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Development of sustainable retrofitting material for energy conservation of existing buildings

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Abstract

Energy conservation in buildings plays a vital role for sustainable development of societies and nations. Although, newer buildings in developing nations are being constructed using energy conservation approach, existing buildings have higher energy demand to meet the desired comfort. Excessive energy demand for cooling the built environment is a major problem over most of the arid climatic zones. The problem is predominant in all the top storied buildings which are directly under exposed roof condition. In order to reduce the overheating of the roof surface a composite combination of reflecting-cum-insulating (R-I) material was developed. The sustainable materials viz., expanded polystyrene (construction waste), saw dust (industrial waste), and the false ceiling panels prepared from industrial waste were used for the development of sustainable R-I material. The R-I material was retrofitted over the existing roof of a model room in an educational building over composite climate (Nagpur, India) and was analyzed experimentally for the period of a year. The thermal resistance of the overall roof assembly was increased from 0.28 to 0.55 m² K/W, which in turn helped to achieve 16% of the duration of the year under thermal comfort. The developed R-I material has also an advantage of low cost (INR 900 per sq. m.) of installation as well as light weight (50 kg/m²) retrofitting solution. The R-I product can further be applied on larger roof areas by the designers to reduce the cooling load of the built environment as well as increase the occupants comfort over the local climatic zone.

Keywords: *Energy conservation, Cooling demand, Sustainable reflecting-cum-insulating (R-I) material, Low cost, Light weight.*

1. Introduction

Thermal insulation plays significant role in reducing cooling requirement inside a building in hot climate. Improved thermal insulation of the buildings results in better comfort and conservation of energy that is otherwise required for excessive cooling. In a typical commercial establishment space conditioning account for 50-70% of the total energy used [1]. Large organizations across the globe today are working on programs to perform energy efficiency retrofits that guarantee energy and cost-savings. Appropriate material selection plays significant role for energy conservation inside the buildings. The roof of buildings receives the thrust of heat during the day. The construction practices adopted mainly involve concrete as the roofing element which is noted for its high thermal conductivity.

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The exposed roof surfaces absorb solar heat that will input continuous heat inside the building and will add to the cooling load.

Thermal barrier provided in buildings are generally installed either as over or under deck insulation. Al-Homoud [2] presented an overview of the basic principles of thermal insulation along with detailed investigations on the most commonly used building insulation materials and their performance characteristics. Alvarado *et al.* [3] investigated the thermal effects of newly designed passive cooling systems on concrete roofs in existing buildings. Each tested passive cooling system consists of a combination of materials that can reduce heat load in buildings. Commercially available materials such as aluminum-1100 and galvanized steel were used as radiation reflectors; and polyurethane, polystyrene, polyethylene, and an air gap were used as insulation. Experimental results based on laboratory-scale prototypes showed that the developed passive cooling system led to reduction in heat conduction by 65%. Double envelope roof constructions were investigated either as a preheating system of the external air [4] or as a double shell system in tilted roofs [5]. In this case, ambient air passes through the air gap that incorporates a wet surface into its lower part, becomes cooler through evaporation and thus, lowers the surface temperature of the internal part of the roof. The

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developed computational model resulted in 47.5% reduction in the wetted surface temperature as compared to ambient temperature. Heat-insulating materials used as additions to mixtures with high porosity provide an effective means of reducing the apparent density and improving the refractory properties of manufactured components. Materials of natural occurrence – vermiculite, diatomite, infusorial earth, perlite [6-9], as well as synthetic materials - hollow microspheres obtained by sputtering of high-melting oxides such as Al_2O_3, mullite, spinel can be used as porous fillers. However, the hollow spheres are costly products and are normally used to fabricate special high-temperature heat insulators [10]. Al-Malah and Abu-Jdayilb [11] made focus on the formulation of polyester–clay composite as an insulating material. Researchers concluded that the developed product can improve the thermal resistance of conventional walling systems by 50%. Korjenic *et al.* [12] developed, optimized and observed the behavior of thermally insulating materials composed of renewable raw material resources originating from agricultural sources which could be used in new building structures and for renovating the existing structures. He revealed that with the increase in moisture content, thermal conductivity of the proposed insulating material (Hemp fibers) reduces. The rooftop lawn is seen to have many merits such as; reduction in the air conditioning load of buildings and contribution to the mitigation of the heat island phenomenon. In earlier research on rooftop spraying system, Hasegawa and Konna [13] carried out an analysis on the thermal effect of spraying system on slant roof. Tanabe *et al.* [14 & 15] carried out the field study on a rooftop spraying system. The effect of roof spraying contributed to room temperature reduction in the summer season. Regarding the rooftop lawn, Ishihara *et al.* [16] investigated the thermal characteristics and water performance of rooftop lawn experimentally. On the other hand, Hoyano *et al*. [17] analyzed the indoor thermal control effect of rooftop lawn planting with thin soil layer on a wooden building. Al-Sanea [18] evaluated and compared the thermal performance of building roof elements subject to steady periodic changes in ambient temperature, solar radiation and nonlinear radiation exchange. An implicit, control volume finite-difference method was developed and applied for six variants of a typical roof structure used in the construction of buildings in Saudi Arabia. The dynamic R-values of the roofs were determined under the climatic conditions of Riyadh for representative days for July and January. The results, when compared with a reference uninsulated roof section using a heavy weight concrete foam as a leveling layer, produced the following: 45% of the reference daily average heat-transfer load when using a light weight concrete foam; 32%, 27% and 22% of the reference daily average heat-transfer load when using a 5-cm thick layer of insulation made of molded polystyrene, extruded polystyrene and polyurethane, respectively. Tsang [19] developed a theoretical basis of green roof thermal performance and applied theoretical calculations to estimate the effectiveness of green roof thermal performance and associated energy saving. He concluded that green roof can block excess solar heat gain upto 24% as compared to bare roof.

The literature review reveals that the substantial amount of energy is required for space conditioning. The appropriate design of thermal barrier over the roof surfaces plays significant role to increase the thermal comfort inside the buildings. Application of appropriate reflecting–cum-insulating material either over or under the roof slab is an effective solution to conserve the energy and the cost of operation (cooling load) as well. A very few research revealed the application of sustainable materials for the reduction of overheating in buildings. The present paper focuses on retrofitting of a sustainable reflecting-cum-insulating material for reducing cooling load of the built environment. The composite R-I combination with false ceiling developed from industrial waste was experimentally designed and the techno-economic feasibility of the product was analyzed over the specific geographic location.

2. Methodology

To provide the retrofitting solution by the application of sustainable R-I material for reducing cooling load of the built environment the following stepwise methodology was adopted.

- The ambient temperature data over the specific geographic location was collected for the study of thermal variations.
- The volume of the built room under the study was estimated.
- The structural element compositions and their thermal behavior were analyzed experimentally to prioritize the elements for retrofitting.
- Locally available low cost sustainable materials were identified.
- Possible suitable reflecting and insulating materials and the several combinations like over deck and under deck application were analyzed for the best possible heat insulation by estimating thermal resistance of the assembly as a whole.
- The developed composite R-I combination retrofitted over the study room were analyzed further experimentally and statistically (using the area under the curve approach) to check the effectiveness of thermal barrier at various retrofitted layered assembly.
- The developed R-I combination was checked for economic viability and structural loading.

The outcome of the application of the developed R-I combination is emphasized in terms of reduction of heat load in the built environment.

3. Experimentation

A non air conditioned test room of dimension

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3.2X3.2X4.0 cum was selected for the thermal environmental analysis at VNIT, Nagpur (Latitude: 2106 'N, Longitude: 79°03 'E, Elevation: 310 m.), India (Fig. 1). The geographic location has varying seasonal conditions as summer (February-May), rainy (June–September), winter (October-January). The monthly average ambient temperature and relative humidity are in the range of 27-41°C and 24-70% respectively [20]. The roof of the test room is made up of conventional concrete slab (0.15 m. thick) and is directly exposed to sun. The vertical walls are made up of burnt clay bricks with a wooden door (0.9X2.1 m.) on North facing wall and a window (1X1.2 m.) on the West and South wall. West facade has a common porch of 1.5 m. width due to which there is no direct entry of sun through the window. The wall on East is surrounded by adjacent rooms.

The internal (I) surfaces (I-Roof, I-South, I-West, I-East, I-North, I-Floor) of the test room were monitored over three months of time (September–November 2010) on alternate hourly basis during working hours (8 am to 6 pm). For analyzing the thermal behavior of all the construction elements the internal surface temperature data were recorded (Fig. 3) with the help of temperature gun (Fig. 2). The temperature data was recorded on four corners as well as center of all the surfaces and average values were used for the analysis. Fig. 3 indicates that roof surface is the primary concern due to which there is excess heating in the model test room.

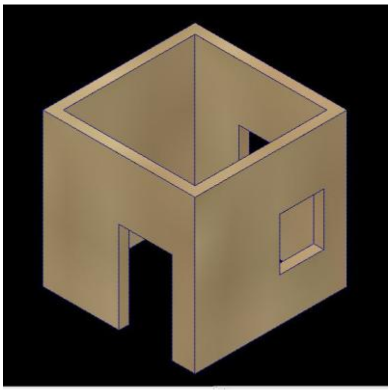

Fig. 1 Layout of test room

Fig. 2 Temperature gun

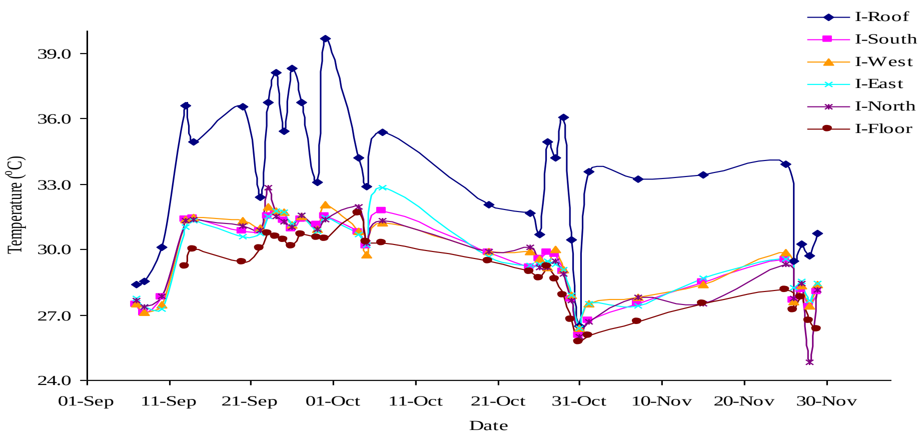

Fig. 3 Indoor temperature vs date

Retrofitting an appropriate R-I material is an apt solution to enhance the thermal performance of the conventional concrete roof and to reduce the cooling load inside the building. To design a sustainable composite assembly of R-I material locally available raw materials were identified. The thermal conductivity (k) of selected R-I materials were considered from the available standard [21].

For the R-I composite locally available sustainable and waste materials were used. The test samples of different combinations as insulating material with expanded polystyrene (15mm thick), mortar (5mm thick), and saw dust (0.05mm thick) were chosen. The glazed tiles and aluminum foil were selected as reflecting material. The different combinations of reflector and insulator were prepared in a sample size of 2'X2'. Four different combinations (expanded polystyrene+ ceramic tile) (Fig. 4), (expanded polystyrene + saw dust + glazing tile) (Fig. 5), (Expanded polystyrene with aluminum sheet) (Fig. 6), and (Expanded polystyrene with saw dust and aluminum sheet) (Fig. 7) were tested experimentally (9th -19th May 2011). To analyze the best possible combination for the heat reduction of the roof surface, the surface and sub surface readings of the four different combinations were recorded with the temperature gun over the roof in shadow free area.

Fig. 4 Expanded polystyrene & ceramic tile

Fig. 5 Expanded polystyrene with saw dust and broken glazed tiles

Fig. 6 Expanded polystyrene with aluminum sheet

Fig. 7 Expanded polystyrene with saw dust and aluminum sheet

The temperature differences were recorded on hourly basis during peak summer season (9th -19th May 2011), where during day time ambient temperature raised up to 47°C. The tested reflector-cum-insulator (R-I) combinations resulted in an average temperature difference findings over and under the R-I combinations (Fig. 8). Fig. 8 indicates combination 4 (Expanded polystyrene + saw dust + aluminum sheet) had the best performance followed by combination 3, 2 and 1 respectively.

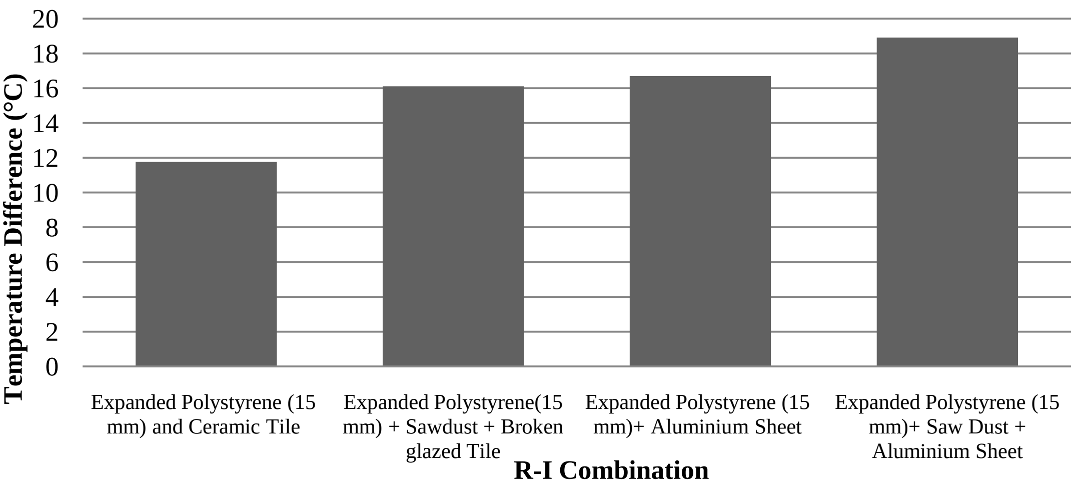

Fig. 8 Recorded temperature difference between over and under R-I combinations

Therefore, combination 4 was selected as best retrofitting over the roof for the heat reduction among the four combinations. The selected composite assembly of locally available materials, expanded polystyrene (15mm thick), mortar (5mm thick), saw dust (0.05mm thick) and reflectors with aluminum foil (reflectivity (r) 0.80, [21]) was applied over the RCC roof surface (150 mm thick). The commercially available aluminum was reinforced with expanded polystyrene and sawdust composite. From the industrial waste available false ceiling material (12 mm thick) was selected as an insulating material with thermal conductivity (k) as 0.3 W/m K [22].

A non-ventilated air cavity of 1 m. (Thermal conductance (C_a) as 6.22 W/m²K, [21]) was maintained between concrete roof slab and the false ceiling. The reflecting material was then retrofitted over the deck (Fig. 9) and the composite insulator assembly was retrofitted as under the deck (Fig. 10). Experimental temperature log for various surfaces of the designed composite roof were recorded with the help of contact type temperature sensors and data logger (Fig. 11).

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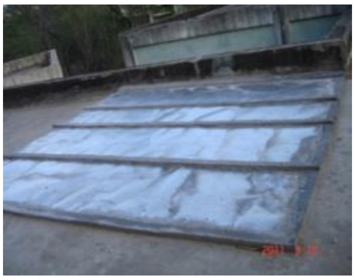

Fig. 9 Retrofitted expanded polystyrene with saw dust and aluminum sheet

Fig. 10 Retrofitted industrial waste material false ceiling

Fig. 11 Temperature data logger

4. Results and Discussion

Fig. 12 shows the retrofitted overall assembly of aluminum over the concrete roof with the false ceiling developed from the industrial waste. The thermal conductivity of the assembly (expanded polystyrene with saw dust and aluminum sheet) was estimated using Lee's Disc Apparatus. After substituting all the desired inputs in equation 1 thermal conductivity of the R-I assembly was found out to be 0.268 W/m K.

$$K = \frac{M * S * D * \frac{dT}{dt}}{3.14 * \mathrm{r}^2 * (\mathrm{T2} - \mathrm{T1})} \qquad (1)$$

Where;

M - Mass of metallic disc = 776 grams.

S –Specific heat of material disc = 4186.1 J /kg °c

D – Thickness of bad conductor whose conductivity has to be found =20 mm.

r – Radius of bad conductors whose conductivity has to be found = 15 mm.

dT/dt – Rate of cooling found from graph (Fig. 13) = 0.16

T_2 and T_1 steady temperature of steam and of metallic disc.

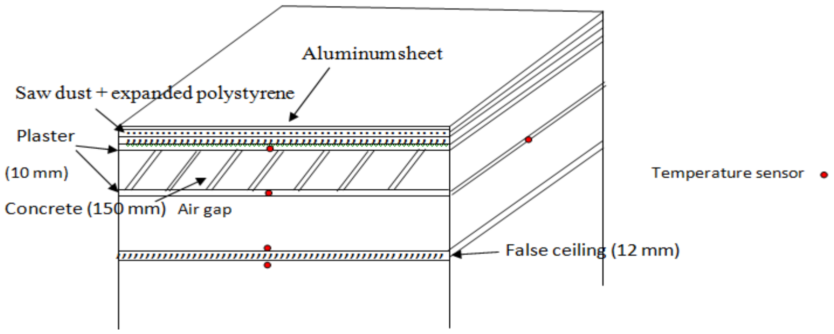

Fig. 12 Overall R-I combination retrofitted over the existing concrete roof

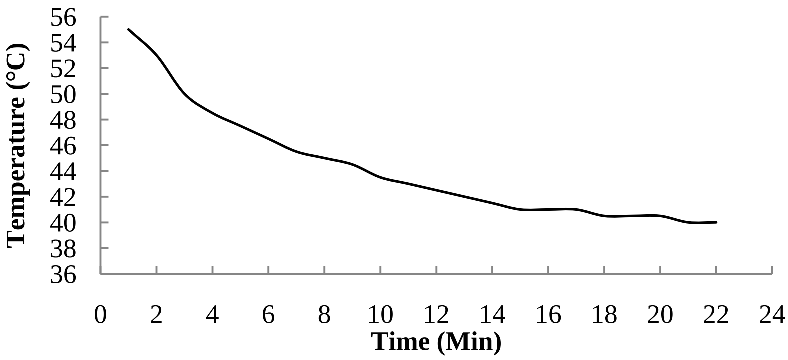

Fig. 13 Temporal temperature profile

To reduce the cooling load of the built environment, the thermal conductivity of various materials used for the development of composite roof slab (Fig. 12) was studied further (Table 1) [21]. In order to evaluate the effectiveness, the overall thermal resistance for the developed sustainable R-I combination was estimated using equation 2 as 0.55 m² K/W. The overall thermal resistance of untreated concrete roof slab in combination with the external and internal plaster including film coefficients was estimated as 0.28 m^2 K/W. Therefore, the retrofitted R-I combination over the concrete roof resulted in 1.9 times increase in thermal resistance.

Table 1 Thermal conductivity of the applied materials

Sr No	Materials for roof assembly with thickness in m.	Thermal conductivity, *k* (W/mK)
1	Aluminum + expanded polystyrene + saw dust (0.02005)	0.268
2	External plaster (0.010)	0.721
3	Concrete slab (0.150)	1.580
4	Internal plaster (0.010)	0.721
5	False ceiling (0.012)	0.3
6	Air gap (1)	Thermal conductance, C_a=6.22 W/m²K [21]

Total thermal resistance (R_T) of overall R-I composite assembly was estimated using Eq. 2 [21]

$$R_T = \left[\sum_{i=1}^{7}\left(\frac{L}{K}\right)_i\right] + \frac{1}{C_a} + \frac{1}{f_i} + \frac{1}{f_o} \;=\; 0.55 \text{ m}^2\text{ K/W} \qquad (2)$$

Where; L-Thickness of material (m),
k- Thermal conductivity (W/mK),
C_a - Thermal conductance of air (W/m²K),
f_i − Inside film coefficient = 9.36 ,
f_o − Outside film coefficient = 19.86

To analyse the thermal variations of the assembly below concrete slab (untreated & treated) and at false ceiling bottom surface with respect to ambient temperature, hourly temperature data were recorded over the period of September–November (Fig. 14 & Fig. 15). Using the area under the curve approach, the estimated areas under untreated concrete slab and false ceiling (bottom) were estimated as 2783 sq. units and 2506.9 sq. units respectively. Thus, when compared with internal untreated concrete roof slab, the average temperature reduction at the bottom surface of false ceiling was estimated as 11% (Fig. 15).

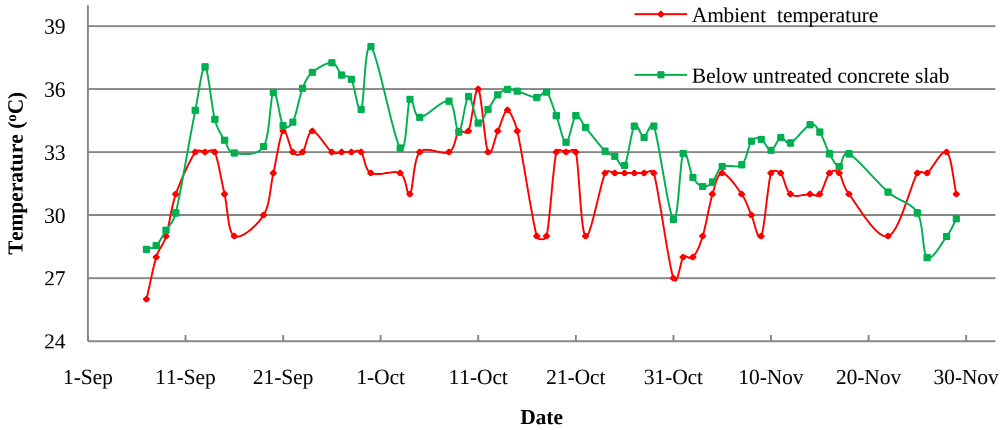

Fig. 14 Thermal variations below untreated concrete slab

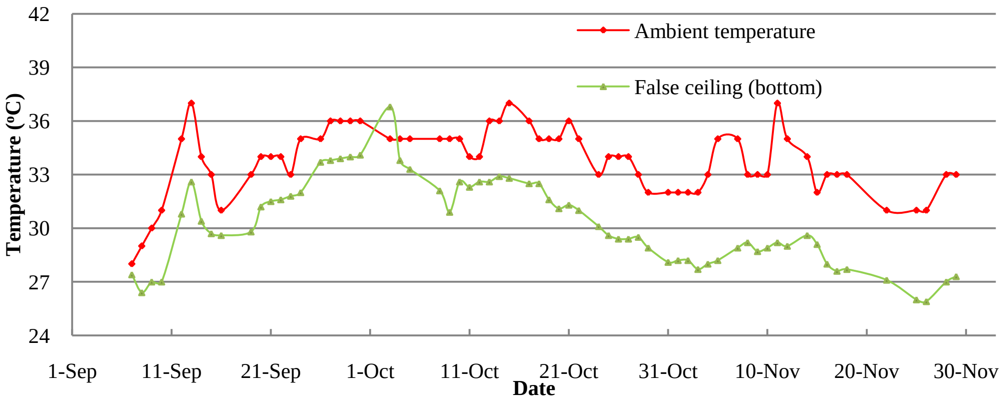

Fig. 15 Thermal variations below treated concrete slab and false ceiling

For the retrofitted R-I assembly the temperature log were recorded for a year (July 2011-12) over the various salient composite roof surfaces (Fig. 12). Fig. 16 indicates the temperature control in the built environment of test room over various salient surfaces. Using the similar (area under the curve) approach the area under the internal treated concrete slab was estimated as 12056 sq. units and internal exposed false ceiling bottom surface was computed as 11355 sq. units. Thus, reduction of 709 sq. units in temperature was resulted as compared to concrete slab and 16% of the area at the bottom of false ceiling was observed under comfort zone (18-27°C). In turn, that helped to reduce the cooling load of the built environment.

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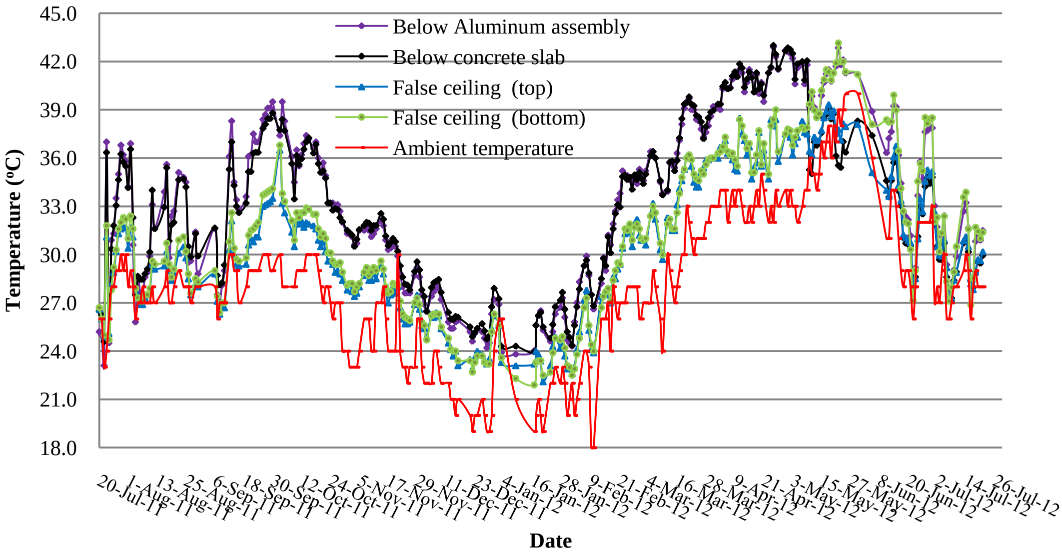

Fig. 16 Overall thermal variations below treated concrete slab

To reduce the cooling load of buildings, the reviewed literature [3, 5, 11, 18, 19] showed the application of several insulating and reflecting materials like polyurethrene foam, double envelope tilted roofs, insulate walling system, corrugate metal sheets, etc. Although, aforesaid approaches could achieve significant reduction in thermal conductivity (20-65%) there was a little discussion on physical control of the temperature inside the building. The approaches didn't thrust on use of sustainable materials as well as economic viability of reflecting cum insulating materials. The developed R-I assembly resulted in 49% reduction in the thermal conductivity which helped to achieve the thermal comfort for 16% of the duration of the year.

The developed R-I product from aluminium sheet, expanded polystyrene, saw dust were locally available materials and false ceiling panels were made up of industrial waste material. The R-I composite was cost effective (Rs. 900 per sq. m, Table 2) and can even be effectively retrofitted over the existing buildings due its low dead load (less than 50 Kg/m²). The approach can further be extended to larger roof areas for significant energy conservation in the built environment.

Table 2 Actual cost incurred for the R-I construction for 3.2 X 3.2 m^2 roof area

Sr. No.	Item	Lumsum Local Market Rate (Rs.)
1	Aluminium Sheet	2440
2	Expanded polystyrene	360
3	False ceiling (industrial waste)	4400
4	Mortar, Fibre Mesh+ Labour	1800
	Total	**9000**

5. Conclusion

Detailed analysis regarding thermal performance of considered exposed building surfaces (roof and walls) revealed that the roof surface is most predominant for causing excess heating within the built form.

Locally available sustainable materials (construction and industrial waste) were used to develop the appropriate R-I material. The developed R-I assembly resulted in 49% reduction in the thermal conductivity as compared to conventional untreated concrete roof. 11 % reduction in the average temperature at the bottom surface of false ceiling was resulted in comparison with bottom surface of untreated roof. The developed retrofit material resulted in 16% of the duration of the year under thermal comfort, which inturn will conserve energy required for meeting the cooling demand inside the building.

The sustainable composite material assembly can be effectively designed as per the geographic location and local climatic condition. As the retrofitting R-I material is lighter in weight (50 Kg/m²) and cost effective (Rs. 900 per sq. m) it can be effectively applied to the larger areas for reducing cooling load of the built environment.

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