JAET

Journal homepage: http://jae-tech.com

Journal of Applied Engineering & Technology

ISSN : 2523-6032 ISSN-L : 2523-2924

Heat Transfer Rate Analysis of Different Roof Insulation Materials

Sadam Hussain[1,*], Qadir Bux Jamali[1], Imdad Ali[1], Adnan Ali Rajput[2], Abid Ali Khaskheli[1]

[1]Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Science, and Technology (QUEST) Nawabshah, Sindh, Pakistan.

[2]Department of Civil Engineering, Quaid-e-Awam University of Engineering, Science, and Technology (QUEST) Nawabshah, Sindh, Pakistan.

*Corresponding Author

DOI: https://doi.org/10.55447/jaet.06.02.84

Abstract: The building sector is crucial in Middle East countries because it is one of the primary energy consumers. Currently, reinforced cement concrete (RCC) is preferred for roof construction due to its durability and possesses higher strength. Heat is conducted rapidly through rooftops composed of RCC because it has more thermal conductivity compared to other roofing materials. In the Middle East, RCC roofs are usually lined with marble and polyurethane to increase thermal insulation and reduce heat transfer from the roofs. In this research, the thermal conductivities and temperature reduction capabilities of distinct material combinations for roof insulation have been investigated. The rates of heat conduction were estimated, and a suitable roof combination was found based on the maximum heat resistance and temperature reduction ability. The hot plate guarded method determines the thermal conductivity of marble and polyurethane sheets. Fourier law of heat conduction was employed to calculate the rate of heat flow through roof samples. According to the experimental findings, compared to concrete without insulation, the rate of heat conduction was reduced by 11.8% with combination B (RCC lined with marble) and by 84.3% with combination C (RCC lined with marble and polyurethane).

Keywords: Heat transfer rate, thermal conductivity analysis, thermal behavior of roof materials

1. Introduction

A building sector is one of the largest energy consumers in Saudi Arabia, representing about 50% of the total energy utilization [1]. About 55% of the global inhabitants lives in metropolitan regions, which use approximately 75% of the primary energy supply [2]. A study conducted in Taiwan has shown that energy efficiency measures can reduce apartment energy consumption by

*Corresponding author: sadamrajput92@gmail.com

51.3% to 54.2% [3]. Housing, markets and government offices and building utilizes about 40% of total world’s electrical energy in urbanized and growing states, current estimates proposed that by 2040 advancing countries may takes up to 65% of the total electricity of the world [4].

A roof is the key building block of the building responsible for dissipating the highest heat energy inside the building, and the outside temperature of an RCC roof may reach up to 65°C [5]. These concrete roofs radiate energy in the form of heat into the environment and are major contributors to the urban heat island effect [6]. This urban island results in warmer air; resultantly, the air temperature in urban areas is more than in adjacent rural areas by 10°C [7-10]. Another research work suggested that electrical energy expenditure could be decreased up to 25% with the adoption of thermally insulated roofs [11].

A study on cool roof techniques proved that 295000KWATThr unit of electricity which costs 59 Euros, may be saved annually, this electricity saving reduces the emission of 136000 metric tons of CO_2 into the atmosphere [12]. A case study found that the thermal behavior of concrete directly affects the energy requirement of a building in terms of cooling load [13]. The heat transfer rate has been reduced to 79% with the implementation of concrete tile, sand, air, and Cork on a concrete roof in Iraq [14]. Comparatively, the specific heat of concrete is higher; therefore, it may contribute to extra power utilization, therefore, encourage the occurrence of urban heat island [15]. RCC's thermal conductivity is higher; therefore, more heat flows through the RCC roof; accordingly, the interior temperature of the building increases, and a larger capacity and energy requirement of air conditioning and refrigeration equipment is needed.

This augmented application of such a device directly depends on non-renewable energy sources. Still, with the implementation of the insulation technique, the significant amount of heat transfer through the roof may be bargained. The decline in heat transfer rate reduces the indoor temperature, reducing the electricity consumption and CO_2 emission into the atmosphere [16]. The Thermal conductivity of rigid foam polyurethane can be decreased from 0.045 WATT/mK to 0.0227 WATT/mK which is about 75 times less than RCC [17]. The metal roof sheet is integrated with phase change materials, resulting in better thermal performance and electrical energy conservation [18]. The particleboard may be synthesized by spreading the preheated natural rubber latex onto pineapple leaf yarns, these boards are used for roof insulation and possess thermal conductivity between 0.035 watts/mK to 0.043Watt/mK [19].

The heat conductivity of foamed concrete is dependant of density, if the density of light weight concrete is 180 kg/m^3 then its thermal conductivity is 0.13W/mK therefore heat transfer from foamed concrete reduces considerably due to voids [20]. Heat-resistive materials, like other natural or synthesized materials, show temperature reliance that varies from material to material, and thermal conductivity rises with the rise in temperature [21]. The heat flow meter (HFM) and the guarded hot plate (GHP) method are the most imminent techniques to find out the heat conductivity of a material [22]. Another study revealed that coating on roofs reduces heat conduction through the roofs [23].

The relationship between thermal conductivity and temperature is linear for various materials. Still few materials, such as blown foam insulations (e.g.Polyisocyanurate), express a non-linear relationship between thermal conductivity and temperature [24]. Adding marble waste to make hollow concrete blocks will have a negative influence on thermal conductivity [25]. Findings from a study suggested that the white roof tile decreases the outer surface temperature of roof and rate of heat transfer through roofs [26]. It was proved experimentally that for better insulation, higher thermal conductivity material is placed on the top of the roof [27].

A CFD simulation-based study showed the thermo chromic building envelope's positive and significant impact on local thermal indoor comfort conditions [28]. The Mangalore pattern tile possesses low thermal diffusivity and conductivity to resist heat dissipation from or to the building envelope [29]. An experimental result proved that the efficiency of rigid polyurethane sheets does not depend on the quantity of incorporating phase change material but is influenced by operating temperature value and thermo characteristics of PCM [30]. Cool roof techniques can reduce the surface roof temperature from 1.4°C to 4.7°C[31].

(a) Roof combination A **(b) Roof combination B** **(c) Roof combination**

Fig. 1 – Different Roof Combinations

The thermal conductivity of RCC roof is superior, which causes more dissipation of heat to or from the RCC building. Heat transfer through RCC roofs can be declined significantly by lining the RCC roof with materials of better thermal insulation performance. In the world, many studies are conducted on the mechanical properties of RCC roofs but little attention is paid to the thermal characteristics of roofs [32]. In Pakistan and Middle Eastern countries, heat transfer rate through RCC roof lined with burnt clay, wood, plaster of Paris, gypsum plaster, chemical coatings is determined. In this experimental study marble and polyurethane are opted which are frequently used with RCC in Pakistan and Middle Eastern countries, ability of heat reduction and temperature reduction of common roof combinations are determined.

2. Materials and Methods

In this current experimental work, marble and polyurethane are selected, commonly lined with RCC roofs in Middle East countries as heat insulators. The thermal behavior of each material differs from one to another. Table 1 illustrates the details of the materials studied in this research work.

Table 1- Code and Type of Selected Roof Insulation Combination

S.No.	**Materials**	**Thickness (cm)**	**Code**
1	Reinforced cement concrete (RCC)	6.5	A
2	RCC lined with Marble	7.3	B
3	RCC lined with Marble and Polyurethane	9.1	C

The thermal behavior of different roof materials has been estimated by measuring their thermal conductivities. These roofs include Bare RCC roofs (roof combination A), an RCC roof lined with marble (Roof combination B), and an RCC roof lined with polyurethane and marble (Roof combination C) denoted in figure 1a, b, c respectively. The model roofs of 4ft by 4ft and a depth of 2.5inches were constructed in Pakistan, and these roofs are directly exposed to solar radiation.

A heat conduction unit is engineering equipment that comprises temperature sensors and a heater of known power used to determine thermal conductivity. It is also known as the hot plate guarded method based on Fourier's law of heat conduction. A heat conduction unit of serial number H940/03362 manufactured by P.A. Hilton Limited shown in figure 2 was decided to compute the heat conductivity of bare RCC, Marble, and Polyurethane foam.

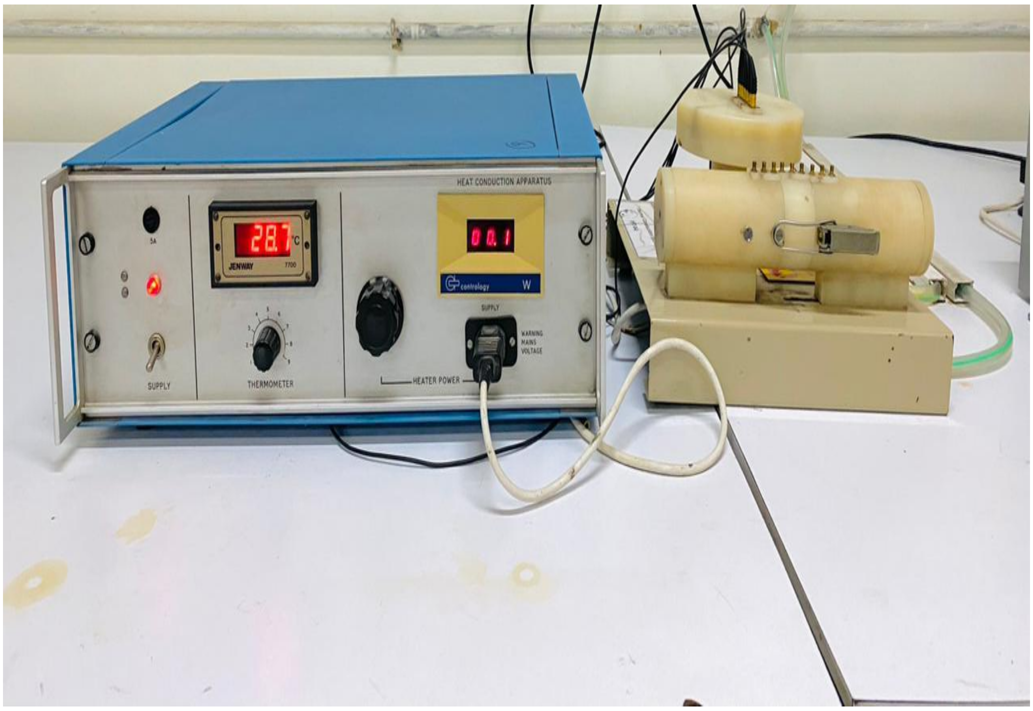

Fig.2- Hot plate guarded heat conduction unit

Fourier law of heat conduction is applied to evaluate the heat transfer rate through roof samples and thermal resistivity of roof combinations A, B & C. To evaluate the equivalent thermal resistance of composite slabs (roof sample B and roof sample C), the below relation of Fourier law of heat conduction is used (roof sample B and roof sample C) as in Equation 1 [27]:

$$\text{Thermal resistance}_{eq} = \frac{x_1}{K_1} + \frac{x_2}{K_2} \quad (1)$$

An Infrared thermometer measures the inner surface and outer surface temperature of the roof. The infrared thermometer is a famous instrument that is carried out in high-temperature industrialized environments entire of the world. However, hourly ambient air temperature is recorded using a mercury thermometer and weather online.

2.1 Proposed samples

The combination of samples denoted in Figures 1 (a,b,c) was examined in this research. These combinations are generally implemented in the Middle East. The materials and combinations are selected based on their commercial availability and application. The details of each combination are listed in table 2.

Table 2- The Thermal Conductivity, Thickness and Thermal Resistivity of Roof Combination Materials

S.NO	Materials of roof combination	Thickness (m)	Thermal conductivity (Watt/mK)	Thermal resistivity K/Watt
01	RCC	0.0635	1.7	0.0373
02	Marble	0.008	2.00	0.004
03	Polyurethane foam	0.018	0.0045	4.00
04	Roof combination A	0.0637 m	1.707	0.0373
05	Roof combination B	0.0717 m	17.4	0.00412
06	Roof combination C	0.0735 m	0.167	0.441

The heat conductivity of marble, RCC, and polyurethane sheets was calculated using a heat conduction unit (hot plate guarded method), as denoted in figure 2. Total thermal resistivity and heat transfer rate are estimated using the Fourier law of heat conduction mathematical relation.

3. Results and Discussion

The experimental studies were conducted on three model roofs (roof combination A, roof combination B and roof combination C) which are constructed in Pakistan. Thermal conductivity, heat conduction rate, and temperature reduction capability of each roof combination are determined.

3.1 Estimation of thermal conductivity & thermal resistivity

The thermal conductivity of each roofing material was found experimentally using heat conduction unit H940 P.A Hilton. This equipment determines the thermal conductivity of any cylindrical solid diameter of 25 mm and length of 30 mm based on the Fourier law of heat conduction. The cylindrical-shaped specimens having 25 mm diameter and 30 mm length are made from RCC, Marble, and polyurethane. They are placed in the equipment test section to estimate the roof material's thermal conductivity. The thermal resistivity of roof combinations A, B, and C were calculated from mathematical relations derived from the Fourier law of heat conduction as in Equation 2 [27].

$$R_{th} = \frac{x_1}{K_1} + \frac{x_2}{K_2} + \frac{x_3}{K_3} +, \dots, + \frac{x_N}{K_N} \tag{2}$$

Where x= thickness of each constituent
K= thermal conductivity of each constituent

The experimental results of thermal conductivity and resistivity are illustrated in table 2.

3.2 Determination of temperature reduction

The inner surface temperature and outer surface temperature of roof samples were determined three times each day i.e., Morning at 10.00 AM, afternoon at 01.00 PM, and evening at 04.00 PM from

04 June 2022 to 13 June 2022 using an Infrared thermometer. Figures 3, 4, and 5 shows the daily temperature reduction of every roof combination, which is the difference between outer surface temperature and inner surface temperature recorded at 10.00 AM, 01.00 PM, and 04.00 PM, respectively from 03 June 2022 to 13 June 2022.

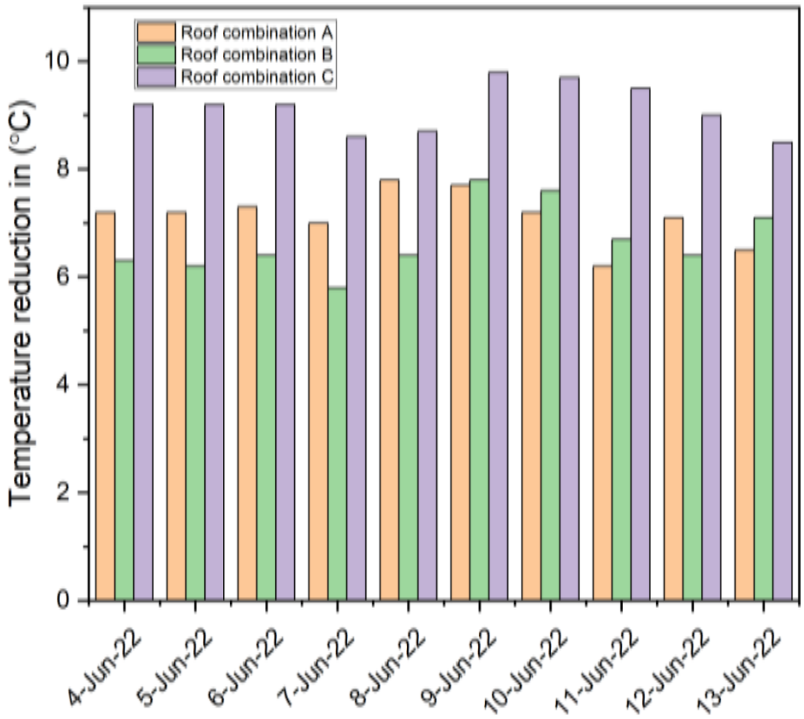

Fig.3- Temperature reduction in roof combinations A, B &C at 10.00 AM

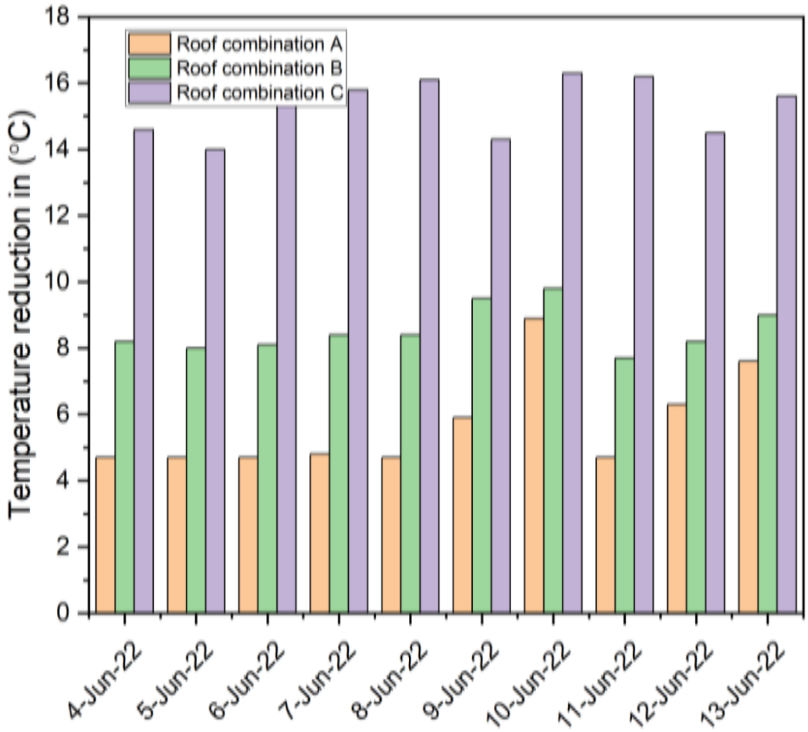

Fig.4- Temperature reduction in roof combinations A, B &C at 01.00 PM

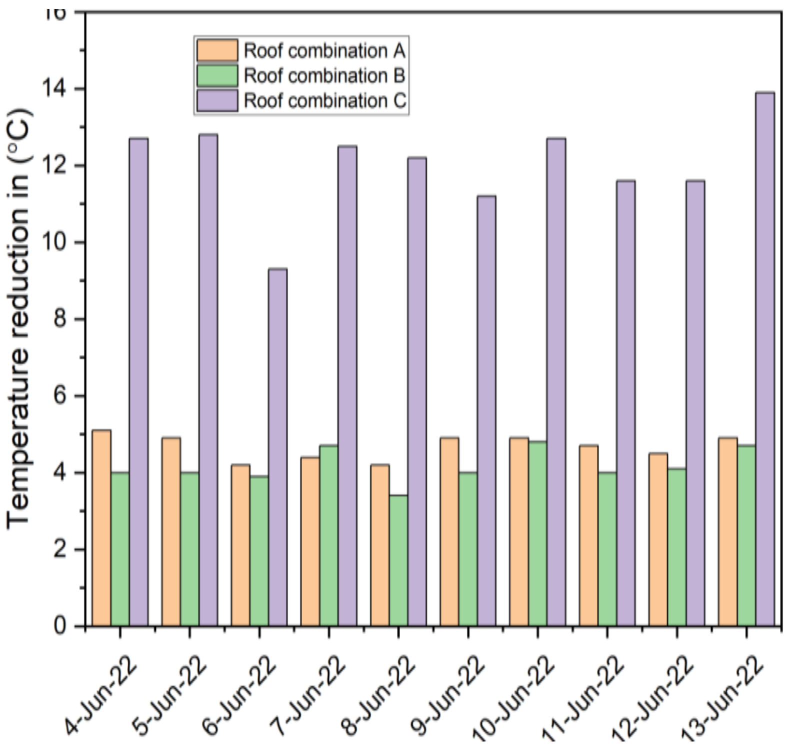

Fig.5- Temperature reduction in roof combinations A, B &C at 04.00 PM

Figure 6 indicates the average temperature reduction of roof combinations (A, B & C) at 10.00 AM, 01:00 AM, and 04:00 PM. Average temperature reductions by roof combinations A, B & C are 5.83°C, 6.4°C, and 12.18°C respectively. It was found that temperature reduction is more in roof combination C and least in roof combination A. Roof combination C proves better temperature reduction performance than roof combinations B and C.

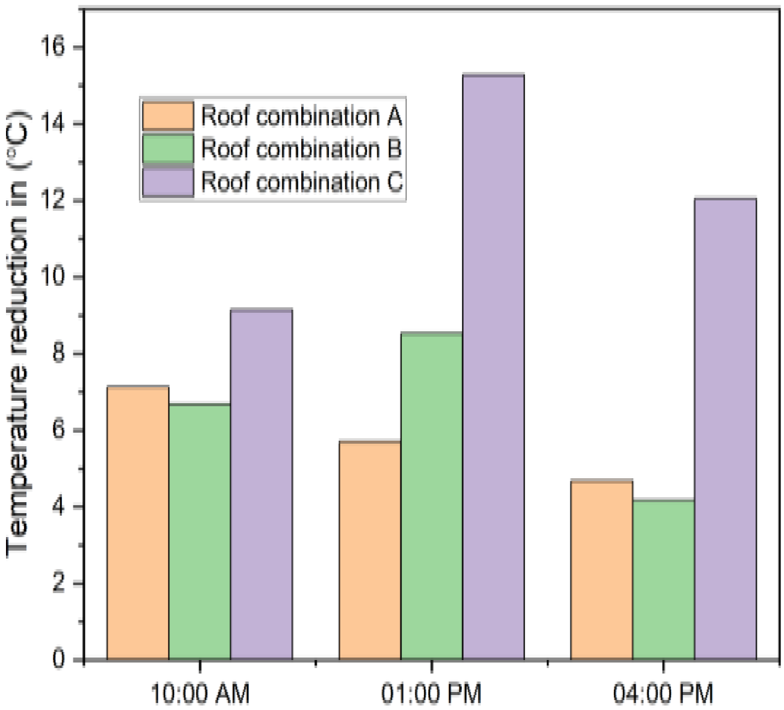

Fig.6- Average Temperature reduction in roof combinations A, B &C

3.3 Heat analysis

Heat transfer rates through roof combinations A, B & C were determined based on the Fourier law of heat conduction relation i-e as in Equation 3 [27]:

$$Q = \frac{KAdT}{dx} \quad (3)$$

The heat transfer rate for each roof sample was analyzed three times per day i.e. Morning at 10.00 AM, afternoon at 01.00 PM, and evening at 04.00 PM from 04 June 2022 to 13 June 2022. In this experimental study, it was determined that the rate of heat transfer per unit area through roof combination C is least, and through roof combination A is more; therefore, roof combination C is the better combination to resist the heat from outdoors to indoors which subsequently decreases energy requirement and capacity of air conditioning device.

It is also found that roof combination A was more conductor of heat at 10:00 AM and 04:00 PM as compared to B, but at 01:00 PM, heat transfer through roof combination B is more than roof combination A. Average heat transfer rates in watt/m2 through combinations A, B, and C were 156.38, 137.89, and 24.46, respectively. With the adoption of roof combination C, 84.3 % heat dissipation per square foot of roof can be reduced compared to roof combination A. Similarly, roof combination B can save 11.8% of building energy in terms of cooling and heating load.

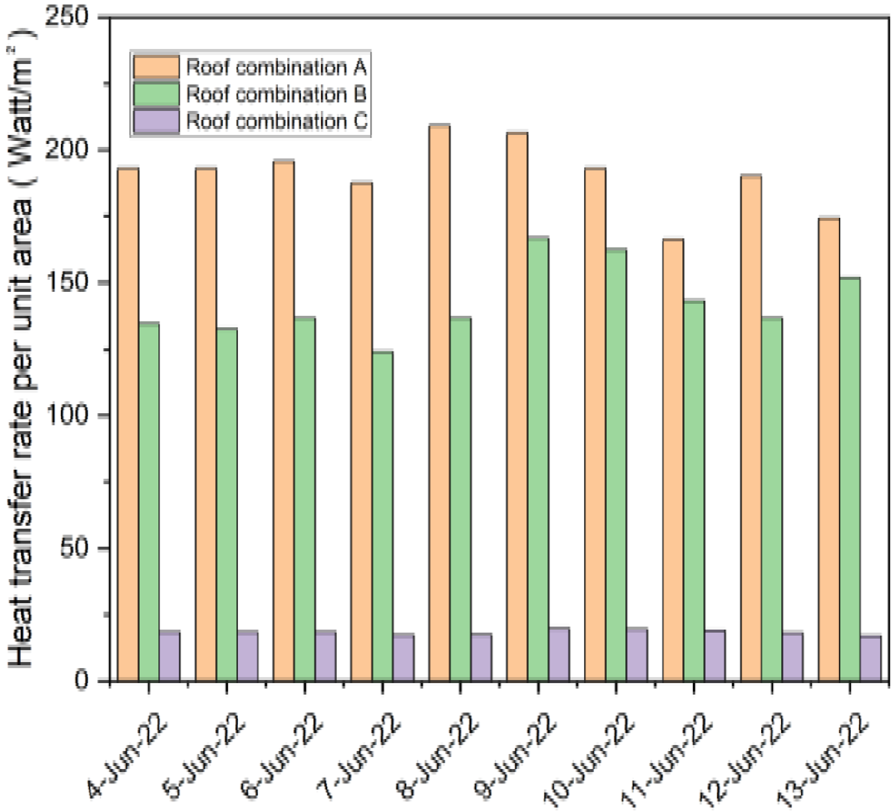

Fig.7- Heat transfer rate per unit area in roof combinations A, B &C at 10.00 AM

Figure 7 to figure 9 represent the rate of heat transfer per unit area through each roof combination A, B & C in the morning time (10:00 AM), afternoon (01:00 PM), and evening (04:00 PM), respectively, from 03 June 2022 to 13 June 2022. Figure 10 denotes the average heat transfer rate per unit area of roof combinations A, B & C at 10:00 AM, 01:00 PM, and 0400PM.

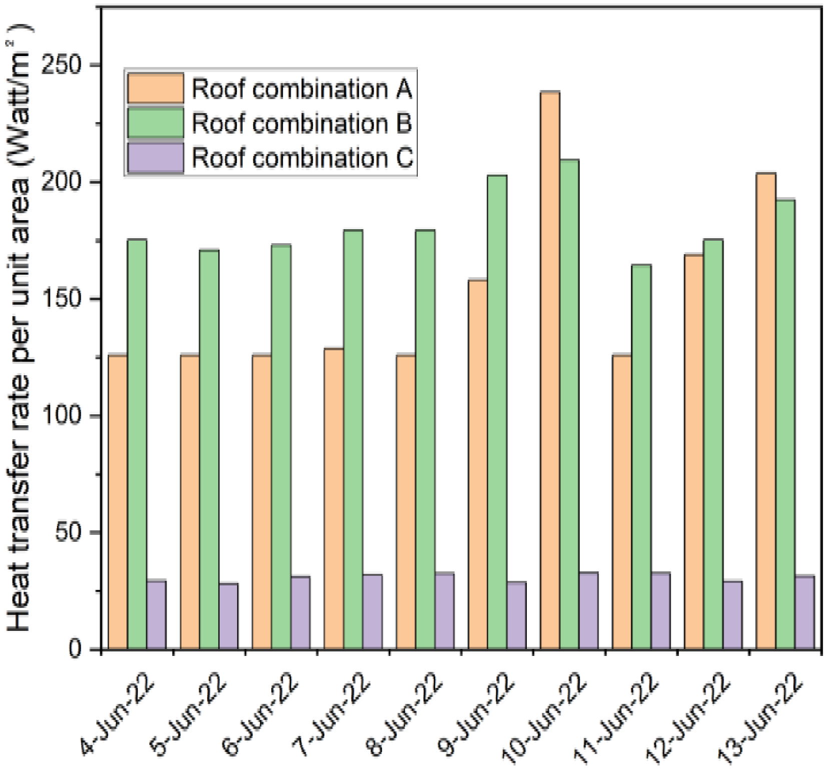

Fig.8- Heat transfer rate per unit area in roof combinations A, B &C at 01.00 PM

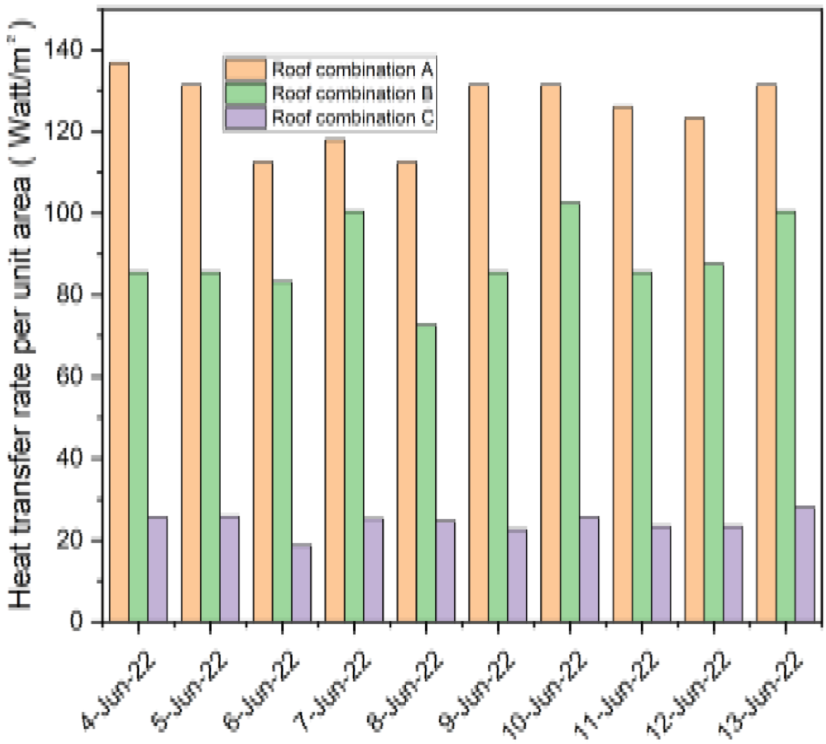

Fig.9- Heat transfer rate per unit area in roof combinations A, B &C at 4.00 PM

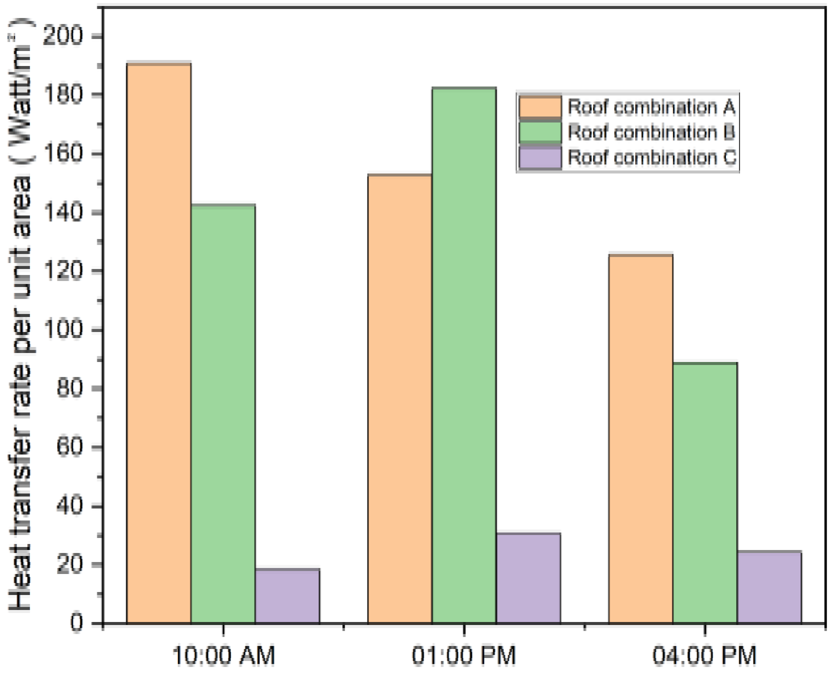

Fig.10- Average heat transfer rate per unit area in roof combinations A, B &C

4. Conclusion

In this study, three roofs (A, B & C) are selected for comparative study. These roofs are constructed in Pakistan and are exposed to solar radiation directly. An investigation of the thermal behavior of the distinct combinations of roof-tops adopted in Pakistan and the Middle Eastern countries has been performed for the early ten days of June 2022. The rate of heat transfer has been calculated. Fourier law of heat conduction is applied to estimate the rate of heat conduction. The findings revealed the rate of heat flow was lowered by 11.8% and 84.3 % with the implementation of combinations B and C, respectively, compared to the RCC roof without insulation. From the results, it was concluded that roof combination C is highly significant in Middle Eastern countries because it retards the maximum entrance of outside heat energy up to 84.3%. However, roof combination C is recommended for Pakistan and South Eastern countries, it can reduce the maximum cooling load requirement of a building

References

[1] J. Mustafa, F. A. Almehmadi, and S. Alqaed, "A novel study to examine dependency of indoor temperature and PCM to reduce energy consumption in buildings," *Journal of Building Engineering*, vol. 51, p. 104249, 2022.

[2] R. Kotharkar, A. Ghosh, S. Kapoor, and D. G. K. Reddy, "Approach to local climate zone based energy consumption assessment in an Indian city," *Energy and Buildings*, vol. 259, p. 111835, 2022.

[3] L. F. Yi, S. T. Ching, and Y. P. Yu, "Analyze the energy-saving benefits of Taiwan's existing advanced energy-saving strategies through energy simulation," in *CLIMA 2022 conference*, 2022.

[4] S. Azhar and M. A. Khan, "Low-Cost Roof Insulation Solutions for Low-Rise Residential Buildings and Houses in Pakistan," in *Proceedings of the 55th ASC Annual International Conference, Denver, CO, USA*, 2019, pp. 10-13.

[5] M. Santamouris, *Energy and climate in the urban built environment*. Routledge, 2013.

[6] A. Mohajerani, J. Bakaric, and T. Jeffrey-Bailey, "The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete," *Journal of environmental management,* vol. 197, pp. 522-538, 2017.
[7] A. Gray, "Cool Roof Pays off in Energy Saving and Enviromental Benefits," Building Operating Management, 2005.
[8] (2010). *Guidelines for Selecting Cool Roof.*
[9] A. Synnefa, M. Santamouris, and K. Apostolakis, "On the development, optical properties and thermal performance of cool colored coatings for the urban environment," *Solar energy,* vol. 81, no. 4, pp. 488-497, 2007.
[10] M. Santamouris, "Heat island research in Europe: the state of the art," *Advances in building energy research,* vol. 1, no. 1, pp. 123-150, 2007.
[11] "cool roofs mandatory for all new buildings," in *indianexpress*, ed.
[12] S. Boixo, M. Diaz-Vicente, A. Colmenar, and M. A. Castro, "Potential energy savings from cool roofs in Spain and Andalusia," *Energy,* vol. 38, no. 1, pp. 425-438, 2012.
[13] Y. H. Lee *et al.*, "Thermal behavior and energy efficiency of modified concretes in the tropical climate: A systemic review," *Sustainability,* vol. 13, no. 21, p. 11957, 2021.
[14] A. S. Hasan, O. M. Ali, and A. A. Hussein, "Comparative study of the different materials combinations used for roof insulation in Iraq," *Materials Today: Proceedings,* vol. 42, pp. 2285-2289, 2021.
[15] A. A. Jhatial, W. I. Goh, N. Mohamad, T. A. Rind, and A. R. Sandhu, "Development of thermal insulating lightweight foamed concrete reinforced with polypropylene fibres," *Arabian Journal for Science and Engineering,* vol. 45, no. 5, pp. 4067-4076, 2020.
[16] C. A. o. B. E. Efficiency, "Research Report on Building Energy Consumption in China," *Constr. Archit.,* vol. 7, pp. 30-39, 2020.
[17] L. Hou *et al.*, "Synergistic effect of silica aerogels and hollow glass microspheres on microstructure and thermal properties of rigid polyurethane foam," *Journal of Non-Crystalline Solids,* vol. 592, p. 121753, 2022.
[18] C. Mano and A. Thongtha, "Enhanced thermal performance of roofing materials by integrating phase change materials to reduce energy consumption in buildings," *Journal of Renewable Materials,* vol. 9, no. 3, pp. 495-506, 2021.
[19] S. Tangjuank, "Thermal insulation and physical properties of particleboards from pineapple leaves," *International Journal of Physical Sciences,* vol. 6, no. 19, pp. 4528-4532, 2011.
[20] H. Xi, Y. Yao, Y. Sun, B. Mobasher, Y. Liu, and H. Ma, "Compressive and thermal properties of foamed concrete at high temperature," *Journal of Sustainable Cement-Based Materials,* pp. 1-25, 2021.
[21] M. Khoukhi, "Change of the Thermal Conductivity of Polystyrene Insulation in term of Temperature at the Mid Thickness of the Insulation Material: Impact on the Cooling Load," *International Journal of Mechanical and Mechatronics Engineering,* vol. 10, no. 5, pp. 884-888, 2016.
[22] D. Kim, S. Lee, and I. Yang, "Verification of thermal conductivity measurements using guarded hot plate and heat flow meter methods," *Journal of the Korean Physical Society,* pp. 1-7, 2021.
[23] Y. Anand *et al.*, "Comparative thermal analysis of different cool roof materials for minimizing building energy consumption," *Journal of Engineering,* vol. 2014, 2014.
[24] U. Berardi and M. Naldi, "The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance," *Energy and Buildings,* vol. 144, pp. 262-275, 2017.
[25] O. I. A. Massoud, D. M. Sadek, M. I. M. A. Hady, M. Mohamed, and K. E. A. S. Abd Elrazike, "The Thermal Performance and Economic Impact of Using Marble Wastes for Hollow Concrete

Block Production," *Al-Azhar University Civil Engineering Research Magazine (CERM)*, vol. Vol. (41) No. (2) no. april 2019.

[26] S. A. Farhan *et al.*, "Effect of Roof Tile Colour on Heat Conduction Transfer, Roof-Top Surface Temperature and Cooling Load in Modern Residential Buildings under the Tropical Climate of Malaysia," *Sustainability*, vol. 13, no. 9, p. 4665, 2021.

[27] R. K. Rajput, "Heat and Mass Transfer. ," no. 3rd Edition, 2012. S.Chand and Company Limited, Ram Nagar, New Delhi, 2018.

[28] C. Fabiani and A. L. Pisello, "Effect of thermochromic coatings on the indoor thermal behavior of a case study building," in *E3S Web of Conferences*, 2021, vol. 238: EDP Sciences, p. 06003.

[29] V. Joshima, M. Naseer, and E. L. Prabha, "Assessing the real-time thermal performance of reinforced cement concrete roof during summer-a study in the warm humid climate of Kerala," *Journal of Building Engineering*, vol. 41, p. 102735, 2021.

[30] C. Amaral *et al.*, "Experimental and numerical analysis of the thermal performance of polyurethane foams panels incorporating phase change material," *Energy*, vol. 216, p. 119213, 2021.

[31] M. Rawat and R. Singh, "A study on the comparative review of cool roof thermal performance in various regions," *Energy and Built Environment*, 2021.

[32] N. M. Zahari, I. A. Rahman, A. M. A. Zaidi, and A. Mujahid, "Foamed concrete: potential application in thermal insulation," in *Malaysian Technical Universities Conference on Engineering and Technology*, 2009, pp. 47-52.