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Sustainable Roofs for Warm Humid Climates - A Case Study in Residential Buildings in Madurai,tamilnadu, India

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Abstract: Roof thermal performance is one of the most important factors for achieving indoor thermal comfort in tropical houses designed for natural cross ventilation. This research aims to find the suitable roof constructions for naturally ventilated residential buildings in warm humid climates of India. The research has been carried out at Madurai, Tamilnadu, India. The roof constructions included the types which are widely used in Residential Buildings in Madurai and also the new ones. This study, based on field study data, discusses roof design strategies for a warm-humid climate by investigating the impacts of roof thermal performance on indoor thermal comfort in naturally ventilated houses. This study is aimed to find the roof constructions which gain the least amount of heat during the hottest days of summer and to find how much thermal comfort is provided though out the year. In this respect the Traditional Madras terrace roofs and the Sloped Reinforced concrete roofs with clay tile roof showed the best performance. It was experimentally demonstrated that it is possible to maintain the indoor temperature 2°C -6°C lower than the outdoor temperature using passive roofing in a warm humid climate. This study uses an experimental approach in which the measurements of outdoor and indoor environments are conducted on residential buildings during extreme summer days. The Thermo physical properties of the roofs are also analyzed.

Key words: Roof thermal performance · Warm humid Climate · Passive Cooling · Thermal Comfort · Thermal Transmittance · Average Temperature

INTRODUCTION

Generally, the tropical climatic countries have a high population density. Most of these countries still remain as developing countries. With the economic development, the energy consumption for thermal comfort is also rising. Many designers in this region have ignored the climate in their designs, primarily because they are pre-occupied with fashionable building forms [1]. They have tried to separate the building from nature rather than integrate it. Once separated, indoor thermal comfort should be achieved using air-conditioners, fans etc. As a result, such buildings using expensive heating, cooling and lighting systems are highly dependent on mechanical and electrical systems to control the indoor environment of occupants. This situation in turn provokes the consumption of large quantities of fossil fuels that causes a severe negative impact on the environment. Therefore, it is necessary to modify these trends and to apply corrective measures oriented towards the application of sustainable actions in buildings and communities likewise.

The thermal performance of the building envelope can make a significant contribution in reducing the overall building energy usage [2]. The building envelope such as the interface between the interior of the building and the outdoor environment, including the walls, roof and foundation serves as a thermal barrier and plays an important role in determining the amount of energy necessary to maintain a comfortable indoor environment relative to the outside environment. Minimizing heat transfer through the building envelope is crucial for reducing the need for space heating and cooling.

The primary function of building envelope is to control the solar heat loads. It is necessary to shield any windows from direct sun penetration and to reduce the heat transmitted through the sunlit walls and the roof. The east and west walls receive a good deal of radiation, but when the angle of incidence is small (early morning and late afternoon) the intensity of radiation is not at its maximum. The north and south walls receive comparatively little radiation and are much easier to shield with overhangs. The walls are easily shaded by

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overhanging eaves, verandas or verdant environment and therefore gradually acquire temperatures near to the air temperature. However, the roof is the most exposed to impacts of solar radiation, as it receives sunlight for practically the whole of the day and in the tropics the angle of incidence is close to the normal in the hotter parts of the day. Heat gain through roof elevates ceiling surface temperature and causes radiant heat load on the occupants [3]. Roofs in particular are envelope components for which advanced solutions can provide significant energy savings in cooled buildings or improve indoor thermal conditions in not cooled buildings [4]. The term roof includes the roof structure, the outer covering and layers of insulating materials or membranes and the ceiling.

The thermal performance of a building is affected by the solar absorbance of roof. During a clear sky conditions up to about 1 KW/m² of radiation can be incidental on a roof surface and between 20% and 90% of this radiation is typically absorbed [5]. In many studies [6-8] the heat gain through the roof present 50% of the total heat gain in buildings. In recent years, several investigations were performed and showed that there can be multiple solutions to the excessive heat problem through the roof [9-11]. Nahar and Sharma in [12-14] conclude that the heat entering into the building structure through roof is the major cause for discomfort in case of non air-conditioned building or the major load for the air-conditioned building [10].

Warm climatic conditions generally prevail in low altitude areas between 15° north and south latitudes. A significant portion of the global population lives in this region, notably countries in North and South America, Africa, India, Indonesia, Malaysia, Thailand and the Philippines. In this region, the path of the sun generally goes through high altitudes during the daytime, subjecting the roofs of dwellings to intense sunlight. Unlike vertical surfaces such as walls, the roof is exposed to the sun throughout the daytime round the year, significantly contributing to building heat gain [15].

The roofing should be tightly fixed and the material should insulate the building from both excessive heat and humidity. Primary requirements for roofing: low thermal capacity (to avoid heat build-up, which cannot be dissipated at night, since there is no temperature drop); resistance to rain penetration, yet permeable enough to absorb moisture and release it when the air is drier; resistance to fungus, insects, rodents and solar radiation; good reflectivity (to reduce heat load and thermal movements); resistance to temperature and moisture fluctuations; freedom from toxic materials (especially if rainwater is collected from roofs). The optimization of the thermal performance of the roof can be achieved through different levels of thermal mass, insulation, geometry of ceiling, external colour and levels of ventilation (attic).

Optimizing roof materials can play a vital role in lowering down the heat built up in both air-conditioned spaces and naturally ventilated spaces. This research is designed to study the roof constructions in terms of thermal comfort of the users.

Experimental Procedure: This study aimed to find the roof construction which gains the least amount of heat during the hottest days of summer and provide thermal comfort throughout the year. This research aims to study the behavior of roofs in a climate where the warm period is longer than the cool period and thermal discomfort occurs in buildings only in summer.

Passive cooling is defined as the removal of heat of the building environment by applying the natural processes of elimination of heat to the ambient atmosphere by convection, radiation and evaporation or to the adjacent earth by conduction and convection. The term “passive cooling” was clearly defined by Jeffrey Cook as any building technique that not only avoids outdoor heat, but also transfers indoor heat to natural heat sinks [16]. The temperature of house is primarily dependent upon the temperature of the roof and walls. A 50% of the heat load in the building is from roof only. Therefore various roof treatments have been studied for comparing their effective passive cooling. Six roofs executed on various residences in Madurai, Tamilnadu, India which comes under Warm humid Climate have been considered for the present analysis. For this study Madurai city has been chosen because Madurai is fascinated by the interesting mix of architectural styles: the indigenous traditional and contemporary architecture of modern ages.

The study area Madurai, Tamilnadu, India comes under Warm Humid Climate zone. Warm humid climates have a temperature range from 64°F to 100°F (18-38°C). There is usually no great temperature difference between the seasons and night temperatures are close to daytime temperatures. Humidity is high during most of the year and can vary from 55% to 100%. Precipitation is quite high and can vary from 49” to 197” (1250-5000 mm). The air temperature and relative humidity are the important factors in determining the comfort level in warm humid region In this type of climate, the main function of the buildings is to simply moderate the daytime heating effects of the external air.

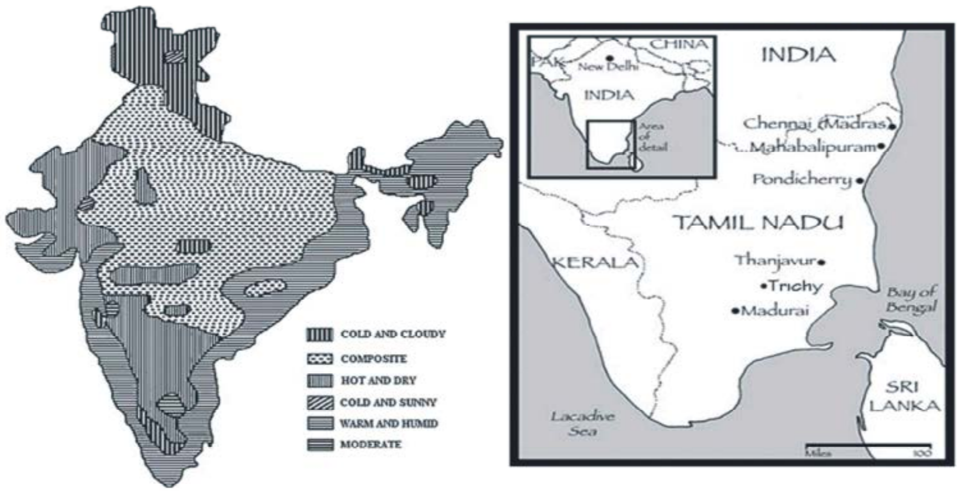

Fig. 1: Existing bioclimatic classification of India and Map showing Madurai in Tamilnadu, India

Table 1: Climate data for Madurai, India

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature Average high °C(°F)	30.6(87.1)	33.2(91.8)	35.8(96.4)	37.3(99.1)	37.7(99.9)	36.8(98.2)	36.0(96.8)	35.7(96.3)	34.8(94.6)	32.7(90.9)	30.6(87.1)	29.7(85.5)	34.24(93.64)
Temperature Average low °C(°F)	20.1(68.2)	21.1(70)	23.0(73.4)	25.4(77.7)	26.1(79)	26.1(79)	25.6(78.1)	25.3(77.5)	24.3(75.7)	23.6(74.5)	22.6(72.7)	21.1(70)	23.69(74.65)
Relative Humidity in %	66	60	54.5	61	56	56	56	56	65	68	78	71	62
Precipitation mm	7.4	11.8	14.1	37.1	72.6	32	83.2	80.3	146.9.	159.4)	140.3	53	838
Avg. precipitation days	0.9	1.1	1.1	2.4	4.4	2.0	3.6	4.1	7.8	8.1	6.3	3.4	45.1

Source: Indian Meteorological Department Mean data from 1971-2000

Madurai is located between 9° 58' North Latitude and 78° 00' East Longitude at an altitude of about 135 meters from sea level. Temperatures during summer generally reach a maximum of 40°C and a minimum of 26.3°C, although temperatures up to 42°C are not uncommon (Figure 1). The hottest months are from March to July (Table 1). Air temperature is moderately high with little variation between day and night. Relative humidity (RH) varies from 50% and 80% and wind velocity varies from 3.5 m/s to 7 m/s.

This study is an evaluation to the indoor thermal performance of various roofs in thermal performance of the residential buildings in the Warm humid climate Madurai, Tamilnadu, India. This study is carried out in three steps: first step, the field measurements were carried out in indoor of residential buildings using different roof solutions, standard Reinforced concrete slab with lime concrete terracing, Madras Terrace roof, Thatch roof, Reinforced concrete slab with filler materials and Reinforced concrete slab with roof shading by clay pots and clay tiles. The second step, calculation of the U-value of the selected roofs is done to find out which one has lower U-value and better insulation. In the third step a computer simulation Ecotect is utilized to find out the percentage of comfort provided by each roof throughout the year and a comparative evaluation of the selected roofs are done.

Experimental investigations of indoor/outdoor thermal performance of the selected roofs were done through field study. This was done to compare the direct effect of various roofs in the thermal comfort of indoor within the same condition of the outdoor ambient environment. The field measurement was not influenced by any shadows or reflected solar radiation since there were no high-rise buildings around it. The building was fully occupied by residents and no mechanical cooling was used during the field measurements period. The measurements of indoor and outdoor microclimates of test room with different types of roof treatments were conducted for 6 days starting from April 15 to April 19, 2013 which is the overheated period in summer in Madurai. The experiment was conducted to appreciate the traditional construction and to explore the present trends in house-building technology and identify the problem of designing roof for thermal comfort in warm humid zone. A data acquisition system (Easy log –Temperature (T) /Relative Humidity (RH) data logger) was installed in the test room of houses in Madurai with different passive roof construction. The outdoor air temperature, indoor air temperature and indoor humidity were monitored during the experiment. At this time the weather was reasonably clear and the outdoor air temperature in shade varied from 31 to 39°C in Madurai. The door was shut during the measurement while the window remains opened during daytime hours and was shut during night-time hours.

Table 2: U value of the experimented roofs

S.No	Type of Roof	U Value W/m2K
1.	RC slab with lime concrete Terracing	3.09
2.	Madras terrace roof	1.59
3.	Filler Slab	3.36
4.	Thatch roof	0.35
5.	Roof shading with inverted mud pots	2.04
6.	Roof shading with clay tile and air space in between	1.37

*Calculations detailed in appendix

The placement of sensors is illustrated in Fig. 10. The data were logged every 30 minutes using the data acquisition system for 6 days period in peak summer (April 15 to April 19 2013). The houses with uniform room sizes with uniform ceiling heights and window sizes have been chosen for the comparative study. The air velocities inside and outside the house were measured in different time of the day using a hand-held anemometer. The indoor air velocities were between 2 and 4 m/s. The outside readings were between 3 to 7 m/s.

When comparing the effect of changes to buildings, either changes to the building structure, the materials used or the installations, an important boundary condition is that the thermal comfort quality must, in all cases, be maintained [17]. The American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc (ASHRAE) provides guidelines that are intended to satisfy the majority of building occupants wearing a normal amount of clothing while working at a desk. The ASHRAE Standard 55-2004 specify that the occupants would feel comfortable at 27°C operative temperature and 75% relative humidity (with 0.27 Clo and 1 Met) if the air velocity was at least 1 m/s. In India according to the National Building Code (NBC) 2005, the thermal comfort of a person lies between 25°C and 30°C, with an optimum condition at 27.5°C. Sensible air movement of 1.5 m/s can make temperatures up to 35 deg C acceptable, which is rarely exceeded in warm- humid climates.

The most widely-used parameters for wall/roof thermal evaluations are the thermal transmittance, U and its reciprocal the thermal resistance, R. It is considered that the smaller U (the bigger R), the better the thermal performance [18]. As per Indian Standard I.S. code 3792 – 1978, the maximum value of overall thermal transmittance (U-value) of a roof should not exceed 2.33 W/m2-K in hot-dry and warm and humid climates [19]. The Thermal Transmittance value ('*U*' value) was calculated by the author for all the roofs and is presented in Table 2. Detailed calculations of the U value of the investigated roofs and the Thermo Physical properties of various materials used in the construction of investigated roofs are included in the legend.

Solar Reflectance is the fraction of sunlight that a surface reflects. Sunlight that is not reflected is absorbed as heat. Solar reflectance is measured on a scale of 0 to 1. Thermal emittance describes how efficiently a surface cools itself by emitting thermal radiation. Thermal emittance is measured on a scale of 0 to 1, where a value of 1 indicates a perfectly efficient emitter. Solar Reflectance Index (SRI) is another metric for comparing the "coolness" of roof surfaces. It is calculated from solar reflectance and thermal emittance values. The higher the SRI, the cooler the roof will be in the sun. The SRI for the roof coverings of the investigated roofs is included in legend.

Reinforced Concrete (Rc) Slab with Terracing of Brick Bat Lime Concrete and Weathering Tiles–reference Roof: With the advent of Reinforced Concrete, flat floors and roofs of all modern buildings are now a day's made of reinforced concrete. Horizontal slabs of steel reinforced concrete, typically between 100 and 500 millimeters thick, are most often used to construct floors and ceilings. A 10 cm thick layer of brick-bat concrete is laid, consisting of 3 parts of brick-bats, 1 part of gravel and sand and 50 percent of lime mortar by volume is laid over the RC slab. The concrete is well rammed so that the thickness reduces to 7.5 cm. When the brick bat is set a course of Madras flat tile (15cmx10cmx12mm) is laid in lime mortar (1:1 ½). The joints of tiles in top layer are left open to provide key for top plaster. Finally the top surface is plastered with three coats of lime mortar. This type of roof is conventionally used in most of the residences in warm humid climates in Tamilnadu which is taken as a reference roof for study.

The ease of maintenance and affordable costs, are making RC roofs the most popular roof form today. Vijaykumar *et al*. (2007) claim that Indian concrete roofs in single or two storey buildings with 150 mm thickness of

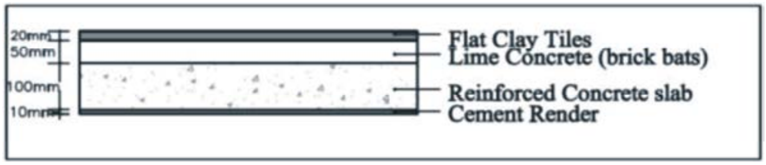

Fig. 2: Schematic diagram of Flat clay tiles laid on cement concrete on the Reinforced concrete slab

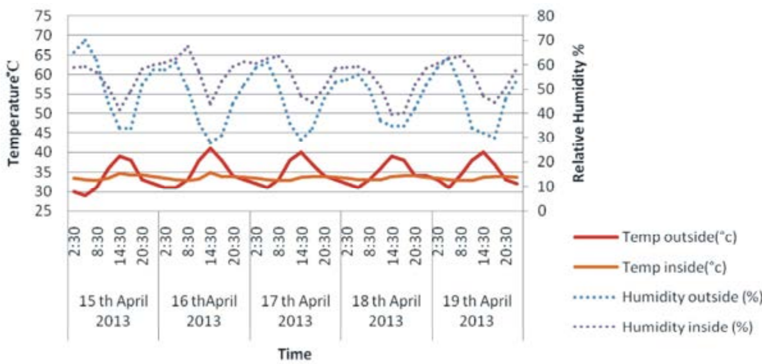

Fig. 3: Temperature /Humidity Graph - Reinforced Concrete roof

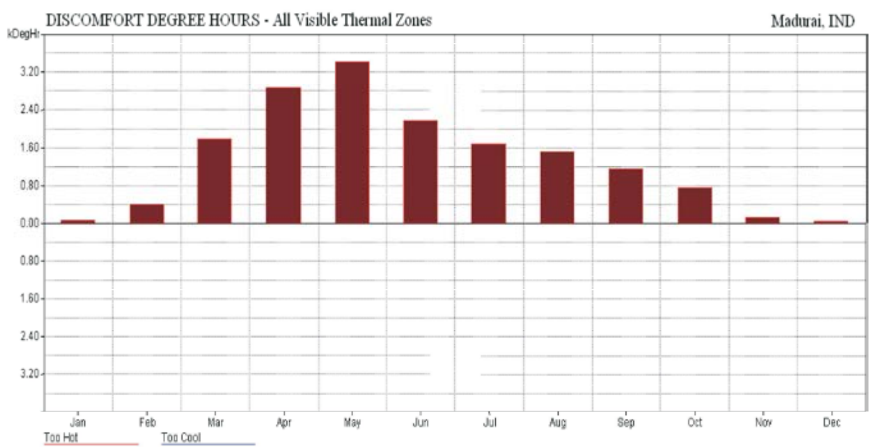

Fig. 4: Conventional Reinforced Concrete roof slab, Monthly load discomfort; Discomfort Degree Hours too hot = 19197.1 too cool = 0;total discomfort = 19197.1; Annual Comfort Distribution 4828 Hrs (55.1%)

reinforced cement concrete (RCC) and a weathering course (WC) having 75–100 mm thick lime brick mortar, account for about 50%- 70% of total heat transmitted into the occupant zone and are responsible for the major portion of electricity bill in air-conditioned buildings [13]. RC slabs absorb a great deal of heat which continues to be emitted through the night time affecting the comfort of residents. Though thermal improvements are done with terracing the thermal performance of roofs exceeds the comfort limits during the extreme summers. Schematic diagram (Figure 2), indoor thermal performance (Figure 3) of the room with RC roof with terracing of Brick Jelly Lime concrete and weathering tiles and annual comfort distribution chart generated by ECOECT software (Figure 4) are presented below.

Madras Terrace Roofing (Traditional Building): Wooden beams, normally teak wood in those days, would be first placed upon opposite walls across the width of the room, 450 to 600 millimeters apart. In case room spans are wider, steel sections would be first placed dividing the room into shorter spans, along which teak beams run. High density and high strength clay bricks, made to special thin size measuring 25mm x 75mm x 150mm, are used in Madras terracing. Properly mixed and matured lime mortar is used for bonding the flat tiles that are placed at an angle of 45 degrees to the wall, or diagonally across the room width. These terrace tiles, placed on the edge, ensured tensile strength. Thereafter, a three-inch thick layer of broken bricks or brick bats would be laid where nearly half the volume would be made up of lime

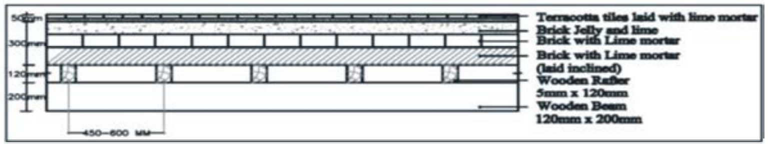

Fig. 5: Schematic diagram of Madras Terrace roof

Fig. 6: Interior View of the ceiling with Madras Terrace Roof

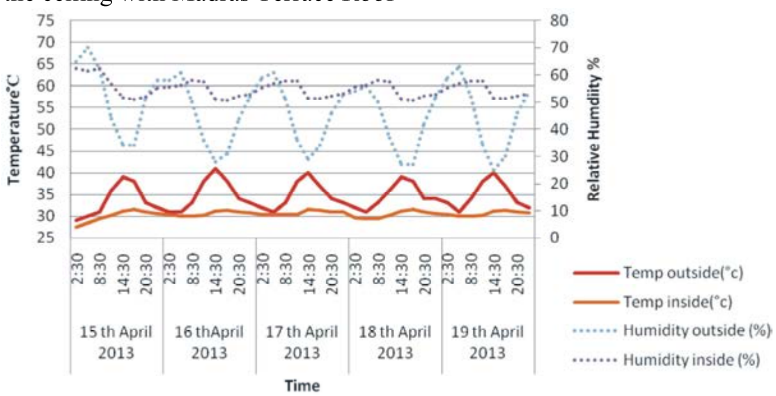

Fig. 7: Temperature /Humidity Graph - Madras Terrace roof

mortar, three parts brick, one part gravel and one part sand. This layer provided the compressive strength and load bearing capacity to the roof. This layer needs to be well compacted, cured and leveled. The final layer would depend upon the slab being an intermediate one or the final roof. If intermediate, a floor finish like red oxide or lime mortar would be applied and if final, there would be courses of flat weather-proof tiles topped by thick mortar to slope.

This system with wooden cross beams does not need centering, allows faster construction and demands less structural skills. Instead of the same old terrace tiles, thin perforated weather proof tiles, cladding tiles and such others that can be used to build up the roof, supported by steel sections. The main components of roof are clay tiles, lime mortar and timber. All these components have a very low effective thermal conductivity and do not allow the horizontal surface to gain any heat throughout the day and a stable internal temperature is maintained all the time. Schematic diagram (Figure 5), interior view of the room with Madras Terrace roof (Figure 6), indoor thermal performance of the room with Madras Terrace roof (Figure 7) and annual comfort distribution chart generated by ECOECT software (Figure 8) are presented below.

Filler Slab: The filler slab is a mechanism to replace the concrete in the tension zone. The filler material, thus, is not a structural part of the slab. By reducing the quantity and weight of material, the roof become less expensive, yet retains the strength of the conventional slab. The most popular filler material is the roofing tile. Mangalore tiles are placed between steel ribs and concrete is poured into the gap to make a filler slab. The structure requires less steel and cement and it is also a good heat insulator. Light weight, inert and inexpensive materials such as low grade Mangalore tiles, Burnt Clay Bricks, Hollow Concrete blocks, Stabilized Mud blocks/ Hollow Mud blocks, Clay pots, Coconut shells etc. can be used as filler materials. These materials are laid in the grids of steel reinforcement rods and concreting/concrete topping is done over them. The quantity of concrete in the tension zone of the slab that can be replaced by a filler

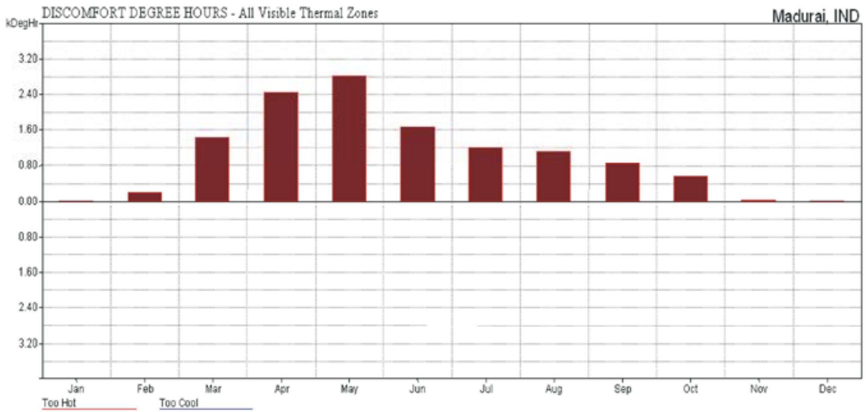

Fig. 8:. Madras Terrace roof Monthly load discomfort; Discomfort Degree Hours too hot = 12408.5, too cool = 0; total discomfort = 12408.5; Annual Comfort Distribution 6100 Hrs (69.6%)

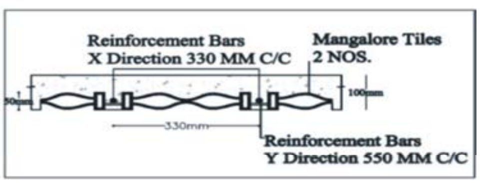

Fig. 9: Schematic diagram of Filler slab with cement render outside only

Fig. 10: Interior view of the room showing the position of Data Logger

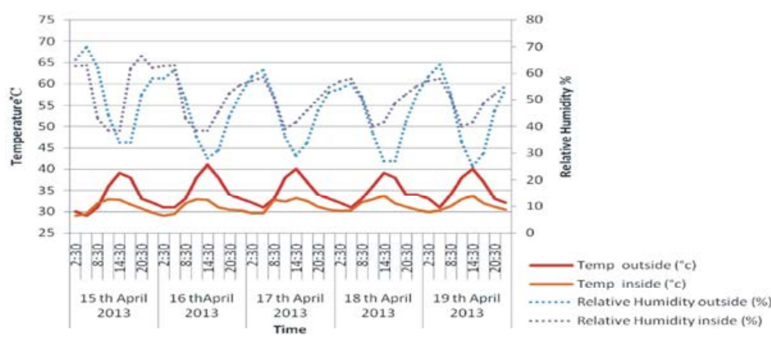

Fig. 11: Temperature /Humidity Graph -Filler Slab

material depends upon the shape of the filler material and the thickness of the solid slab. The air pocket formed by the contours of the tiles makes an excellent thermal insulation layer.

The filler slab chosen for the experimental study consists of Filler materials like Mangalore tiles/Clay tiles installed in two layers (2 nos. one over the other) entrapping an air cavity between the two tile. A pair of Calicut tiles at the centre of each rectangular space between the reinforcement steel. There should be a clear cover of reinforcement (minimum 15 mms). Each pair of Calicut tiles were accurately laid in a line. The filler material is left open without plastering to form aesthetic design symmetry. Schematic diagram (Figure 9) interior view of the room showing the position of the Temperature/Relative Humidity Data logger (Figure 10) indoor thermal performance of the room with Filler slab with cement rendering on outside only (Figure 11) and annual comfort distribution chart generated by ECOECT software (Figure 12) are presented below.

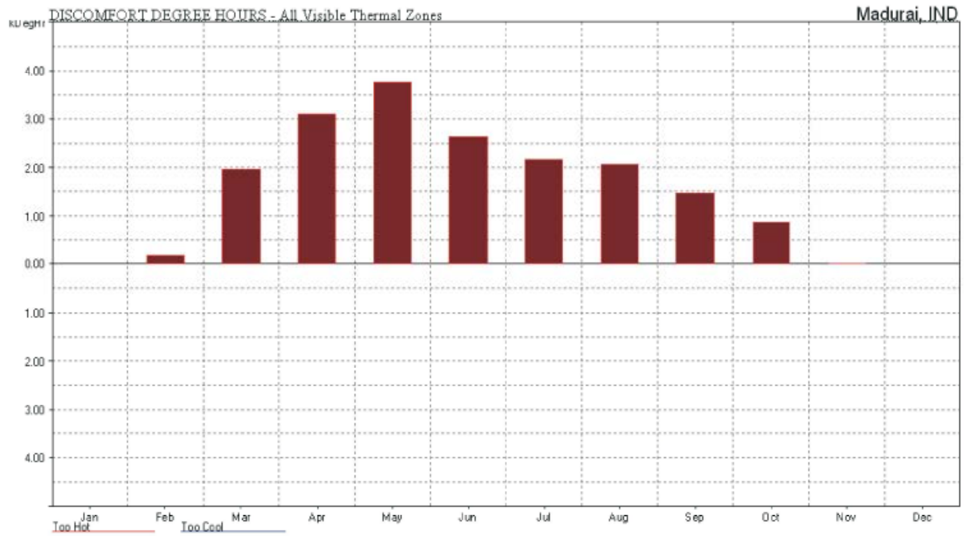

Fig. 12: Filler Slab, Monthly load discomfort; Discomfort Degree Hours too hot = 15020, too cool = 0; total discomfort 15020; Annual Comfort Distribution 5186 Hrs (59.2%)

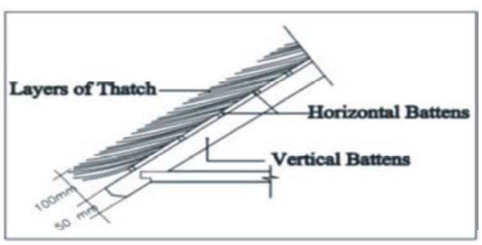

Fig. 13: Schematic section of Thatch roof

Fig. 14: Exterior view of house with thatch roof

Thatch Roof: Thatching is the craft of building a roof with dry vegetation such as straw, water reed, sedge, rushes, or heather, layering the vegetation so as to shed water away from the inner roof. It is a very old roofing method and has been used in both tropical and temperate climates. Thatch is a natural insulator and air pockets within straw thatch insulate a building in both warm and cold weather. A thatched roof will ensure that a building will be cool in summer and warm in winter. Their thermal insulation value is high, so thatch roofs are comfortable in warm climates. The actual degree of insulation provided by the thatch will depend upon both the type of material and how it is fixed. The Experimented Thatch roof consisted of layers of Palm reeds, Bamboo reeds, Thagavai reeds and layer of Nannai straw. Schematic diagram (Figure 13) exterior view of the house (Figure 14) indoor thermal performance of the room with thatch roof (Figure 15) and annual comfort distribution chart generated by ECOECT software (Figure 16) are presented below.

Roof Shading: Most of the roof slab of the buildings in hot humid is made of cement concrete. Cement concrete always absorbs heat from sunray. In summer, top roof slab of building is heated due to increasing temperature in atmosphere and lot of heat is transferred into inside of room. As a result inside temperature of a room of top floor is very high which is unbearable for inhabitants. Shading the roof surface is an easy and cost–effective way of reducing solar heat gain. Surface shading can be provided as an integral part of the building structure or as a separate cover [20]. Two types were experimented; the first one involved shading provided by inverted earthen pots on Reinforced Concrete roof and the other is of layer of clay tile over the 100mm Reinforced Concrete roof with an air gap of 25 mm

Inverted Earthen Pots on the Roof: Earthen pots are placed on the concrete roof slab, as a result lot of air pocket formed inside of the pot. Air gap is always heat insulating. Inside air is lighter and tends to go upwards as

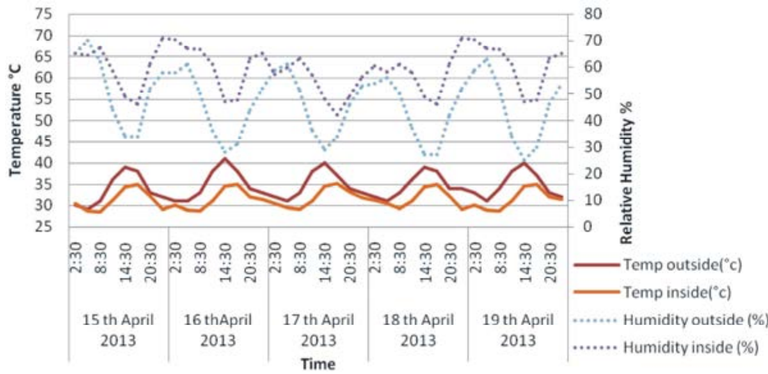

Fig. 15: Temperature /Humidity Graph - Thatch Roof

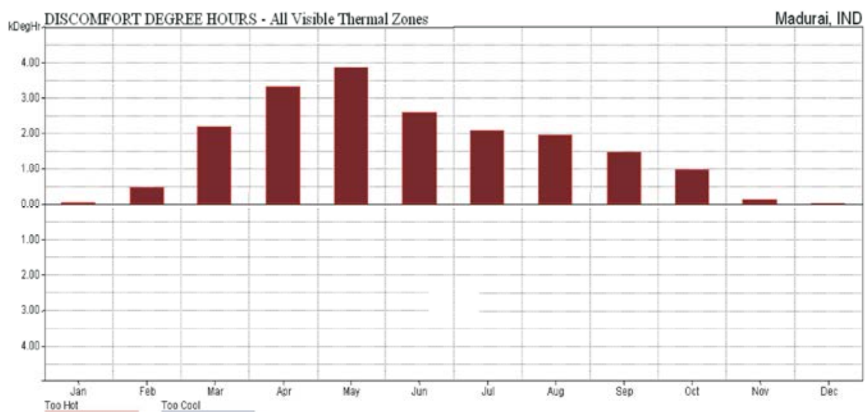

Fig. 16: Thatch roof Monthly load discomfort; Discomfort Degree Hours too hot = 16816.9, too cool = 0;total discomfort = 16816.9; Annual Comfort Distribution 5673 Hrs (60.6%)

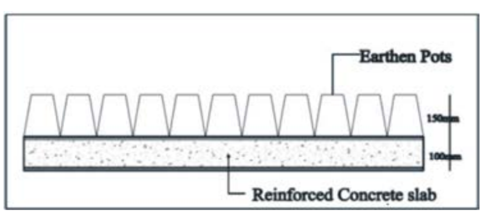

Fig. 17: Schematic section of RC roof with Roof shading by earthen pots

Fig. 18: Exterior view of house with Roof shading by earthen pots

a result contact surface of roof should be free from air and no heat can be in touch with the mother surface of concrete roof. In this system earthen pot is self waterproof materials and there are a lot of microscopic pores on the surface of pot. Air bubble fill up all pores and make a barrier to protect penetrating heat into the pot. Therefore no heat can reach to the mother roof surface and maintain the normal temperature in the room. Schematic diagram (Figure 17) exterior view of the roof (Figure 18), indoor thermal performance of the room with roof shading by inverted earthen pots (Figure 19) and annual comfort distribution chart generated by ECOECT software (Figure 20) are presented below.

Clay Tile over the Reinforced Concrete Roof with an Air Gap: The roof component taken for the experimental study consists of a sloped reinforced concrete slab with cement rendering on both the sides—an air gap that allows the

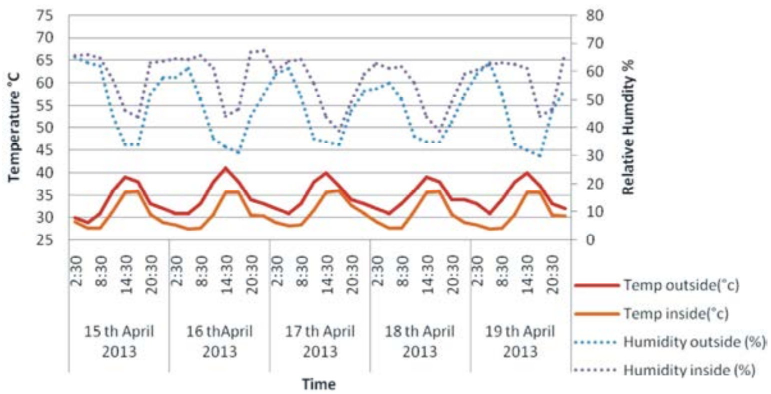

Fig. 19: Temperature /Humidity Graph - roof shading by earthen pots

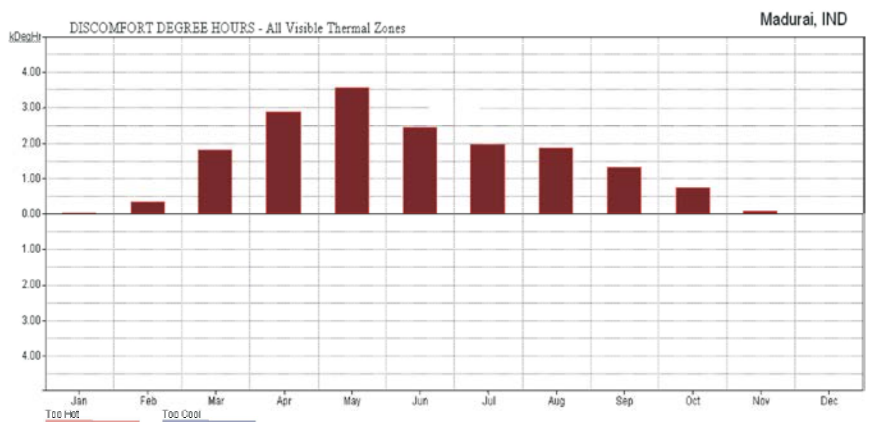

Fig. 20: Roof shading by inverted earthen pots, Monthly load discomfort; Discomfort Degree Hours too hot = 17052.0, too cool = 0; total discomfort = 17052.0; Annual Comfort Distribution 5263 Hrs (60.1%)

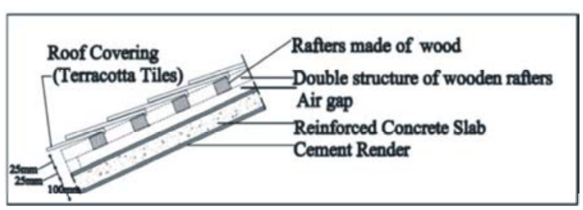

Fig. 21: Schematic section of sloped RC roof with roof shading of clay tiles

Fig. 22: Exterior views of sloped RC roof with roof covering of Terracotta tiles

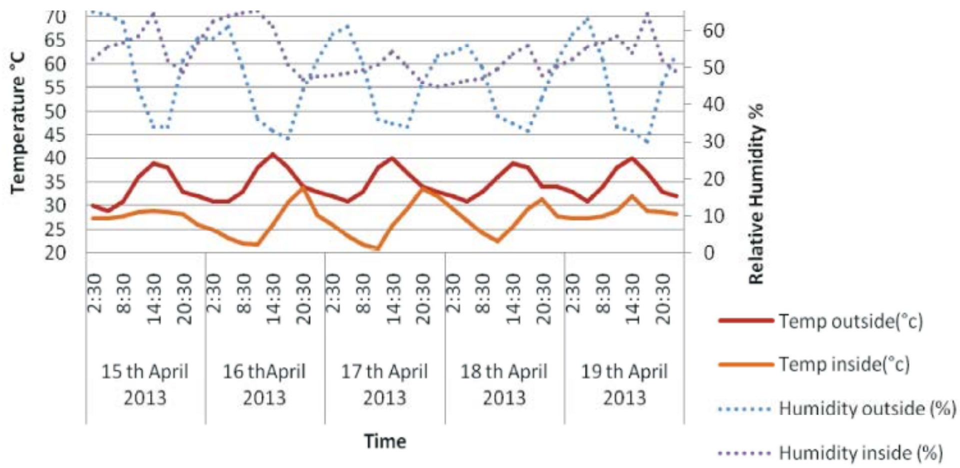

Fig. 23: Temperature /Humidity Graph - sloped reinforced concrete slab

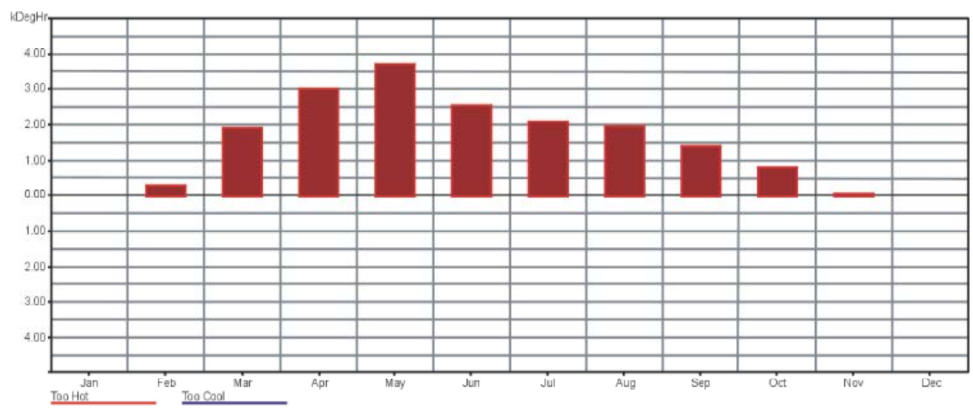

Fig. 24: Sloped Reinforced Concrete roof slab and clay tile roof covering, Monthly load discomfort; Discomfort Degree Hours too hot =16011.5, too cool = 0;total discomfort = 16011.5; Annual Comfort Distribution 5588 Hrs (63.8%)

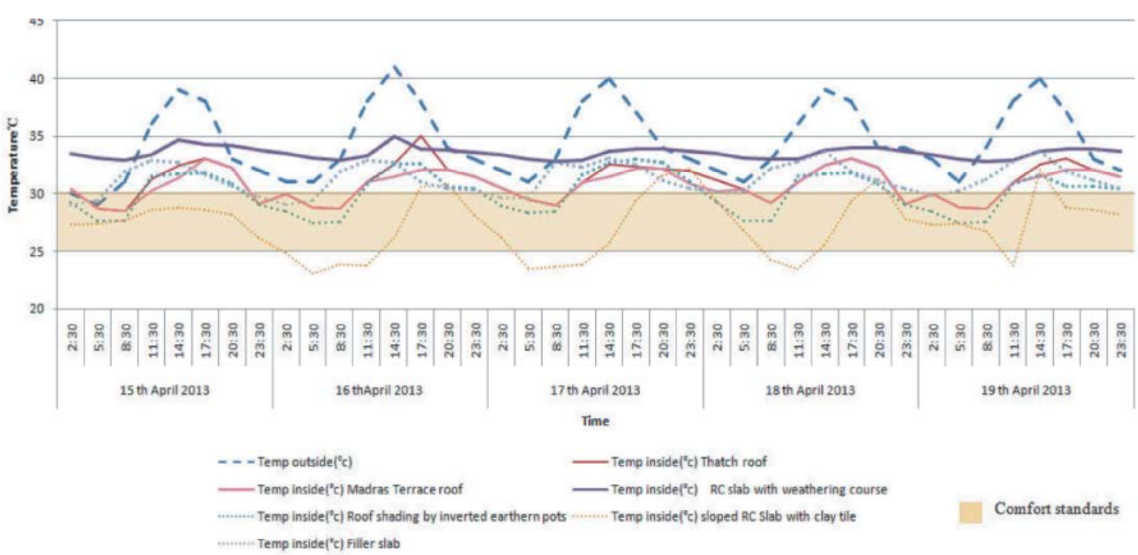

Figure 25: comparative temperature graph of all the experimented roofs

movement of the ambient air and an external layer made of terracotta roof covering. Use of air gap is similar to use of a insulating material. If an air space is left between two layers making a wall or roof in any building, the air trapped between two layers being poor conductor of heat acts as a barrier to heat transfer. The roof is laid in such a way that the air flows inside the hollow passages, about two third of heat entering into the room can be blocked, when compared to the conventional roof. Schematic diagram (Figure 21), exterior view of the roof (Figure 22), indoor thermal performance of the room with roof shading of RC roof with clay tiles and air space in between (Figure 23) and annual comfort distribution chart generated by ECOECT software (Figure 24) are presented below.

RESULTS AND DISCUSSION

This experiment reflects wide variations in thermal performance of houses and confirms that the roof played the dominant role because of diverse constructions. Comparison of Hourly variations of the inside air temperature and Relative Humidity for typical summer days are presented in the Figures (3,7,11,15,19,23). Comparison of the indoor temperature of all the investigated roofs is presented in Figure XV.

The the average indoor air temperature measured in Reinforced concrete roof slab was about 33.57°C, when compared with the ASHRAE standards it was observed that the indoor temperature does not fall in the comfort zone. It is observed from the Figure 3 that during the night times the indoor temperature is above the outdoor temperature. The reason for the deviation in comfort levels in conventional buildings is due to lack of sufficient thermal insulation in walls and roofs. Filler slab-Reinforced Concrete slab with clay tiles, (Figure 11) performed better than conventional Reinforced Concrete slab (Figure 3). The reason for the same could be that it consists of air pockets in between tiles.

In the investigated traditional roofs the Madras Terrace roof is considered to be a good thermal insulator since it possesses a high unit-mass. Its high thermal capacity is conducive to storing the absorbed heat for a longer period of time and releasing it back into the surrounding space more slowly than the other materials being investigated in this study. The average indoor temperature reading of the Traditional building with Madras Terrace roof (Figure 7) measured on peak summer days is 30.55°C which is nearly equal to the Thermal comfort level mentioned in ASHRAE standards. This shows that to achieve a better thermal performance of the roofs, it is desirable to have a multi-layered roof comprising materials of different thermo physical properties. The relative humidity of the experimented traditional building was also with in the comfort levels. In case of modern roofs sloped reinforced concrete slab with roof shading by clay tile and air space in between showed the optimum indoor thermal performance and remained closer to comfort levels during all the investigated duration (Figure XXIII). An experimental investigation has been carried out to study the possibility of reducing air temperature in buildings. The results show that the air temperature can decrease with a range from 3 to 6°C with the various passive roofs.

It is preferable to have low U-values in hot climates, because it can substantially bring down the heat gain and hence the cooling loads. The analysis thermal properties of experimented buildings (Table 2) shows that except for the RC slab and filler slab all the other experimented roofs have the U values within the acceptability limit.

An analysis of the simulation studies revealed that contemporary building materials have significantly equal thermal properties as compared to indigenous materials. A closer look at the simulation graphs (Figure 4,8,12,16,20,24) shows that the behavior of reinforced concrete sloped roof with clay tile roof covering and air space in between has nearly the same properties as Madras Terrace roof in traditional buildings. The thermal properties of thatch roof are also better than conventional building materials. The only disadvantage of thatch roof is it requires frequent maintenance. Modern day industrially improved thatch can be used with all the good thermal properties intact and the disadvantages of thatch gone.

Also noted that Madras terrace roof was the best in total thermal comfort in Traditional construction. In modern construction with alternative building materials, sloped reinforced concrete roof with clay tile roof covering and air space in between has the best thermal comfort. The thermal performance of above can be further improved by adding insulative materials like cellulose insulation or glass wool in the cavity. The thermal comfort level of conventional construction technique reinforced concrete slab is not satisfactory. This problem will be easily solved by increasing the ventilation levels, shading of the building envelope, by using insulation with low U-value in walls and roofs and by using light coloured coating with high reflectance in the exterior envelope.

CONCLUSION

Under warm humid conditions various the thermal performances of various passive roofs used in residential buildings of Madurai region, Tamilnadu, India which is used to improve space cooling in buildings has been tested. The experimental results examined the effectiveness of such roof cooling system in comparison to a conventional Reinforced Concrete roof with insulation of clay tile. The parameters used for the analysis are the indoor Air temperature and Humidity of the rooms under the experimented roofs. The thermal transmittance values (U value) of the experimented roofs are also compared. The results showed that cooling inside buildings can be considerably improved by the application of passive roof design. It was also seen that the Air temperature and Relative Humidity of rooms with Madras Terrace roof and Sloped Reinforced Concrete roof with clay tile roof covering and air space in between remained stable and were close to the comfort limits. This shows that to achieve a better thermal performance of the roofs, it is desirable to have a multi-layered roof comprising materials of different thermo physical properties. It can be concluded that the most important physical property of a roof is the thermal conductivity, which must be as low as possible. The results obtained are useful for designing appropriate building envelope configurations for passive solar building.

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APPENDIX -Calculated thermal Transmittance Values for roofs in Table 2.

		Thermo Physical Properties				
S.No	Description of roof	Resistance m2K/W	Conductivity W/mK	Density K/ m3	Specific heat J/Kg°K	U Value W/m2K
1.	RC slab with lime concrete Terracing					3.09
	Outside film	0.0386				
	1. 20 terracotta tiles	0.0217	0.798	1892	880	
	2. 50 lime concrete (brick bats)	0.0593	0.73	1646	880	
	3. 100 Reinforced Concrete	0.0548	1.58	2288	880	
	4. 12 Cement render	0.0144	0.721	1762	840	
	Inside film	0.1386				
Roof covering – terracotta tile		solar reflectance - 0.33	Emissivity - 0.9		SRI - 36	
2	Madras terrace roof					1.59
	Outside film	0.0386				
	1. 50 Terracotta tiles laid with lime mortar	0.0626	0.798	1892	880	
	2. 50 lime concrete (brick jelly)	0.0593	0.73	1646	880	
	3. 100 brick with lime mortar	0.1306	0.764	1769	880	
	4. 150 brick with lime mortar	0.1963	0.764	1769	880	
	Inside film	0.1386				
Roof covering – terracotta tile with lime mortar		solar reflectance - 0.53	Emissivity - 0.89		SRI - 62	
3	Filler Slab with cement rendering on both sides					3.35
	Outside film	0.0386				
	1. 12 Cement render	0.0144	0.721	1762	840	
	2. 100 Filler slab	0.0531	0.188	704	1050	
	Inside film	0.1386				
Roof covering – cement render		solar reflectance- 0.35	Emissivity – 0.96		SRI - 40	
4	Thatch roof					1.36
	Outside film	0.0386				
	1. 75 Reed	1.11	0.09	270	1000	
	2. 25 Straw	1.43	0.07	240	1000	
	Inside film	0.1386				
Roof covering – reeds		solar reflectance - 0.34	Emissivity – 0.85		SRI - 37	
5	Roof shading with inverted mud pots					2.04
	Outside film	0.0386				
	1. 120 terracotta pots	0.1482	0.81	1700	840	
	2. 20 terracotta	0.0217	0.798	1892	880	
	3. 50 lime concrete (brick bats)	0.0593	0.73	1646	880	
	4. 12 Cement render	0.0144	0.721	1762	840	
	5. 100 Reinforced Concrete	0.0548	1.58	2288	880	
	6. 12 Cement render	0.0144	0.721	1762	840	
	Inside film	0.1386				
Roof covering – mud pots		solar reflectance- 0.33	Emissivity – 0.91		SRI - 36	
6	Roof shading with clay tile and air space in between				1.36	
	Outside film	0.0386				
	1. 20 Mangalore tile	0.0163	0.798	1892	880	
	2. 25 Air space	0.46				
	3. 12 Cement render	0.0144	0.721	1762	840	
	4. 100 Reinforced Concrete	0.0548	1.58	2288	880	
	5. 12 cement render	0.0144	0.721	1762	840	
	Inside film	0.1386				
Roof covering – Mangalore tile		solar reflectance- 0.33	Emissivity – 0.93	SRI - 36		