Thermal Performance of Exposed Composed Roofs in Very Hot Dry Desert Region in Egypt (Toshky)

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ABSTRACT

Thermal performance for any building in hot dry region depend on the external climatic factor, the ability of the construction materials used in gained heat through day time and loss this heat through night time through the nocturnal radiation. Roof is considered the major part of the building envelop which exposed to high thermal load due to the high solar intensity and high outdoor air temperature through summer season which reach to 6 months. In Egypt the thermal effect of roof is increased as one go towards from north to south. This study evaluate the thermal performance of different test rooms with different roofs construction; uninsulated concrete, insulated concrete, double, plant, and active concrete roofs, constructed under the effect of external climatic condition of very hot and dry region in Egypt (Toshky region). The external climatic conditions and the temperature distribution inside the roof construction and the indoor air temperature were measured. The results of this study recognized that the thermal transmittance (U-Value) has a major role in chosen the constructed materials. Also the thermal insulation considered the suitable manner for damping the thermal stresses through day time and makes the interior environment of the building near the comfort zone during most months of the year. Natural night and forced ventilation are more important in improving the internal conditions. The construction roof systems show that the indoor air temperature thermal damping reach to 96%, 90%, 89%, and 76% for insulated concrete, double, planted and uninsulated concrete roofs. The results also investigate the importance of using the earth as a cooling source through the active concrete system. Evaporative cooling and movable shading which are an integrated part of the guidelines for building design in hot dry region must be using.

KEY WORD

Thermal insulation, roof, double roof, green roof, shaded roof, building envelope, and thermal comfort

INTRODUCTION

Toshky region is a desert region located in the south east of Egyptian westran desert at the Tropical cancer; 23.5^{o}N Latitude and at 31^{o}E longitude. This region is very hot and dry region; it is about 200m above see level. In such climate human comfort is crucial to provide the reasonable environment for people in this new community and save energy. The thermal response of building is defined as the reaction of the building envelope to some form of heat input and amount of internal loads. It depends mainly on the orientation, size, windows to wall ratio, also on the thermo-physical and optical properties of the building material, and on the external environmental conditions.

A building envelope is defined as the separation between the interior and the exterior environments of a building. It serves as the outer shell to protect the indoor environment as well as to facilitate its climate control. Building envelope design is a specialized area of architectural and engineering practice that draws from all areas of building science and indoor climate control. Building envelope design includes four major performance objectives; structural integrity, moisture control, temperature control, and control of air pressure boundaries of sorts. control of air includes air movement through the components of the building envelope (interstitial) itself, as well as into and out of the interior space, which affects building insulation greatly. The physical components of the envelope include the foundation, roof, walls, doors and windows. The dimensions, performance and compatibility of materials, fabrication process and details, their connections and interactions are the main factors that determine the effectiveness and durability of the building enclosure system. Common measures of the effectiveness of a building envelope include physical protection from weather and climate (comfort), indoor air quality (hygiene and public health), durability and energy efficiency. In order to achieve these objectives, all building enclosure systems must include a solid structure, a drainage plane, an air barrier, a thermal barrier, and may include a vapor barrier[1].

Thermal Comfort has been defined as "the condition of mind which expresses satisfaction with the environment". The indoor environment should be designed and controlled so that occupants comfort and health are assured. Although comfort models mostly talks about indoor climate but both indoor and outdoor climate should be taken into consideration not only in urban design but also in buildings. So both indoor and outdoor comfort is a matter of attention for architects and urbanizes. In comfort and climate study there are some problems that architect face and for designing a successful model it is best to know them which are; human factors, building factors, climatic factors. Thermal comfort can be discussed on building bioclimatic charts. Bioclimatic charts facilitate the analysis of the climate characteristics of a given location from the viewpoint of human comfort, as they present, on a psychometric chart, the concurrent combination of temperature and humidity at any given time. They can also specify building design guidelines to maximize indoor comfort conditions when the building's interior is not mechanically conditioned. All such charts are structured around, and refer to, the comfort zone [2 - 4]. Figure (1) shows the bioclimatic chart for Toshky region through the very hot and dry period (July, August and September). The figure illustrates that it is important to tack all the available passive system (evaporative cooling, massive building, thermal insulation and shading) to help the outdoor condition to inter or nearest to comfort zone [5].

In Egypt different field measurements and theoretical studies were carried out to investigate the thermal performance of the traditional houses under the effect of local external climatic condition of Cairo (30^{o}N), Egypt. The results of these studies showed that double roof, ventilated double roof and insulated roof were improved the internal environmental conditions under the external climatic conditions of Cairo [6,7]. Theoretical and experimental study was carried out to investigate the thermal performance of a pre-fabricated concrete flat in 15 May city, the results show that reasonable agreement between the theoretical and experimental indoor air temperature of the flat is achieved. It clears that shading devices, insulation materials and suitable orientation achieve a harmony building with environment. Also it shows that the indoor air temperature of rooms in the middle floor is better than that of the final floor; this is due to the direct exposed of the final floor to the high incident solar intensity [8]. Saving energy consumption in hot arid region and the effect of nocturnal radiation in increasing the thermal efficiency of the building was studied theoretically under the climatic conditions of Aswan (24^{o}N), Egypt. This study showed that, thermal insulation thickness of about 5-7cm thick in roof help in reducing the total thermal transmittance (U-Value) to be 0.4W/m^{2o}C, which is the perfable value in Upper Egypt[9], also this thickness led to save cooling load by about 80% in conditioned building. Concrete roof slab without thermal insulation case thermal stress in night and early hours of the day on people and this has passive effect on the thermal comfort of people. Ventilating the shaded roof increase the effect of the shading and movable shading help the usefulness of nocturnal radiation in night hours [10]**.** Evaluating the external climatic conditions of Toshky region and evaluating the thermal performance of some traditional building built their, give us a picture view about the climate of Toshky and the periods of warm, hot and very hot in it. This study shows that using Nobaa sandstone in wall alone is not correct due to the high storage, high thermal mass and thermal conductivity of it. The study also shows that domes or vault built from concrete without using material with special thermal characteristics is not the good solution, and if dome hasn't top opening to loss the hot air, a hot heat island is found and led to discomfort[5,11&12]. Other study developed a new building material with three line defense of thermal insulation used in walls and apply the concept of domes and vault with good thermal insulation help in valid the thermal comfort in building in Toshky region, and let the indoor climate of the building to be within the comfort zone in the very hot and dry period in summer [13]. More theoretical and experimental study was carried out using different passive approach; shading, insulation, roof pond, movable shading, and evaporative cooling for roof [14-20]. All these study show that applying different passive approaches help in improving the indoor air temperature of building. Theoretical and experimental study was carried out to evaluate the thermal performance of building with different building envelope; in Mediterranean countries, these study investigate that ventilating roofs have been widely used. Also the effect of roof tiles on the thermal performance of ventilated ducts were studied[21], and indicate that the presence of air permeable layer and elements to protect the ventilation duct eliminate any difference in performance which were due to the cross section of the ventilation duct [22]. A theoretical study was carried out using the finite element model to investigate the thermal performance of non air conditioned buildings with vaulted roof and flat roof. It clears that building with a vault roof have lower indoor air temperature compared to those with a flat roof , that is because such roof dissipate more heat by convection and thermal radiation at night due to the enlarged curved surfaces [23]. Different insulation materials (mineral wool, polyurethane, and polystyrene) were used to evaluate the thermal performance of building for decreasing the thermal demand and heating and cooling load [24]. The usefulness of low earth temperature was discussed theoretically and experimentally to show the effect of earth-pipe –air heat exchanger systems in reducing the cooling load of building in summer [25].

As building envelope regards as the main construction element which has an important role in the thermal performance of unconditioned building and also has important role in saving energy in conditioning building. Roof is considered the major part of the building envelope. In Egypt the thermal effect of roof is increased as one go towards from north to south. This study evaluates the thermal response of different roof construction under the effect of the external climatic conditions of Toshky region. The study was carried out in January as a warm season and in July, August and September as the very hot and dry period in summer season.

MATERIALS AND METHODS

Measurement for all the climatic factors and the thermal performance of all the rooms were recorded through different seasons to illustrate the thermal behavior of the rooms through the different climatic period. In order to compare the thermal behavior of different roof structure 5 full scale test rooms with different roof systems (uninsulated roof, insulated roof, double roof, green roof and active concrete roof) were built with internal dimension of 3.4x3.15x3m and measured under the external climatic conditions of Toshky region in winter and summer seasons, which are the critical and important period. Table (1) shows the maximum, minimum, and means temperature and the upper limit temperature for thermal comfort in Toshky region [5]. Figure (2) show photos for the test rooms with (a) double roof, (b) green roof, (c) active concrete roof and (d) the active concrete roof description. The test rooms were made up by a single volume in order to grant the same interior condition to all the roofs. Local building materials were used. The description of the roofs and their thermal characteristics are illustrated in table (2). To specify the effect of the roof only on the thermal performance of the indoor air temperature, the walls of all the rooms were built from the same material, from 12.5cm hollow clay brick, an air cavity of 10cm and 20cm light sand block covered from outside and inside with 2.5cm plaster. All the walls are painted with white color. The description of the wall and its thermal characteristics were illustrated in the first report "Thermal performance of exposed roofs and walls for test rooms in desert area, Toshky region" [26]. For measuring the thermal performance of the roofs, thermocouple of type T were installed in different position of the roofs (the exposed and the interior roof surfaces, and at the interface surfaces) and the indoor air temperature. All these thermocouple were connected to a scan thermometer instrument to measure and recorded the temperature. Thermo-hygrometers were installed in the rooms to measure and recorded the indoor air temperature and humidity. The outdoor climatic factor (outdoor air temperature, the relative humidity, and wind speed and direction and the solar intensities) were measured and recorded.

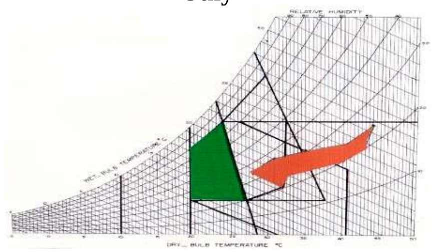
RESULTS AND DISCUSSION

(a) <u>The Thermal Performance of the Rooms in Winter Season.</u>

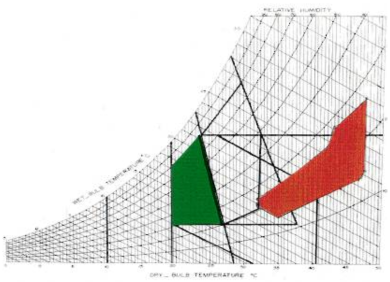
Figure (3) shows the hourly temperature variation of the exposed roof, ceiling, internal layers and the indoor air temperature of room with insulated roof through 26-30 January 2009 in Toshky region. The figure also illustrates the outdoor air temperature. The outdoor air temperature varies between 31 ^{o}C as a maximum value and 10^{o}C as a minimum value, i.e. with a mean value about 20.5 ^{o}C. The figure illustrates the nearest between the exposed roof surface temperature and the interior surface between the tiles and the insulation layer, this due to the accumulation of the heat above the insulation layer. The exposed roof surface temperature reaches to a maximum value of about 46 ^{o}C and decreased to a minimum value of about 5 ^{o}C with a range of about 40 ^{o}C. The ceiling temperature varies between 26 and 18 ^{o}C with a range of about 8 ^{o}C. The figure also clears that the indoor air temperature varies around 20 ^{o}C which is lies in the comfort zone. This figure illustrate that, the roof system with the insulating material prevent the warm indoor air temperature losses to the outside environment through night time. The same results as given in Refs. (6,24).

Figure (4) shows the hourly temperature variation of the exposed roof, shaded roof, ceiling, internal surfaces and the indoor air temperature of room with double roof through 26-30 January 2009 in Toshky region. The figure also illustrates the outdoor air temperature. The roof as described in Table (2) composed of 14cm concrete slab, 70cm

July



August



September

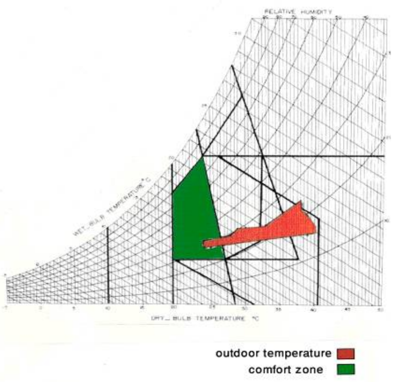
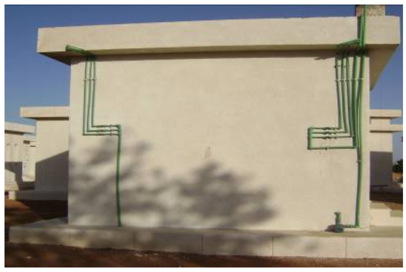


Figure 1. Bioclimatic Analysis of Toshky Region Through the Very Hot and Dry Period.

(a). Room with double roof

(b). Room with green roof



(c). Room with active concrete

(d). Active concrete roof structure

Figure 2. Photo for Test Rooms in Toshky Region.

air gap and 10cm concrete slab. The figure investigates the similarity in the temperature distribution of both the exposed and internal surface of concrete slabs and the shaded surface. The figure also shows the gradual decrease in the temperature from outside to inside. In night and early hours of the day, the temperature of the different surfaces nearest to each other, due to the thermal radiation loss and the loss of heat from both the slabs due to the flow of air between the two slabs[10]. The temperature of the exposed slab concrete surface varies between 38 and 8 ^oC, while the concrete slab of the room varies between 29 and 12 ^oC. This high variation of both the exposed roof and the shaded roof , led to the variation swing of the ceiling by about 8 ^oC and help the indoor air temperature to be within 18-22 ^oC , i.e. within the comfort zone . This figure illustrate that this system

Table 1. Maximum, Minimum and Mean Temperature and the Upper Limit for Thermal Comfort in Toshky Region.

Temperature	Month					
	May	June	July	August	September	October.
Maximum	40.8	40.6	43.5	46.5	43.5	40
Minimum	25	26	27	28	26	25
Mean	32.9	33.3	35.3	37.3	34.8	32.5
Upper Limit for Comfort	30.4	30.4	31.8	32.8	31.5	30.3

This table shows that people in this region have the ability to live in higher temperature reach to 32^oC through the very hot period, which is due to their adjusted with this very hot environment. Also the low relative humidity plays a significant role in the response with comfort in high temperature, where evaporating sweat led to balance between the people skin and the surrounding environment [2, 4].

Table 2. The Roofs Description of the Test Rooms Built in Toshky Region and Their Thermal Properties and Characteristics.

No.	Building materials used	Thickness	Thermal Conductivity	U-Value	R-Value
		cm	W/m ^oC	W/ m^2 ^oC	m^2 ^oC/W
1.	Concrete slab	14	1.73	2.35	0.426
	Internal plaster	2.5	0.727		
	Gypsum layer	3	0.38		
2.	Concrete slab	10	1.73	1.9522	0.5122
	Air gap	70	-		
	Concrete slab	14	1.73		
	Internal plaster	2.5	0.727		
	Gypsum layer	3	0.38		
3.	Mortar	5	0.8	0.274	3.65
	Dry sand	5	0.59		
	Thermal insulation	14	1.73		
	Concrete slab	14	1.73		
	Internal plaster	2.5	0.727		
	Gypsum layer	3	0.38		
4.	Concrete slab	14	1.73	2.35	0.426
	Internal plaster	2.5	0.727		
	Gypsum layer	3	0.38		
	0.5inch propapline tube				
5.	Concrete slab	14	1.73	2.35	0.426
	Internal plaster	2.5	0.727		
	Gypsum layer	3	0.38		
	Vegetative roof				

From the table we show that the total thermal transmittance of the roof didn't affect by the passive means, but decrease by using thermal insulation.

with the double roof help the indoor air temperature to fluctuate around 20 °C which is a reasonable temperature in this month of the year.

Figure (5) shows the hourly temperature variation of the indoor air temperature of test rooms with different roof structure; un-insulated, insulated, double, green and active concrete Roof through 26-30 Jan. 2009 in Toshky region. As before the figure also illustrates the outdoor air temperature.

The figure illustrate that the outdoor air temperature varies in a range between 31 °C and 10°C. The thermal behavior of both un-insulated and double roof nearest to each other. The green roof investigates the lower indoor air temperature, due to the evaporation process by the effect of the roof heat storage. The figure also shows that the indoor air temperature of all room varies around 20°C. Generally all the roof system valid an indoor air temperature between 17-23°C which is a comfortable temperature, else the green roof which can also be a suitable in winter season were the growth of grass is negligible in winter season.

(b) <u>The Thermal Performance of the Rooms in Winter Season.</u>

Fig (6) show the hourly temperature variation of the exposed insulated / un-insulated roof and ceiling of tow rooms and the outdoor air temperature in Toshky region through 21-24 July 2009. The figure illustrate that the outdoor air temperature reach to a maximum value of about 42°C at 15.00pm and decrease to reach minimum value of about of 24°C at 5.00am with arrange of 18°C**.** The outdoor air temperature still over 30°C for 18 hours, which is 2/3 of the day hours and this led to case the thermal load and increase the heat stress on occupation. The thermal performance of the exposed roofs are the same reach a maximum value at noon, but the insulated roof gives higher temperature value than the uninsulated roof. That is due to the

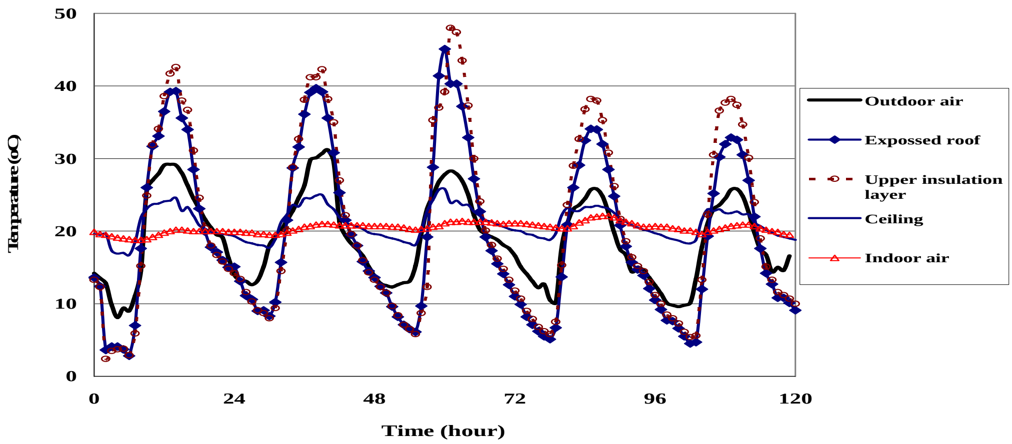


Figure 3. The hourly temperature variation of the exposed roof, ceiling, internal layer and the indoor air temperature of room with insulated roof through 26-30 January 2009 in Toshky region

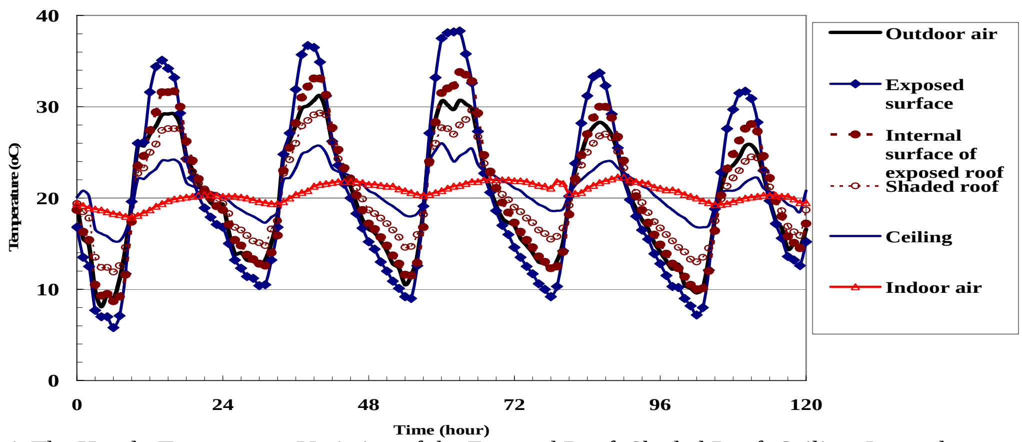


Figure 4. The Hourly Temperature Variation of the Exposed Roof, Shaded Roof, Ceiling, Internal Surfaces and Indoor Air Temperature of Room with Double Roof through 26-30 Jan. 2009.

accumulation of heat in the tiles and mortar layers above the insulation layer. The difference between the two exposed roofs is about 10°C, while at night and early hours of the day the temperature of the exposed un-insulated roof is approximately the same as the outdoor air temperature. The thermal performance of the two ceilings is different, where the ceiling temperature of the insulated roof is approximately stable around 35°C, while the temperature of the ceiling of un-insulated roof has a wide swing of about 10°C and has the same thermal performance of its exposed roof, reduced from it by about 12°C and late by about 4 hours. The temperature of un-insulated ceiling rises above the insulated ceiling by about 8°C. Finally the figure shows the importance of thermal insulation in prevent heat to flow through the roof layers during day time and save the ceiling temperature approximately constant [10].

Fig (7,8) show the hourly temperature variation of the exposed roof, ceiling , internal layers and the indoor air temperature of room with insulated roof. in Toshky region through 21-28 July 2009. The figures also illustrate the outdoor air temperature. Figure (7) shows the distribution of the temperature through the roof in the period 21-24 July, where the room was closed. The figure illustrates that 20°C due to the high solar intensity in that month which reach to about 1000W/m^2 and still over 850 W/m^2 for about 6 hours and also the accumulation of the heat in the external layer above the thermal insulation. The temperature variation of the layer below the thermal insulation and the ceiling has the same thermal behavior and approximately the same value. This result show that how the thermal insulation (10cm thick) stopped the passage of heat from the external layer to the interior layer (14cm thick concrete layer). Also the thermal insulation help the indoor air temperature to fluctuate in a range of 2°C. This insulation layer valid an indoor thermal damping about 88%. We can note that although the outdoor air temperature decreased to reach the comfort level in night and early hours of the day, the indoor air temperature is still higher than the comfort level (the study case is closed windows). Therefore the effect of ventilation through night and early hours of the day was studding. Figure (8) shows this effect where the windows were opened from 10.00pm to 6.00 am (opened case study). It is clear from the figure that, the indoor air temperature through the night and early hours of the day reach to the comfort zone,

i.e. the natural night ventilation improve the indoor air temperature through this time period and help the indoor air temperature to be within the comfort region through most hours of the day. Also this effect may be improved by using fan which help in drawn the low outside air temperature to the interior. Figure (9) shows the hourly variation of the indoor air temperature of room with active concrete system through 26-29 July 2009 in Toshky region. The figure also illustrates the hourly variation of the outdoor air temperature through this time, which varies between 43.1 and 23.6°C as a maximum the temperature of the exposed surface is very high and rise above the outdoor air temperature by about and a minimum temperature and with a range of about 19.5 °C. Due to the roof system with more steel to carry the water tube, the ceiling temperature raise, which in turn led to raise the indoor air temperature to 36°C as a maximum value and with a mean value about 33.2 which is nearest too the upper limit of the comfort zone in this month of the year. In general the indoor air temperature of the room is

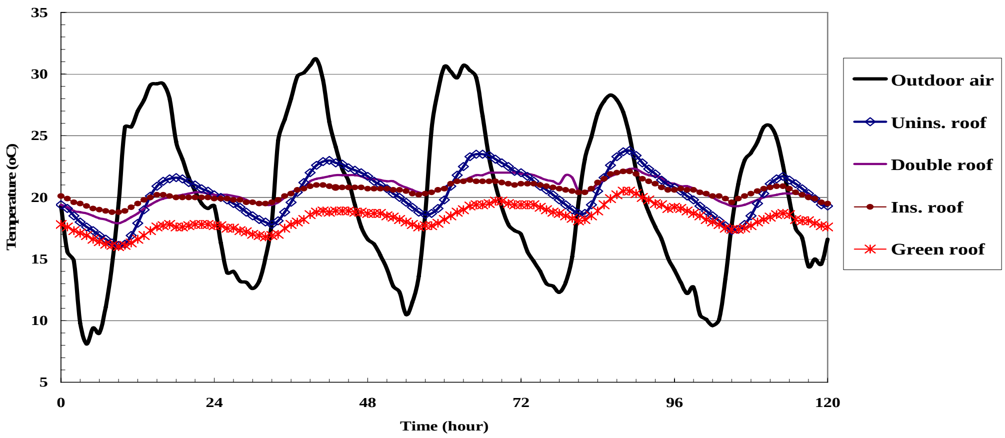


Figure 5. The Hourly Temperature Variation of the Indoor Air Temperature of Test Rooms with Different Roof Structure; Un-insulated, Insulated, Double, Green Roof through 26-30 Jan. 2009.

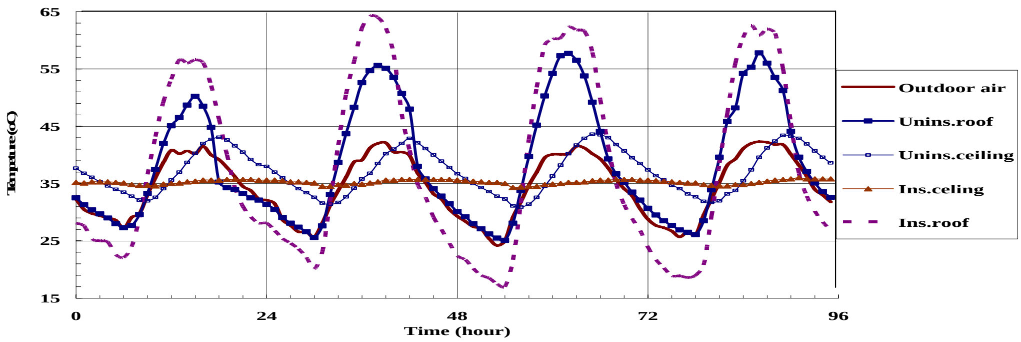


Figure 6. The Hourly Temperature Variation of the Exposed Insulated / Un-insulated Roof and Ceiling of Tow Rooms and the Outdoor Air Temperature through 21-24 July 2009.

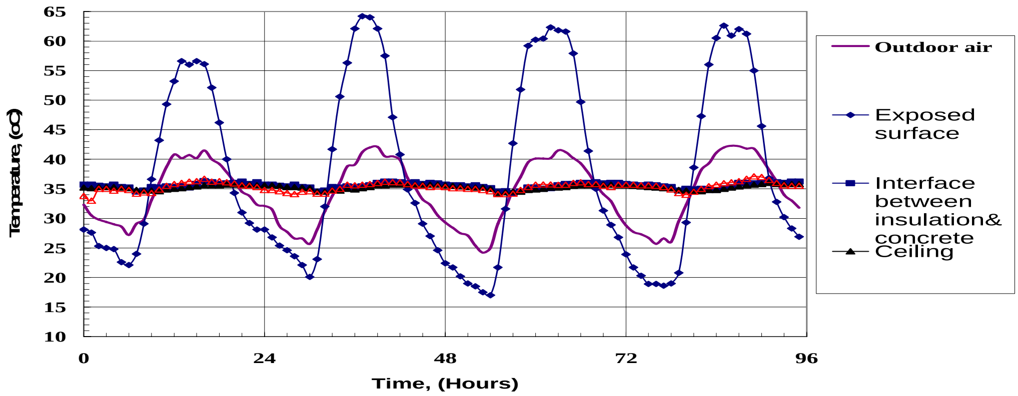


Figure 7. The Hourly Temperature Variation of the Exposed Roof, Ceiling , Internal Layers and the Indoor Air Temperature of Room with Insulated Roof through 21-24 July 2009 (closed case)

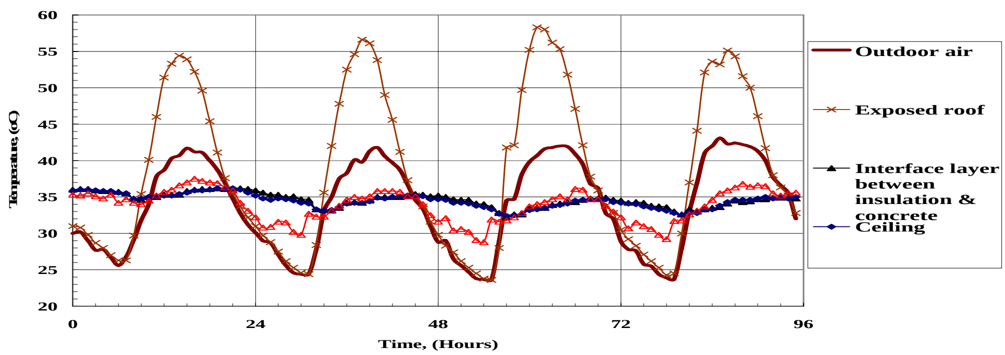


Figure 8. The Hourly Temperature Variation of the Exposed Roof, Ceiling , Internal Layers and the Indoor Air Temperature of Room with Insulated Roof. through 25-28 July 2009 (Opened case)

comfortable for about 9 hours of the day wherever it is closed and this test carried out in a very hot and dry time in Toshky. The figure illustrate that the indoor air temperature vary in a big range about 7^{o}C due to the flow of water in the roof tube, which withdraw some of the heat storage of the concrete slab of the roof without using any protection like shading or insulation. Also the indoor air temperature can be improved by using good thermal conductivity tube material like stanlistail and usefulness from the natural ventilation through night and early hours of the day.

Figure (10) shows the hourly variation of the indoor air temperature of 4 rooms with different system roof structure through 17-20 July 2009 in Toshky region. The figure also illustrates the hourly variation of the outdoor air temperature through this time. The figure clears that the outdoor air temperature varies between 37 &41^{o}C as a maximum value and between 23 & 24^{o}C as a minimum value. The roofs systems are insulated / uninsulated double and green roofs. The figure shows that the indoor air temperatures of all rooms have the same thermal performance but differ in their values and time lag. The figure illustrate that room with uninsulated roof valid the worst one where the maximum indoor air temperature varies between 35.5 &37^{o}C and in the same time room with green roof appear as the best one where its indoor air temperature varies between 27.5 & 33.5^{o}C i.e. the indoor air temperature of this room is within the comfort zone. The figure also shows that the indoor air temperature of rooms with thermal insulation and double roofs nearest to each other. For all the rooms the effect of natural night ventilation is appear on the indoor air temperature, where about half of the day hours is less than 30 ^{o}C and the other half lay near the comfort zone.

CONCLUSIONS

The results of this investigation show that:

1. All the rooms with different roof systems valid an indoor air temperature between 17-23^{o}C which is a comfortable temperature in winter season.
2. As the green roof investigates the lower indoor air temperature, due to the evaporation process by the effect of the roof heat storage, it is required suitable in winter season were the growth of grass is negligible in winter season.
3. The importance of thermal insulation in prevents heat to flow through the roof layers during day time in summer season and vice verse in winter season. Also using thermal insulation save the ceiling temperature approximately constant and help in saving energy.
4. Double roof system helps the indoor air temperature to fluctuate around 20 ^{o}C which is a reasonable temperature in winter season, i.e. shading the roof is also suitable in winter season, where it decrease the loss of heat by nocturnal radiation through night time.
5. In summer season natural night ventilation help the indoor air temperature to be within the comfort zone through most hours of the day.
6. Using fan improved the effect of natural night ventilation and increased the draw of the moderate outdoor air temperature to the interior of the rooms
7. The indoor air temperature of room with active concrete can improved by shading this roof and using good thermal conductivity tube material like stanlistail.
8. The construction roof systems show that the indoor air temperature thermal damping reach to 96%, 90%, 89%, and 76% for insulated concrete, double, planted and uninsulated concrete roofs.
9. Continues of outdoor air temperature more than 30^{o}C for about 18 hours in the day is the case of didn't improve the indoor air temperature, so reducing the outdoor air a temperature before interring the building is more important to improving the indoor air temperature

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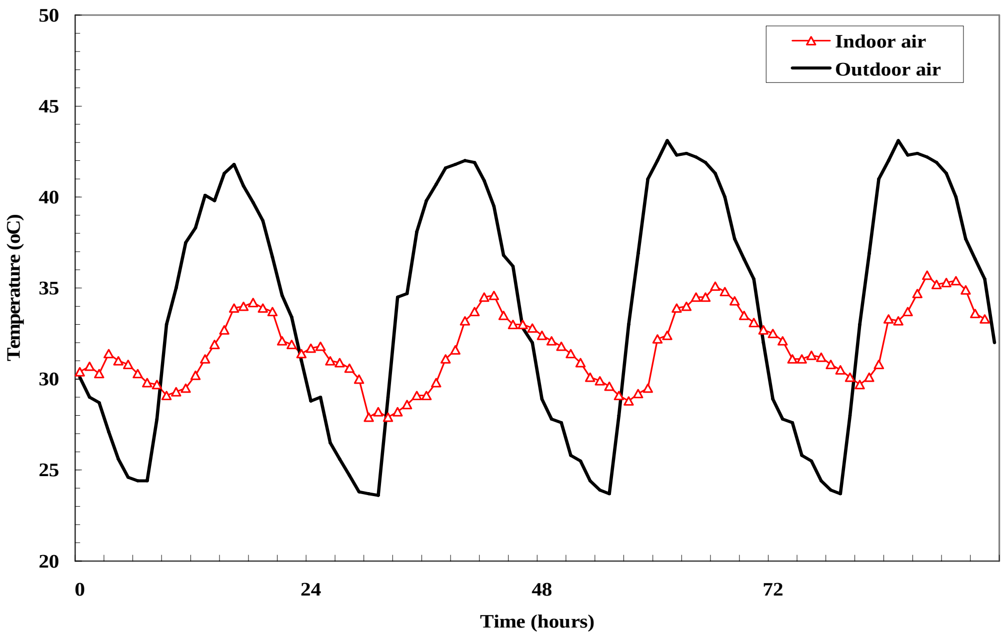

Figure 9. The Hourly Temperature Variation of the Indoor Air Temperature of Room with Active Concrete Through 26-29 July 2009.

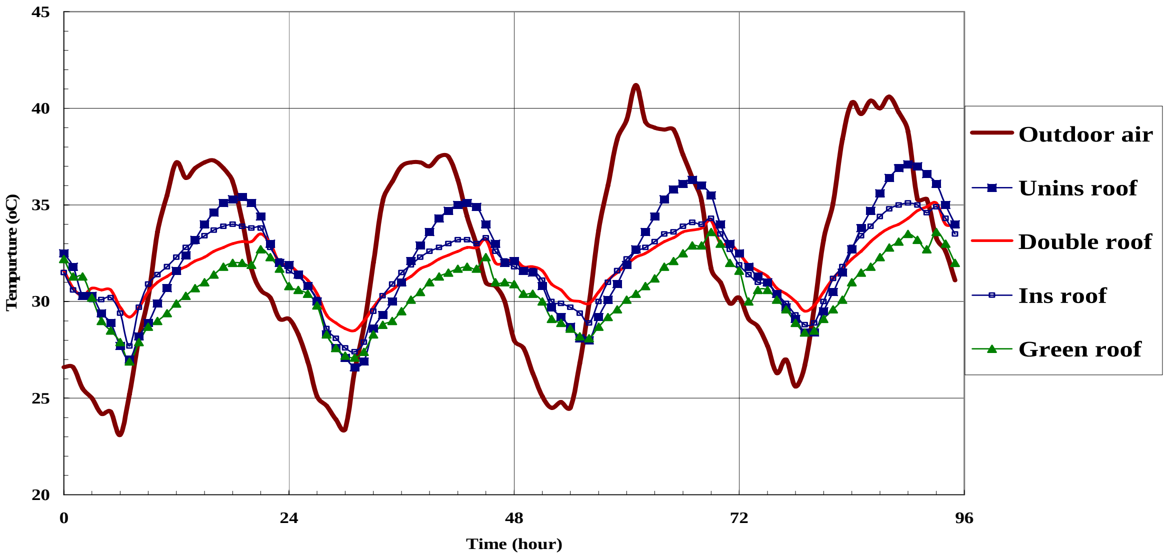

Fig. 10 The Hourly Variation of the Indoor Air Temperature of 4 Rooms with Different System Roof Structure Through 17-20 July 2009 in Toshky Region.

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