initial trial calculations. Then, the system was analyzed for different values of spacing, and the bearable loadings were calculated for each spacing, and each reinforcing arrangement by a reverse calculation of the procedure explained in BS 8110 part 1:1997 (British Standards Institution, 1997). A typical model developed by SAP 2000 software (the model developed for the arrangement shown in Figure 3) is shown in Figure 7.

Figure 8 shows the results obtained by computer simulations (Only hogging bending moment is shown here as it was the critical parameter). It shows the moment capacities for different top

**Figure 7. A typical model obtained by computer simulations with strips only in one direction.**



**Figure 8. Actual bending moments and moment capacities of different reinforcing arrangements when the strips in one direction are removed.**



reinforcing arrangements described in Section 3, and the actual bending moments for different strip-spacings.

Those results suggest that any form of the selected top reinforcement can satisfy the moment resistance required. However, the strips should be spaced in less than 540 mm if no top reinforcement is provided.

This last option was selected for further analysis due to the convenience in construction.

#### 4.2. Step 2: Discontinuing the strips

As it has been mentioned in Section 3, the next step was to find out the optimum arrangements by varying the spacing between strips. A set of computer models were developed for various options of strip-spacing (number 1 in Figure 5), spacing between supports (number 2 in Figure 5) and length of the supports (number 3 in Figure 5). The optimum arrangements obtained for three different values of strip-spacings are presented in Table 1.

**Table 1. The optimum arrangements obtained for different values of strip-spacing**

Spacing between strips (mm)	Spacing between supports (mm)	Length of the supports (mm)
("1" in Figure 5)	("2" in Figure 5)	("3" in Figure 5)
300	400	300
400	300	300
500	100	200



#### 4.3. Flat slab arrangement

The next option was to minimize the size of the supports and to support the system by a set of blocks. In this case, the protective screed layer behaves as a flat slab. Figure 9 shows the actual bending moments and the moment capacities for different block-spacings with a 50 mm × 50 mm gauge 12 mesh as reinforcement.

The results suggest that it is possible to achieve the required structural capacity, if the blocks are spaced at 150 mm or less in both directions.

#### 4.4. Step 4: Selecting a suitable width of the strips/supports

Since the height of the supporting strips is small in comparison with its cross-sectional area, the buckling failure was ruled out. Hence, the minimum width required was calculated by a compressive strength calculation. The results obtained are shown in Table 2.

Results show that a minute width is sufficient to carry the load. However, a minimum width of 25 mm is selected owing to the practicality of construction.

#### 4.5. Step 5: Selecting the best system

The next step was to single out a system out of the four options short-listed (shown in Table 3). Since the intention is to optimize the system, it was intended to minimize the concrete area in the layer, since concrete increases the composite conductivity of the layer as it is not an insulation material.

Figure 9. Bending moments and moment capacities of the protective screed with a 50 mm × 50 mm gauge 12 Mesh for a flat slab arrangement with different support spacings.

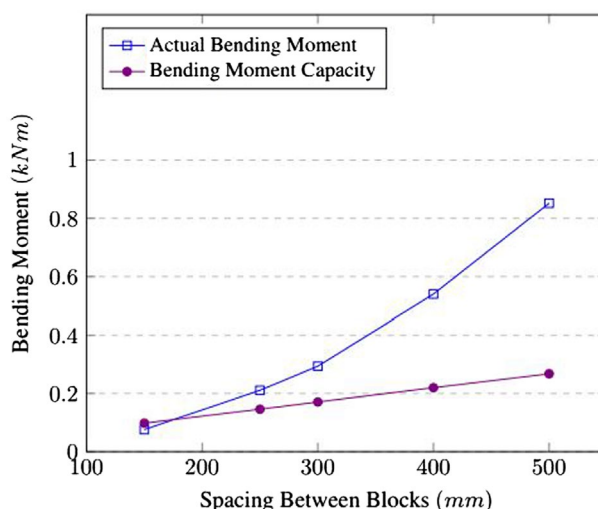
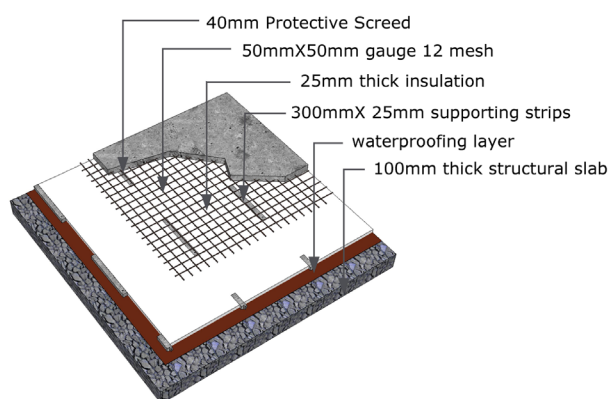


Table 2. Calculations for finding minimum width of strips

Calculation	300 mm spacing between strips	400 mm spacing between strips	500 mm spacing between strips	Flat slab arrangement
Effective area (m <sup>2</sup> )	0.21	0.24	0.15	0.04
Dead load (kN)	0.21	0.24	0.15	0.04
Live load (kN)	1.05	1.20	0.75	0.20
Design load (kN)	1.97	2.26	1.41	0.38
Minimum area of support (mm <sup>2</sup> )	131	150	94	25
Minimum required width (mm)	0.44	0.50	0.47	5.00



**Figure 10. Isometric view of the derived system.**



The concrete/total area ratio of the existing system is shown in Table 3 for comparison purpose. It clearly shows that all the systems selected have a much lower concrete area than the existing system. The system with the lowest concrete area (the system with 400 mm strip-spacing) was selected as the best system. An isometric view of this system is shown in Figure 10.

#### 4.6. Step 6: Selecting a suitable concrete mix

The other variable fixed in Section 3 was the mix proportion of the concrete used. Since the supporting strips of the selected system are only 25 mm thick, it was necessary to specify a lower maximum aggregate size for the concrete. As chipped metal (with a maximum size of 10 mm) is a common construction material, a mix design was performed to achieve the assumed strength of 15 N/mm<sup>2</sup>. Several options were considered by varying the Water–Cement ratio from 0.6 - 0.8.

All the tested mixes gained the required strength of 15 N/mm<sup>2</sup>. Hence, the mix tried out for a water–cement ratio of 0.7, with 1:2:3 volume proportion of cement, sand and metal respectively was selected as the suitable mix proportion due to the convenience of specifying in practice.

#### 4.7. Physical model testing

The next step was to check the strength of the system by physical model testing. The system was loaded with a calibrated proving ring to measure the applied load, and the deflection was measured with a dial gauge. The experimental setup used is shown in Figure 11. Both the readings were continuously taken down till the system failed. The obtained load-deflection curve is shown in Figure 12.

The graph in Figure 12 shows that the system can be loaded up to about 30 kN without cracking, and the system can be loaded up to 37 kN (approximately 4MT) without failing structurally. This value is higher than any practical load specified in BS 6399-1: 1996 (British Standards Institution, 1996). Therefore, it is proven that this system is structurally sound.

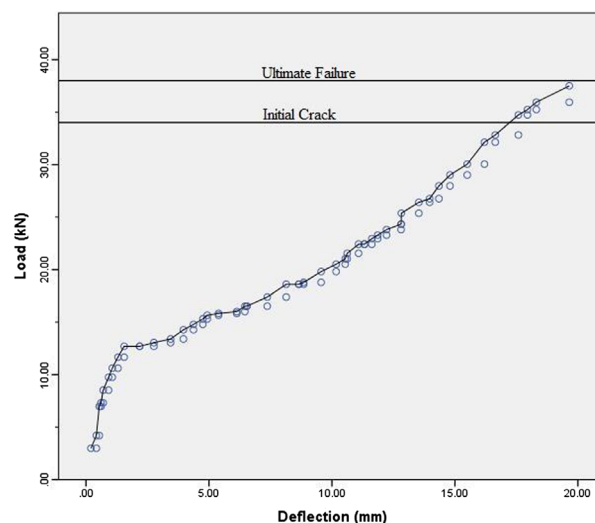
**Table 3. Calculations for finding minimum width of strips**

Calculation	300 mm Spacing	400 mm Spacing	500 mm Spacing	Flat slab	Existing system (Halwatura & Jayasinghe, 2008)
Concrete area (m <sup>2</sup> )	3.71	3.51	3.57	5.61	16.16
Total area (m <sup>2</sup> )	97.5	105.5	101.5	99.0	100.8
Concrete ratio	3.8%	3.3%	3.5%	5.7%	16.0%

**Figure 11. Experimental setup of the actual scale testing.**



**Figure 12. The graph of load vs. deflection obtained by actual scale testing.**



Even though the deflection showed higher values, it was observed that the top screed sags independently without affecting the structural slab. Hence, it was not considered as a serviceability failure of the system.

## 5. Discussion

The necessity of a supporting arrangement for the top screed was to make the insulation system structurally sound, eliminating the restriction for loading the roof slab. The system designed addressing that issue had a durability issue since a drainage path was not provided for the penetrated water. The major aim of developing a new system was to address those two issues.

The actual scale testing in Section 4.7 proved that it is structurally sound, by withstanding a 4 MT point load on the system. Since the supporting strips are discontinued, a drainage path is provided within the insulation layer, addressing the issue of durability.

However, since this is a thermal insulation system, it is necessary to compare the thermal performance of the system with existing techniques.

**Table 4. Comparison of thermal conductivities of the new system and the existing system**

System	Composite conductivity of the insulation layer ( $\text{Wm}^{-1}\text{K}^{-1}$ )	Composite conductivity of the system ( $\text{Wm}^{-2}\text{K}^{-1}$ )
The existing system (Halwatura & Jayasinghe, 2008)	0.039	1.1
Newly designed system	0.034	1.0

An adjustment for thermal conductivity values was necessary to be made since the insulation layer consists of a set of concrete supports within the insulation layer. The adjustment was made according to Equation (1) (Progelhof, Throne, & Ruetsch, 1976).

$$\frac{1}{K_I} = \frac{1 - \phi}{K_p} + \frac{\phi}{K_c} \quad (1)$$

where  $K_I$  is the thermal conductivity of the composite insulation layer ( $\text{Wm}^{-1}\text{K}^{-1}$ );  $K_p$  is the thermal conductivity of the insulation material – polystyrene ( $\text{Wm}^{-1}\text{K}^{-1}$ );  $K_c$  is the thermal conductivity of concrete ( $\text{Wm}^{-1}\text{K}^{-1}$ );  $\phi$  is the volume fraction of concrete.

A comparison of the conductivity values between the newly designed system and the system by Halwatura and Jayasinghe is shown in Table 4 (Please see Appendix A for detailed calculations). It shows a 9% reduction of heat transfer in the new system.

The system by Halwatura and Jayasinghe has proven to achieve a 75% heat reduction into the buildings (Halwatura & Jayasinghe, 2008). Table 4 shows that the newly designed system has a lower thermal conductivity. Hence, the newly designed system should theoretically have a heat gain reduction of more than 75%.

A few limitations of this study can be identified. First, the optimization technique used is simple as it is performed by varying the structural arrangement and mix proportions. A further optimization may be performed by replacing the materials with newly invented, more effective materials, either as the insulator or as a structural element.

In this study, the thickness of the insulation material was taken to be 25 mm. Thus, the only mode of failure of the supporting strips considered was crushing. However, if a researcher intends to vary the thickness of the insulation, other modes of failure like buckling should be considered depending on the thickness considered.

## 6. Conclusions

Roof slab insulation is very significant to mitigate and adapt to global warming. Developing an insulation system that is thermally effective, structurally sound and durable was the main objective of this study. A system that contains an insulation layer on top of the structural slab and a protective screed on top of it, which is supported by a set of discontinuous concrete strips was selected as the option to develop. The discontinuity of the strips provides a drainage path, making the system more durable in comparison with similar existing techniques, while the concrete strips provide the structural stability. The optimization was performed by finite element modeling. It was found out that a set of 300 mm × 25 mm strips in 300 mm longitudinal clear spacing and 400 mm transverse spacing cast by 1:2:3 chip-concrete with a water-cement ratio of 0.7 can withstand an imposed load of 5 kN/m<sup>2</sup>, which is the maximum specified for a roof. An actual scale physical model withstood a 4MT-point load, emphasizing that the system is structurally sound. A calculation of composite conductivities and a comparison with an existing system has proven that this system can reduce the heat gain into a building by more than 75%.

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## Author details

Kasun Nandapala<sup>1</sup>

E-mails: [mpkcnandapala@gmail.com](mailto:mpkcnandapala@gmail.com), [kasuncn@uom.lk](mailto:kasuncn@uom.lk)

ORCID ID: <http://orcid.org/0000-0003-4088-2987>

Rangika Halwatura<sup>1</sup>

E-mails: [rangikauh@gmail.com](mailto:rangikauh@gmail.com), [rangika@uom.lk](mailto:rangika@uom.lk)

ORCID ID: <http://orcid.org/0000-0002-9206-5607>

<sup>1</sup> Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka.

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## Appendix A

### Calculating thermal conductivity of the insulation layer

For the Newly Designed System, (The assumed thermal conductivities are shown in Table A1)

**Table A1. Thermal conductivities of the materials used**

Material	Thermal conductivity (Halwatura & Jayasinghe, 2007)
Concrete	$1.7 \text{ W/m}^{-1}\text{K}^{-1}$
Polystyrene	$0.033 \text{ W/m}^{-1}\text{K}^{-1}$

$$\begin{aligned}\frac{1}{K_I} &= \frac{1-\phi}{K_p} + \frac{\phi}{K_c} \\ &= \frac{1-3.3\%}{0.033} + \frac{3.3\%}{1.7}; \quad (\phi = 3.3\% \text{ by Table 3}) \\ K_I &= 0.034 \text{ Wm}^{-1}\text{K}^{-1}\end{aligned}$$

For the Existing System,

$$\begin{aligned}\frac{1}{K_I} &= \frac{1-\phi}{K_p} + \frac{\phi}{K_c} \\ &= \frac{1-16\%}{0.033} + \frac{16\%}{1.7}; \quad (\phi = 16\% \text{ by Table 3}) \\ K_I &= 0.039 \text{ Wm}^{-1}\text{K}^{-1}\end{aligned}$$

### Calculating thermal conductivities of the systems themselves

**Table A2. Surface resistances of roof slab (Halwatura & Jayasinghe, 2008)**

Location	Symbol	Surface resistance
Top surface	$R_T$	0.04
Soffit	$R_S$	0.14
Insulation system	$R_I$	(calculated above)

$$\begin{aligned}\text{Thermal Resistance of the New System} &= \frac{T_1}{K_1} + \frac{T_2}{K_2} + \frac{T_3}{K_3}; (T_i - \text{Thickness of the layer}) \\ &= \frac{0.04}{1.7} + \frac{0.025}{0.034} + \frac{0.1}{1.7} \\ &= 0.82 \text{ m}^2 \text{ KW}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Air-to-Air Resistance of the New System} &= R_T + R_I + R_S \\ &= 0.04 + 0.82 + 0.14 \\ &= 1.0 \text{ m}^2 \text{ KW}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Hence, the Composite Conductivity of the newly designed system} &= \frac{1}{1.0} \\ &= 1.0 \text{ Wm}^{-2} \text{ K}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Thermal Resistance of the Existing System} &= \frac{T_1}{K_1} + \frac{T_2}{K_2} + \frac{T_3}{K_3} \\ &= \frac{0.04}{1.7} + \frac{0.025}{0.039} + \frac{0.1}{1.7} \\ &= 0.72 \text{ m}^2 \text{ KW}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Air-to-Air Resistance of the Existing System} &= R_T + R_I + R_S \\ &= 0.04 + 0.72 + 0.14 \\ &= 0.90 \text{ m}^2 \text{ KW}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Hence, the Composite Conductivity of the existing system} &= \frac{1}{0.9} \\ &= 1.1 \text{ Wm}^{-2} \text{ K}^{-1}\end{aligned}$$



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