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# DEVELOPING A STRUCTURALLY SOUND AND DURABLE ROOF SLAB INSULATION SYSTEM FOR TROPICAL CLIMATES

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## Abstract

Flat roof slabs are gaining its popularity day by day due to its advantages like cyclonic resistance, possibility for future expansion and the possibility of using them as additional working space. However, the major issue associated with roof slabs is thermal discomfort, for which, active cooling in the forms of fans and air-conditioners is the most common remedy used. This has led to extensive use of energy, increasing the operational cost of the buildings and, in the macro scale, contributing to global warming as well. Hence, the current trend is to go for passive techniques. Insulating roof slabs is identified as a better passive way to address the stated issues. In this study, several existing roof slab insulation techniques were discussed and their benefits and drawbacks were identified. While ensuring the same thermal and structural capacity of the insulation system, a new system was developed to address the drawbacks of existing systems. Computer based modelling were used to optimize the system and the small scale model testing was used to validate the results obtained by the computer simulations. Finally, a new insulation system was developed with enhanced thermal performance, structural capacity and the durability.

**Keywords:** *Passive Cooling, Roof Slab Insulation, Structural performance, durability*

## 1. Introduction

Due to the rapid development taking place in the last couple of decades, 'land' has become one of the most expensive commodities in the world, particularly in urban areas. In this context, multi-storey construction has widespread throughout the world as it enables the users to have a larger working area in a small footprint. Further, use of flat concrete roof slabs has aggravated its popularity as it allows the flexibility to the users to use the space as either a working space or a roof top garden (Banting, 2005; Berardi, GhaffarianHoseini, & GhaffarianHoseini, 2014; Halwatura, 2013). In addition, robustness that a concrete roof slab incorporates to a building enhances the disaster resistance, particularly against cyclones (Halwatura, Mallawarachchi, & Jayasinghe, 2007).

Nevertheless, since concrete is a relatively high thermal conductor, it gets heated up in the daytime and emits long wave radiation to the space underneath, causing a severe thermal discomfort to the occupants in its topmost floor. It has been found that if this issue can be addressed, it will make flat concrete roof slabs more popular among the general public (Nandapala & Halwatura, 2014).

The most common remedy adapted to address this issue is, active means of cooling in the form of fans and air-conditioners. Even though that it solves the issue of thermal discomfort, it is at a higher cost in the form of higher usage of energy, leading us back to the biggest issue that the current world is facing, Global Warming.

It has been found out that in Singapore, buildings use up to 57% of the total energy usage of the country (Kwong, Adam, & Sahari, 2014), and In Malaysia, a country with a similar tropical climatic conditions, more than 30% of the total energy usage is for making buildings thermally comfortable (Dong, Lee, & Sapar, 2005). This proves that around 20% of the total energy used in tropics is for providing thermal comfort in buildings. It is obvious that this is beyond the world can afford, implying that the use of active cooling techniques is not an appropriate solution for thermal comfort in long run. Hence, passive cooling techniques have become popular in the world (Al-Obaidi, Ismail, & Abdul Rahman, 2014; Alvarado & Martínez, 2008; Sadineni, Madala, & Boehm, 2011), insulation in particular (Al-Homoud, 2005; Brito Filho & Santos, 2014; Dylewski & Adamczyk, 2014).

There are several roof insulation techniques tried out in the world, and their heat reduction potentials have been studied. Applying a cool paint is one such technique. In a research carried out in Florida, USA, it has been proven that up to 38% energy saving can be obtained by applying a cool paint (Parker & Barkaszi Jr., 1997). Another research in Italy, a reduction of 54% energy demand is observed (Romeo & Zinzi, 2013). In Greece a set of researchers has used a 60mm air gap as an insulator, and obtained a daily heat gain reduction of 56% (Dimoudi, Androutsopoulos, & Lykoudis, 2006). There is another technique used in Sri Lanka with a 25mm polyethylene layer as the insulator, proving a heat reduction of 75% can be obtained in a tropical climatic condition (Halwatura & Jayasinghe, 2008).

Above figures incontrovertibly suggest that insulation can be very effective in any climatic condition. Since this study focuses on tropics, the system developed in Sri Lanka is found to be the most recent and the best to suit the conditions. However, there are some drawbacks associated with this method. The issues associated and the proposed remedies are discussed in this paper.

## 2. Findings so far

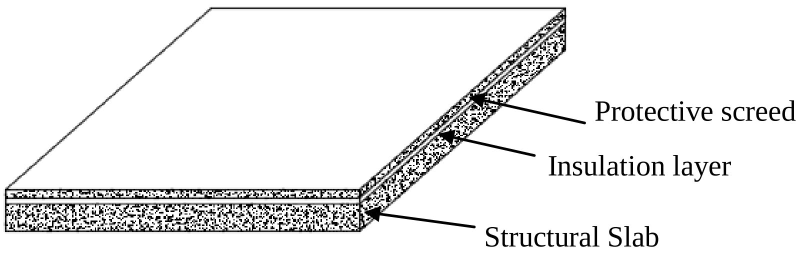


Figure 10: insulation system with a continuous insulation layer

As it has been mentioned, thermal discomfort is the dominant drawback associated with roof slabs, and for which insulation has been identified as a better remedy. The most common arrangement used in practice is shown in Figure 10.

This system is implemented and tested practically, and proven that this performs really well in thermal aspects. However, this imposes a restriction on loading since a layer of weak material is sandwiched in the system.

Figuring this out, a system has been developed with a set of continuous concrete strips within the insulation layer as shown in Figure 11 (Halwatura & Jayasinghe, 2008). This is proven to be structurally sound, with the capability of bearing any practical load acted on a roof.

However, leakages of slabs were observed in long run in the slabs constructed. After an investigation, water was found to be stagnant in the areas where insulation material is. This can be elaborated as follows;

The supporting arrangement of this system in the insulation layer (plan view) is shown in Figure 12. There’s no drainage path for a water drop which passes through the cracked screed to the insuation layer, as the insulation material is enclosed by a set of continuous concrete strips. The waterproofing layer that is used in slabs is not designed to withstand a water head, hence has failed.

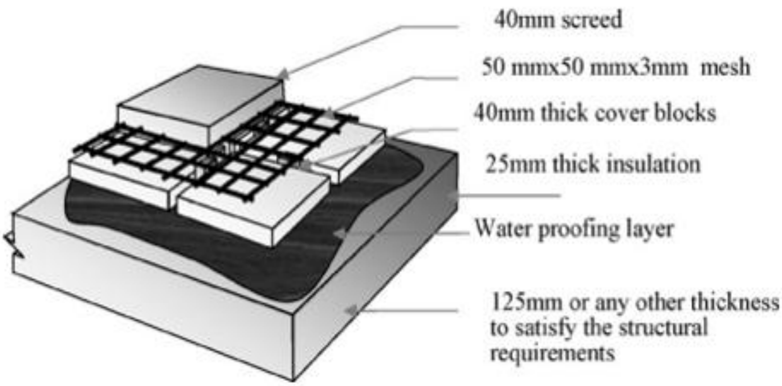


Figure 11: The system with continuous concrete strips (Halwatura & Jayasinghe, 2008)

Hereafter, this paper describes the conceptual design of a drainage path within this insulation system.

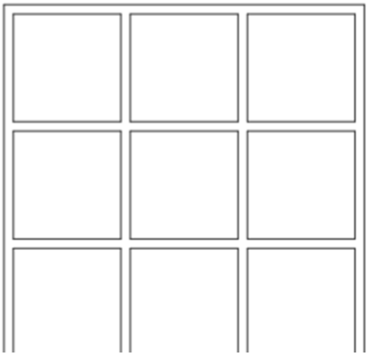

Figure 12: Supporting arrangement of screed within insulation layer in the system with continuous concrete strips (plan view)

## 3. Methodology

A literature survey has been carried out to figure out the requirement of such a technique in the local context. Further, the existing techniques that have been tried out throughout the world were studied, and the systems that is most efficient has been picked out for further improvement.

Then those particular systems is further investigated by means of a further literature review and a field study to identify the practical issues to be addressed.
In the study, it has been identified that structural performance and the durability are the main issues associated with those systems. The method that was adapted to address those is described throughout this paper.

## 4. The Conceptual Design

### 4.1 STEP 1: REMOVING STRIPS IN ONE DIRECTION

The first option considered was to remove strips in one direction as shown in Figure 13. The objective of designing the system, in first place, is to remove the restriction for loading. Hence, the system has 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 that is $5kN/m^2$, which is the maximum specified in BS6399-1:1996 (Code of Practice for Dead and Imposed Loads).

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

1. Spacing between strips
2. Size of strips
3. Mix proportion of concrete used.
4. Reinforcement arrangement of the top screed.

An optimum spacing for the system was to be found out for the system. Because the system could have failed if the strips are too far apart of each other, and the effectiveness of the system reduces drastically if they are placed too closer by since the insulation material is replaced by concrete

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Reducing the concrete area as much as possible is a major objective in this optimization process of the system. Hence, a minimum size that can bear the predicted load had to be found out.

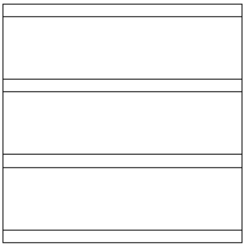

Figure 13: supporting arrangement after removing strips in one direction

The mix proportion to be used in the strips plays a major role as well. It has to be strong enough to carry the load, and should be able to be compacted in an area of a width of 40mm. Hence, a concrete with a lower maximum aggregate size (chip-concrete) was used. A suitable proportionating was necessary to be done.

The screed had to be designed as a slab itself as this system is to be used as a load bearing structure. Since concrete is a material which is very weak in tension, some arrangement of steel had to be incorporated into the system. Several options of having two reinforcement nets were considered. Bottom reinforcement was tried fixed to a 2” x 2” gauge 12 mesh due to the convenience of construction. There were four options considered for the top net: no reinforcement, a 6mm mild steel bar near supports, a 10mm tor steel bar near supports and a same type of a mesh (double nets), with an obvious preference for the ‘no top reinforcement’ case over others.

Since it was not practical to play with all the variables, size of strips was fixed to 50 mm and the concrete was assumed to have a strength of 15 $N/mm^2$ for initial evaluations. The results obtained by computer simulations by varying the spacing of the strips and type of reinforcement is shown in Figure 5. It suggests that the system can be implemented without any top reinforcement if the strips are provided in a spacing of less than 540 mm (

Figure 14). at this stage, the finalized values for the four variables stated above are as follows;

1. Spacing between strips – 540 mm
2. width of the strips - 50 mm
3. Strength of concrete used – 15 $N/mm^2$
4. Reinforcement arrangement of the top screed – a single net of 2” x 2” gauge 12 mesh

## 4.2 STEP 2: OPTIMIZING THE STRIP IN ITS LONGITUDINAL DIRECTION

As it has been stated, reducing the concrete area within the insulation layer is a prime objective of this study. Hence, several options were considered to select the optimum arrangement, varying the spacing of the strips (in transverse diration). In this case, there were three additional variables considered.

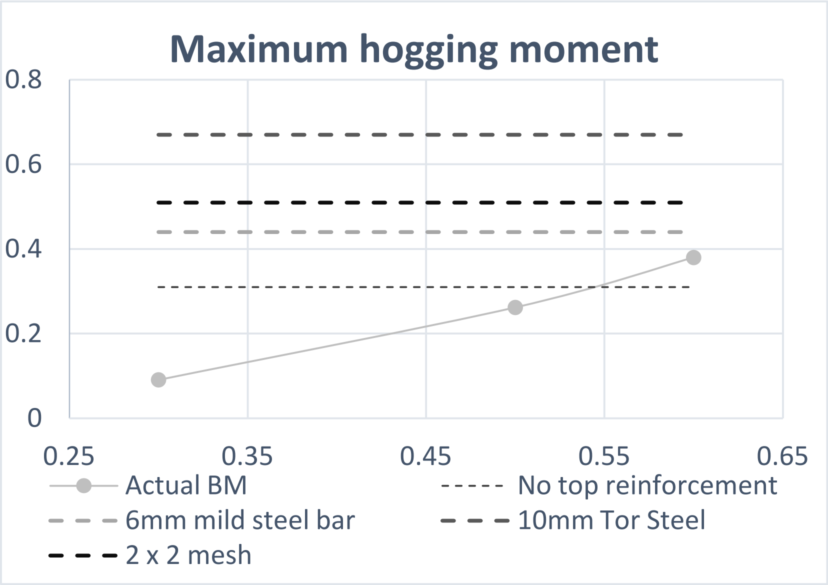


Figure 14: Bending moments and bending moment capacities for different reinforcing arrangements

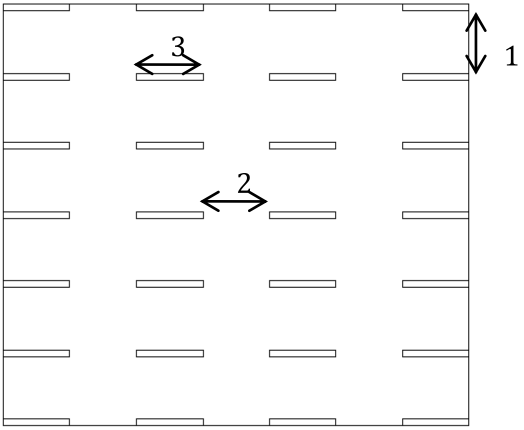


Figure 15: Variables to be considered in optimizing the strips in longitudinal direction

1. Transverse spacing of strips ( number 1 in
2. Figure 15)
3. Longitudinal spacing between strips ( number 2 in
4. Figure 15)

5. Length of the strips (number 3 in
6. Figure 15)

Sixty possible options were considered by varying these variables and three feasible options were picked out considering the structural aspects (Table 1).

Table 1: The short-listed systems with discontinuous concrete systems with supports

| span in transvers direction(mm) | Length of the strip(mm) | Clear spacing between strips (mm) |
|---|---|---|
| 300 | 300 | 400 |
| 400 | 300 | 300 |
| 500 | 200 | 100 |

## 4.3 STEP 3: FLAT SLAB ARRANGEMENT

The options considered so far were of a typical beam-column supporting system of a slab. However, it was worthwhile to consider the option of a flat slab arrangement too. The results obtained are shown in Figure 16 (only hogging bending moment is shown as it was the critical aspect considered). The results suggested that it is possible to implement this system if 50 mm blocks are spaced at 150 mm.

## 4.4 STEP 4: SELECTING A SUITABLE WIDTH OF THE STRIPS

The major objective of this study was to find out the optimum supporting arrangement to carry any possible load acting on it. Further, in section 3.1, only two out of four variables in total were considered in the design. In this step, the minimum width of the strip has been worked out.

Since the height of the supporting strips is short with respect to other length, the most likely way is to fail in compressive strength. Hence, the minimum width required is calculated by a simple compressive strength calculation. The results are as shown in Table 2.

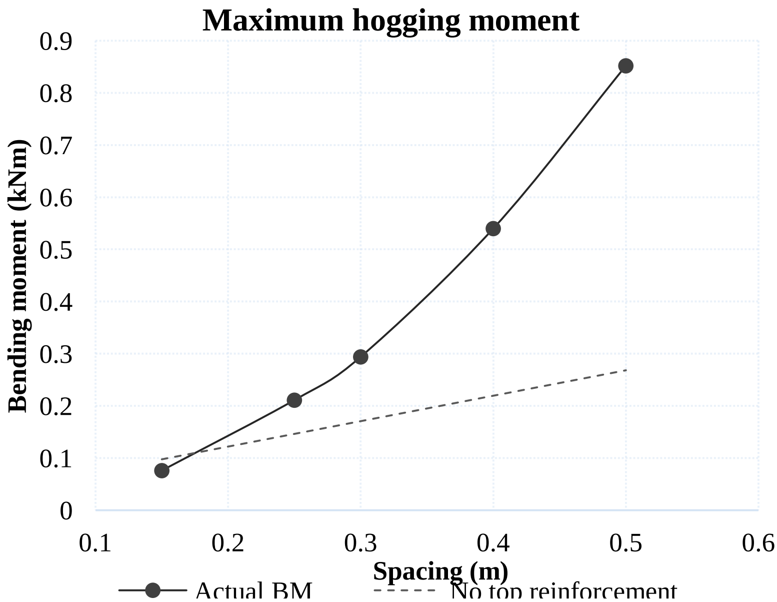


Figure 16: Bending moments and bending moment capacities of flat slab arrangements with different spans

It shows that a very small width is sufficient to carry the load. However, a minimum width of 25mm is selected considering the practical construction aspects.

Table 2: Calculations for finding minimum width of strips

| | **300mm in transverse** | **400mm in transverse** | **500mm in transverse** | **Flat slab arrangement** |
|---|---|---|---|---|
| effective area ($m^2$) | 0.21 | 0.24 | 0.15 | 0.04 |
| Dead load (kN) | 0.2076 | 0.2394 | 0.153 | 0.0399 |
| live load (kN) | 1.05 | 1.2 | 0.75 | 0.2 |
| total load kN (with partial factors of safety) | 1.97 | 2.26 | 1.41 | 0.38 |
| minimum area ($mm^2$) | 131.38 | 150.34 | 94.28 | 25.06 |
| minimum width (mm) | 0.44 | 0.50 | 0.47 | 5.01 |

## 4.5 STEP 5: SELECTING THE BEST SYSTEM

As the process suggests so far, the possible options for the structural arrangement is short-listed to four. The next step was to pick one out.

Since the objective is to minimize the concrete area within the insulation material as much as possible, the concrete area of approximately100 $m^2$- slab was considered. As Table 3 suggests, the flat slab arrangement has a significantly higher percentage than other options, which are more or less having a similar area of concrete. The second option has the lowest value and hence was selected for actual scale testing.

## 4.6 STEP 6: SELECTING A SUITABLE CONCRETE MIX

The other variable that was fixed in section 3.1 was the mix proportion of concrete used. Since the supporting strips are of 400 mm x 25 mm, it was necessary to specify a lower maximum aggregate size for concrete. As chipped metal with a maximum size of 10 mm is a common construction material a mix design was performed to achieve a strength of 15N/$mm^2$. Several options were considered as shown in Table 3.

Table 3: concrete areas of the four short-listed systems

| | **300mm in transverse** | **400mm in transverse** | **500mm in transverse** | **Flat slab arrangement** |
|---|---|---|---|---|
| Concrete area ($m^2$) | 3.71 | 3.51 | 3.57 | 5.61 |
| Total Area ($m^2$) | 97.5 | 105.5 | 101.5 | 99.0 |
| Ratio | 3.8% | 3.3% | 3.5% | 5.7% |

All the mixes tested did achieve the target strength of 15 N/$mm^2$. The next step was to specify a volume batch mix proportion to be used in the industry. From a simple calculation it has been found out that the mix with water-cement ration of 0.7 has roughly 1:2:3 proportion of cement, sand and metal respectively.

## 4.7 STEP 7: ACTUAL SCALE TESTING

Having finalized the system, the next step was to validate results by actual scale casting. The system was loaded with a proving ring calibrated to measure the load applied. The deflection with the applied load was measured by a dial gauge. Both readings were continuously taken till the system fails entirely. The results are shown in Figure 8.

The graph in figure 8 shows that the system can be loaded higher than 30kN without a serviceability failure. This is sufficient to carry any practical load on top of a roof.

## 5. CONCLUSIONS

Using flat slabs as roofs is a good strategy to recover the land, one of the scarcest resources in an urban environment. Further, it enhances the robustness of structures and thereby increases the resistance to natural disasters, of which the intensity and the severity increases day-by-day as a result of the climate change in the world. However, it increases thermal discomfort in the uppermost floor as the slab acts as a heated body and emits longwave radiation to the immediate space underneath. Mechanical cooling is the most common remedy used in the industry, but it increases the energy consumption which is not favourable for a sustainable world.

Table 48: Mix design options tested to obtain 15 $N/mm^2$ strength

| W/C ratio | Cube # | Load (kN) | Size of the Block | | Strength (N/mm2) | Average Strength (N/mm2) |
|---|---|---|---|---|---|---|
| | | | Length (mm) | Width (mm) | | |
| 0.78 | 1 | 517.8 | 150 | 153 | 22.56 | 22.48 |
| | 2 | 530.4 | 148 | 151 | 23.73 | |
| | 3 | 478.3 | 155 | 146 | 21.14 | |
| 0.75 | 1 | 506.3 | 150 | 151 | 22.35 | 23.78 |
| | 2 | 526.7 | 151 | 149 | 23.41 | |
| | 3 | 594.7 | 155 | 150 | 25.58 | |
| 0.70 | 1 | 478.8 | 150 | 153 | 20.86 | 23.97 |
| | 2 | 562.5 | 148 | 147 | 25.85 | |
| | 3 | 551.5 | 150 | 146 | 25.18 | |
| 0.65 | 1 | 536.4 | 150 | 150 | 23.84 | 25.40 |
| | 2 | 567.2 | 146 | 148 | 26.25 | |
| | 3 | 599.5 | 153 | 150 | 26.12 | |
| 0.60 | 1 | 683.4 | 150 | 153 | 29.78 | 27.63 |
| | 2 | 589.1 | 149 | 151 | 26.18 | |
| | 3 | 609.3 | 155 | 146 | 26.92 | |

In this context, insulation of slabs has gained the popularity among the researchers in the modern world. There are many such techniques developed in the world, of those the most effective method was selected. A field study was done to identify the performance of the system. It was noted that this system has a drainage issue as some instances the slabs have become leaked.

The system was further investigated to find out the reason, and a separate technique was developed with a minimum concrete area and a proper drainage path. It has been found out that 300 mm x 25 mm strips with 300 mm clear span, and a transverse spacing of 400 mm is structurally capable.

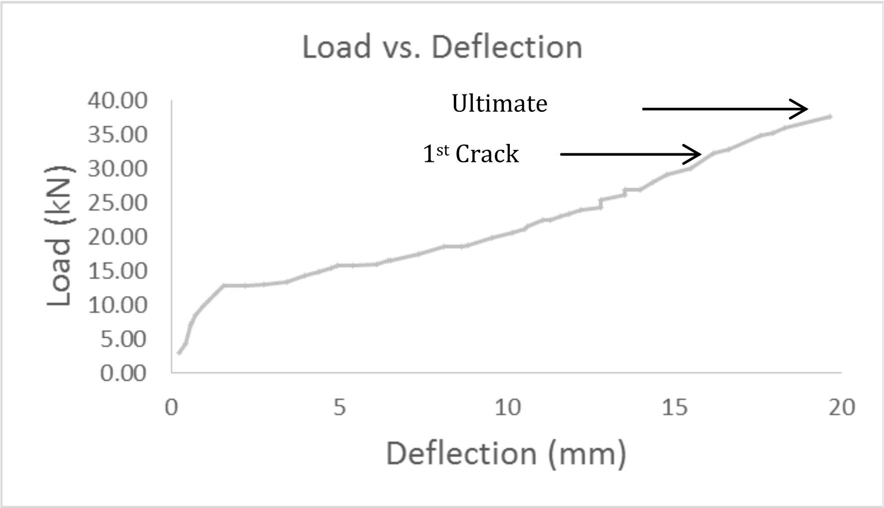


Figure 17: Load Vs. Deflection curve of the actual scale testing

A mix design was done to obtain the required strength out of chip-concrete and 1:2:3 proportion of cement, sand and metal with a water/cement ratio of 0.7 is found to be sufficient to be used in the system.

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