International Journal of Research Publication and Reviews, Vol 6, Issue 7, pp 2438-2446 July 2025

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Influence of Dust Accumulation on Cool Roof Thermal Performance for Residential Buildings in Hot -Dry Climate

Tayseer Goiw[1], Professor Saud Sadig Hassan[2]

[1,2]Sudan University of Science &Technology

ABSTRACT:

This research investigates how the accumulation of dust influences the thermal efficiency of residential cool roofing systems in hot-dry climatic regions, specifically across North Africa, the Middle East, and Australia. Eight cities with varied environmental characteristics Khartoum, Riyadh, Baghdad, Timimoun, Alice Springs, Port Augusta, Mildura, and Meeka Tharra were selected for dynamic simulation analysis. The roofs were modeled with defined parameters for solar absorptivity, emissivity, and thermal resistance, and evaluated under both clean and dust-affected surface conditions.

Results revealed that, when roofs were clean, outer surface temperatures ranged between 44 °C and 57 °C, while inner surface temperatures were recorded between 41 °C and 52 °C. In contrast, the presence of surface dust, which increases absorptivity, led to a marked deterioration in thermal performance. Under these conditions, peak outer temperatures reached up to 74 °C in Alice Springs, and inner temperatures rose to 60 °C in Riyadh. The most substantial increases in heat gain were observed in cities where roofs had higher initial absorptivity values or lower thermal resistance.

The study clearly establishes a strong correlation between dust accumulation and the diminished thermal effectiveness of cool roof systems. It emphasizes the need for the use of dust-repellent materials, high-emissivity surface treatments, and regular maintenance practices in roof design. These findings offer critical guidance for developing climate-responsive architectural approaches in regions that are both hot and susceptible to dust exposure.

Keyword: Thermal Performance, Cool Roof, Absorptivity, Dust Accumulation, Hot Dry Climate

Introduction:

Many studies have focused on the evaluation of the performance of the cool roof in hot dry climate, but not focusing on the impact of dust in thermal performance of roof, although hot dry climate extreme dusty, but there are only a few studies related to accumulation of dust and how influence it of cool flat roof. Dust accumulation on building roofs constitutes a prevalent environmental factor that significantly influences thermal performance in hot-dry climates. The deposition of particulate matter can adversely affect the albedo of roofing materials, leading to increased solar heat absorption. This phenomenon results in elevated surface temperatures, which subsequently raises the thermal load on the building's cooling systems. Moreover, the accumulation of dust may impede the efficacy of thermal insulation. Dust accumulation on building roofs constitutes a prevalent environmental factor that significantly influences thermal performance in hot-dry climates. The deposition of particulate matter can adversely affect the albedo of roofing materials, leading to increased solar heat absorption. This phenomenon results in elevated surface temperatures, which subsequently raises the thermal load on the building's cooling systems. Moreover, the accumulation of dust may impede the efficacy of thermal insulation. Several experimental studies have measured dust deposition rates as an average over fairly short time periods in areas such as North Africa, America, the Middle East, and Asia [1]. Additionally, dust atmospheric models have been designed to predict dust emission, concentration and deposition [2]. North African and Middle Eastern deserts are considered the two biggest natural dust sources, 50% and 25%, respectively [3]. Consequently, dust accumulation on a building's roof can be expected to occur in and around these extremely hot and dry locations.

Dust accumulation can then be calculated as the sum of hourly dust deposition over a selected time period. Due to its relatively high absorptivity, accumulated dust on a roof's surface contributes to an overall increase in the roof's absorptive properties. This augmentation in absorptivity leads to an elevated amount of solar radiation being absorbed by the roof, thereby increasing the thermal load transferred into the building. As a consequence, this can significantly impact indoor temperature regulation and energy consumption for cooling, necessitating a comprehensive assessment of dust management practices to mitigate these effects. Many studies have focused on the evaluation of the performance of the cool roof in hot dry climate, but not focusing on the impact of dust in thermal performance of roof, although hot dry climate extreme dusty, but there are only a few studies related to accumulation of dust and how influence it of flat roof. Fewer studies and field test measurements have been conducted to investigate changes in roof thermal properties due to weathering factors and dirt over a large time interval. For exam-(ple, Berdahl et al,2008). provided an overview of weathering factors that influence roof solar absorptivity of different roof material. The study also explained that roof weathering can increase the solar absorptivity value except in the case of very low-reflective roof materials. (Suehrcke et al,2008) investigated the effect of weathering on building solar absorpotance over a long period of time, after eight years, weathered white paint with a low initial absorptivity of 0.2 demonstrated an increase of 15%. [4] analyzed around 1357 CRRC roof samples and found that the mean solar reflectance loss was −6% to 17% of product type after three years of natural exposure.

Heat Transfer Mechanisms between Roof Surfaces and Dust Particles:

The heat transfer mechanisms between roof surfaces and dust particles can be characterized within the framework of packed bed heat transfer. This concept encompasses several key processes, which can be summarized as follows

1. **Conduction Heat Transfer**: Conduction is the primary mode of heat transfer between dust particles and between dust particles and the roof surface. Within a dust layer, thermal energy is transferred from one particle to another through direct molecular interactions. The rate of conductive heat transfer is determined by the thermal conductivity of the dust material, particle size, and the contact area between particles. Additionally, the conduction from dust particles to the roof surface is influenced by the thermal properties of the roofing material and the effective contact conductance at the interface, which may be affected by factors such as surface roughness and dust layer density.
2. **Convection Heat Transfer**: Convection involves the transfer of heat between the ambient air, the roof surface, and the dust particles. This process is driven by the movement of air over the dust-covered roof, creating a thermal boundary layer. The convective heat transfer coefficient is a critical parameter that quantifies the efficiency of heat exchange in this system. Factors such as wind speed, air temperature, and the geometry of the roof surface and dust layer influence convective heat transfer. The interaction between the moving air and the dust particles facilitates the transfer of thermal energy, contributing to the overall thermal dynamics of the roof system.
3. **Radiation Heat Transfer**: Radiation heat transfer occurs between dust particles and between dust particles and the roof surface. Dust particles can absorb, emit, and scatter thermal radiation, influencing the thermal energy exchange within the system. The emissivity and absorptivity of the dust particles determine their effectiveness in radiative heat transfer. The radiative interaction between dust particles is significant, particularly in terms of longwave radiation exchange, while the radiation from the dust layer to the roof surface affects the thermal balance of the roofing system. The cumulative effects of these radiative interactions contribute to the overall heat transfer dynamics within the dust-covered environment. See fig.1. Due to its high absorptivity, accumulated dust strongly affects total roof surface solar absorptivity, α. As shown in Fig. 2, a fully dusty roof is subjected to double the amount of absorbed solar radiation as compared to a non-dusty concrete roof.

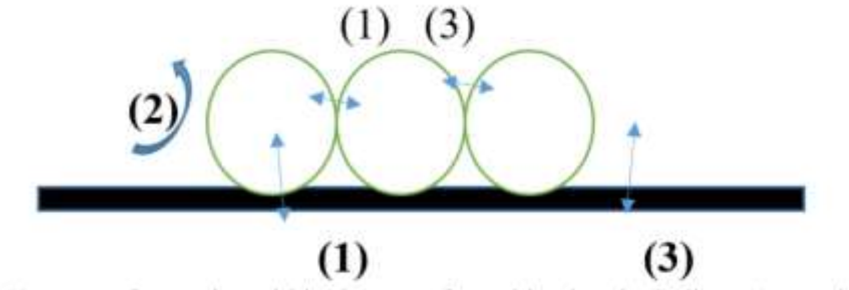


Fig 1: Heat transfer modes within dusty surface-side view including: (1) conduction, (2) convection, and (3) radiation.

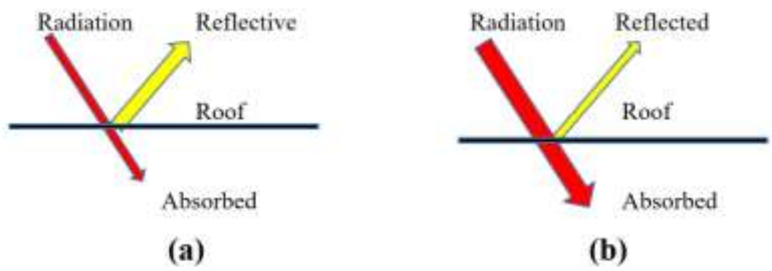


Fig 2: Variation of absorbed solar radiation under two roof conditions; (a) clean roof and (b) dusty roof.

Nomenclature

G solar flux (W/m2)

T_a ambient air temperature (K)

T_s outside surface temperature (K)

T_{sky} sky effective temperature (K)

T_{in} inside surface temperature (K)

$Rtotal$ Total Resistance

h_{out} outside convection heat transfer coefficient (W/m2K)

A ratio of unit area covered by dust

A_{dust} roof area covered by dust (m2)

A_{roof} total roof area (m2)

F shape factor f packing factor

M accumulated dust (kg/m2)

d_p mean dust diameter (m)

r_p mean dust radius (m)

V_p dust particle volume (m3)

Greek

β a soiling resistance

ε thermal emissivity

α solar absorptivity

$\alpha_{new-roof}$ new roof solar absorptivity

α_{dust} dust solar absorptivity

ρ dust density (kg/m3)

Ơ Stefan Boltzmann constant, 5.6685 × 10−8W/m2K4

Role of solar absorptivity and thermal emissivity in building heat gain

Roof solar absorptivity is a key factor in determining exterior roof surface temperature. Generally, lower solar absorptivity maintains a lower roof surface temperature and vice versa. An energy balance equation under steady state conditions can be written as

$\alpha.\ G. = h_{out}(T_s - T_a) + \varepsilon\cdot\sigma\cdot[Ts^4 - T_{sky}^4] + \frac{Ts-Tin}{Rtotal}$...... (1)[5]

Eq. (1) shows solar absorptivity, thermal emissivity, and other environmental factors affecting the roofs outside surface

temperature. In general, low solar roof absorptivity and high thermal emissivity (cool roof) are usually recommended to reduce roof sur face temperature, transient solar absorptivity and thermal emissivity are often not included building energy

calculations. To conclude, solar absorptivity and thermal emissivity are both key parameters that affect the roof surface temperature, and each is influenced by accumulated dust.

Mathematical model of roof solar absorptivity in dusty conditions

The literature indicates a linear relationship between roof solar absorptivity and dust accumulation effect as a function of exposure time see fig 3, and can be written as:

$\alpha = \alpha_{new-roof} + \beta\,(\alpha_{dust} - \alpha_{new-roof})$ (2)

Therefore, total roof solar absorptivity may be written as a function of dust accumulation f(M) as follows:

$\alpha = \alpha_{new-roof} + f(M)\,(\alpha_{dust} - \alpha_{new-roof})$ … (3)

As a result, a ratio of unit area covered by dust (A) is defined and may be written as a function of a packing factor as:

$A = \frac{1.5M}{Ppxdp} f$ ………… (4)

If A=0 $\alpha = \alpha_{new-roof.}$

If A = [0.1] Calculate α.

If A ≥1 $\alpha = \alpha_{dust.}$

Finally, by substituting Eq. (4) in Eq. (3), the roof solar absorptivity can be expressed as a function of dust accumulation, dust size, density, and packing factor as follows:

$$\alpha = \alpha_{new-roof} + \frac{1.5m}{PpXdp} f \, (\alpha_{dust} - \alpha_{new-roof}) \ \ldots \ (5)$$

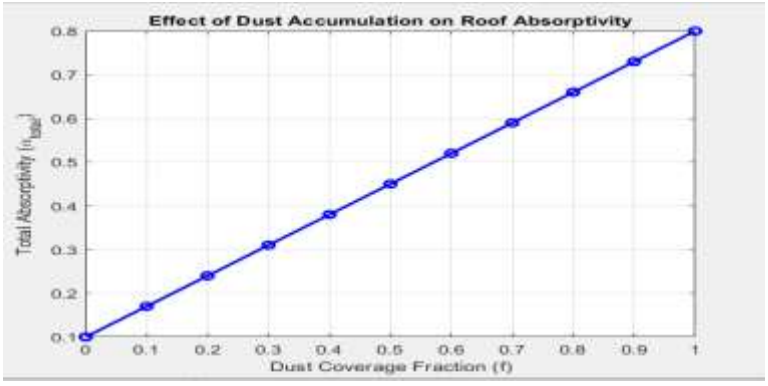


Fig3 Relationship between roof solar absorptivity and dust accumulation

Thermal Performance of Cool Roof:

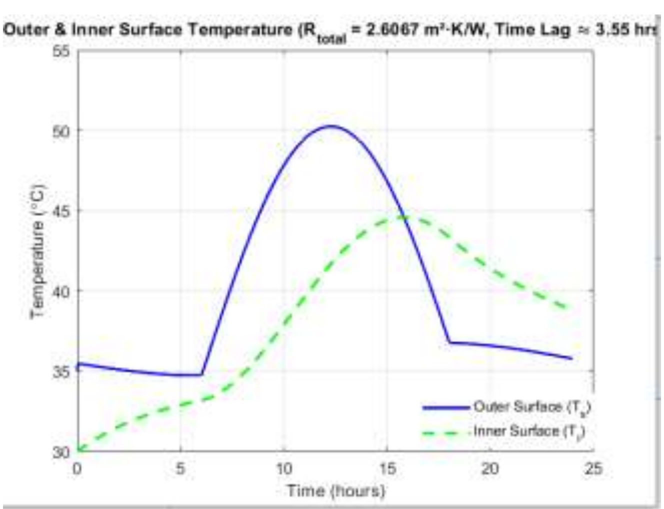
This study focuses on a city situated within the hot-dry climate zone, as defined by the Köppen Climate Classification (see Table 1). For each selected city, a roof sample was analyzed to investigate thermal behavior and heat transfer characteristics of cool roof systems under climate condition and materials properties. The evaluation was conducted using an energy balance approach (Equation 1), and the temperature dynamics were further examined through simulations performed in MATLAB.

Table 1 Hot-Dry Climate Zones

Region	Example Countries / Areas	Latitude Range	Longitude Range
North Africa & the Middle East	Khartoum, Riyadh, Baghdad, Timimoun,	15°N – 35°N	10°W – 60°E
Australia	Alice, Port Augusta Mildura, Meeka tharra	20°S – 30°S	120°E – 135°E

Khartoum City, Sample (1):

In Khartoum, Sudan, the roof system was constructed using materials with a solar absorptivity of 0.2 and an emissivity of 0.95. It was designed to achieve a thermal resistance of 2.64 m²·K/W. Under these conditions, simulation results indicated that the outer surface temperature peaked at 50 °C, while the inner surface reached 44 °C, as illustrated in Figure 4. However, when the roof was subjected to increased absorptivity 0.36 due to dust accumulation, the simulated peak temperatures rose significantly reaching 60°C on the outer surface and 51 °C on the inner surface, respectively. See fig 5.



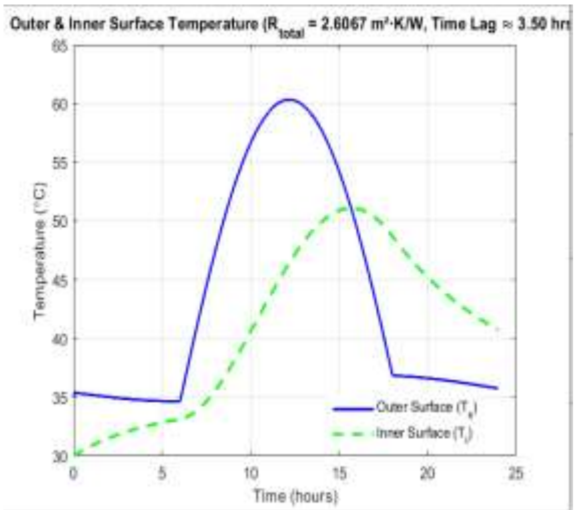


Figure 4 New Cool Roof Thermal Performance

Fig 5 Dust Cool Roof Thermal Performance

Riyadh City, Sample 2

In Riyadh, Saudi Arabia, a cool roof system was constructed using materials with a solar absorptivity of 0.3 and an emissivity of 0.90. The design aimed to achieve a thermal resistance of 2.3 m²·K/W. Simulation results, illustrated in Figure 6, showed that under clean conditions, the roof's outer surface temperature peaked at 57 °C, while the inner surface reached 52 °C. However, when the roof was exposed to dust accumulation which increased the surface absorptivity the peak temperatures rose significantly, reaching 72 °C on the exterior and 60 °C on the interior, as depicted in Figure 7.

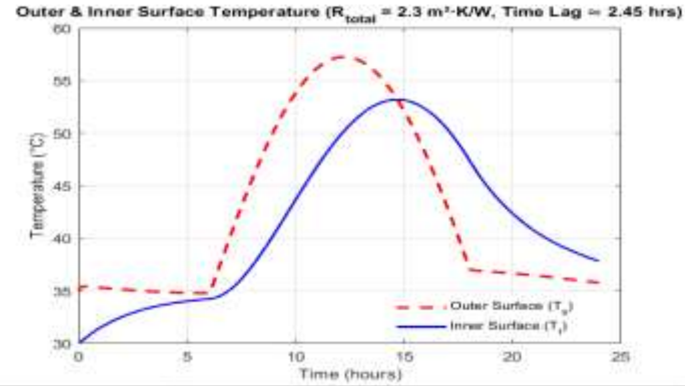


Figure 6 New cool Roof Thermal Performance

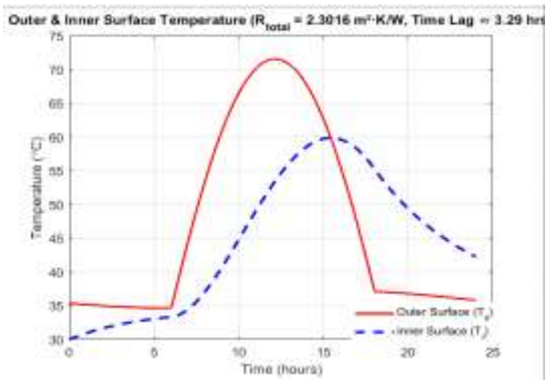


Fig 7 Dust Cool Roof Thermal Performance

Baghdad City, Sample3

The study examines a cool roof system in Baghdad, Iraq, built using materials with an absorptivity of 0.2 and emissivity of 0.90. The system was designed to achieve a thermal resistance of 2.5 m²·K/W. Simulation results show that the outer surface temperature peaked at 50 °C, while the inner surface reached 44 °C. The findings are illustrated in Figure 8, while the inner surface reached 52 °C. However, when the roof was exposed to dust accumulation which increased the surface absorptivity the peak temperatures rose significantly, reaching 61 °C on the exterior and 52 °C on the interior, as depicted in Figure 7.

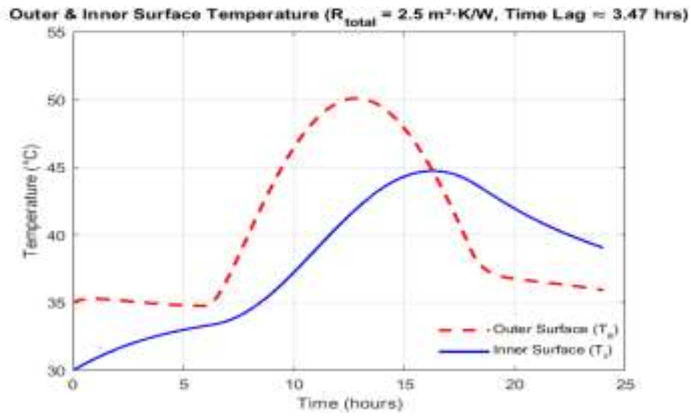


Figure 8 New cool Roof Thermal Performance

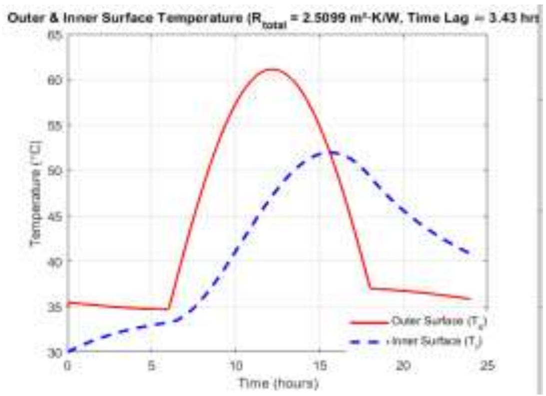
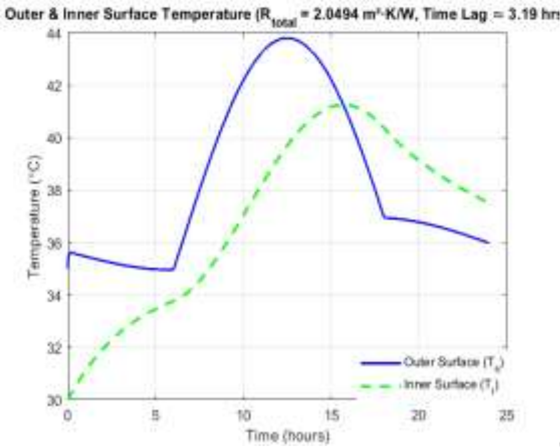


Fig 9 Dust Cool Roof Thermal Performance

Timimoun City, Sample4

The study assesses the thermal behavior of a residential cool roof system located in Timimoun, Algeria. Designed with a thermal resistance of approximately 2.1 m²·K/W, the system incorporates materials with a solar absorptivity of 0.1 and an emissivity of 0.80. Simulation results show that under typical conditions, the outer roof surface temperature peaks at 44 °C during the early afternoon, while the inner surface reaches a maximum of 41 °C, as illustrated in Figure 9. However, following the accumulation of dust which led to an increase in surface absorptivity 0.18 the simulation revealed a substantial rise in temperatures, with the exterior surface reaching 50 °C and the interior surface climbing to 46 °C, as presented in Figure 10.



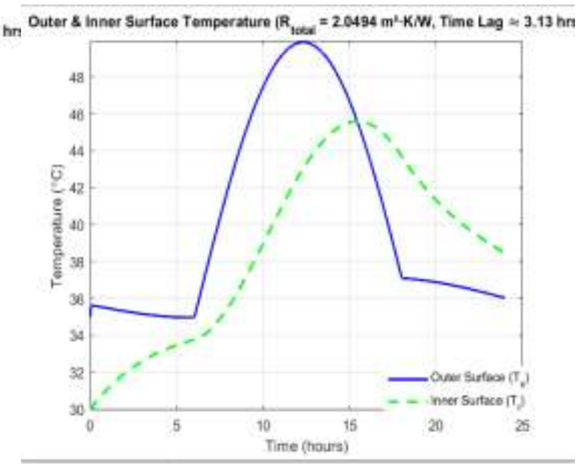
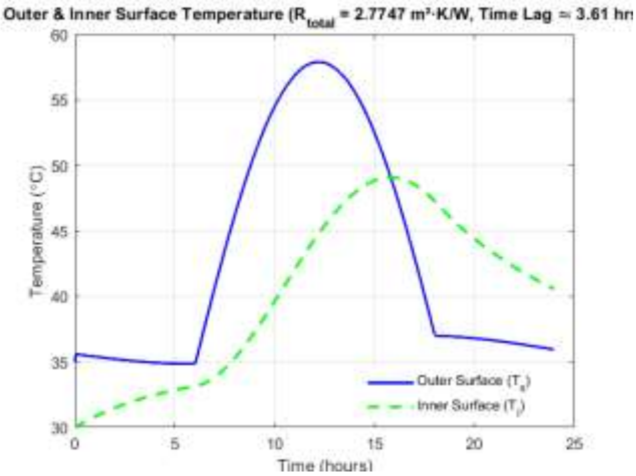


Figure 9 New cool Roof Thermal Performance Fig 10 Dust Cool Roof Thermal Performance

Alice Springs City, Sample 5

This research analyzes the thermal performance of a cool roof system installed in Alice Springs. The roof utilized materials with a solar absorptivity of 0.3 and an infrared emissivity of 0.85. Designed to deliver a thermal resistance of 2.77 m²·K/W, the system was evaluated through simulation-based analysis. Under standard conditions, simulation results showed that the external surface temperature peaked at 56 °C, while the internal surface reached 46 °C, as depicted in Figure 11. However, when dust accumulation was introduced resulting in increased surface absorptivity there was a marked escalation in surface temperatures. The outer surface temperature rose to 74 °C, and the inner surface reached 59 °C, as illustrated in Figure 12



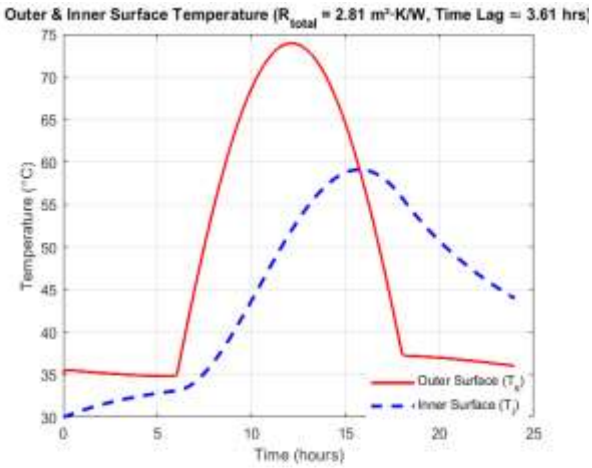


Figure 11 New cool Roof Thermal Performance Fig 12 Dust Cool Roof Thermal Performance

Port Augusta City, Sample 6:

This study evaluates the thermal behavior of a residential cool roof system located in Port Augusta. The system was designed with a thermal resistance of approximately 3.02 m²·K/W and featured surface properties including a solar absorptivity of 0.25 and an emissivity of 0.80. According to simulation results, the outer roof surface reached a peak temperature of 55 °C during the early afternoon, while the inner surface recorded a maximum of 46 °C, as presented in Figure 13. Following the introduction of dust accumulation which increased the surface absorptivity the simulation showed a significant rise in temperature levels, with the external surface reaching 69 °C and the internal surface climbing to 55 °C, as shown in Figure 14.

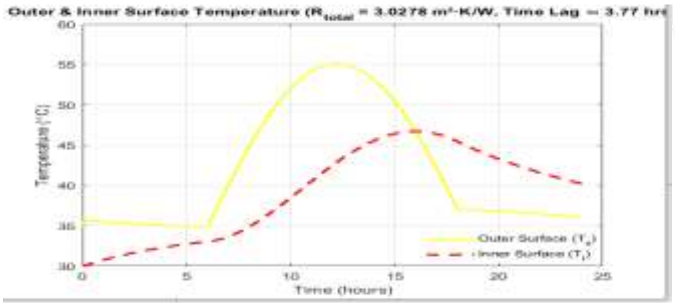


Figure 13 New cool Roof Thermal Performance

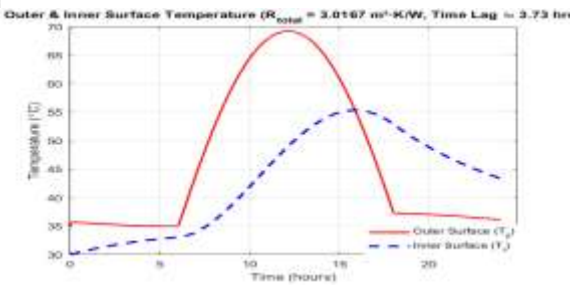


Fig 14 Dust Cool Roof Thermal Performance

Mildura City, Sample 7:

This study investigates the thermal performance of a residential cool roof system in Mildura, designed with a thermal resistance of approximately 3.2 m²·K/W, a solar absorptivity of 0.15, and a high emissivity of 0.85. Simulation results indicate that, under standard conditions, the roof's outer surface temperature peaks at 47 °C in the early afternoon, while the inner surface reaches a maximum of 41 °C, as illustrated in Figure 15. However, following the simulated accumulation of dust which led to an increase in surface absorptivity the thermal performance declined significantly. The outer surface temperature rose to 56 °C, and the inner surface reached 48 °C, as depicted in Figure 16.

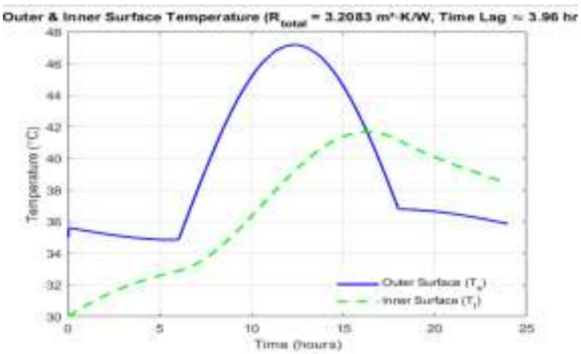


Figure 15 New cool Roof Thermal Performance

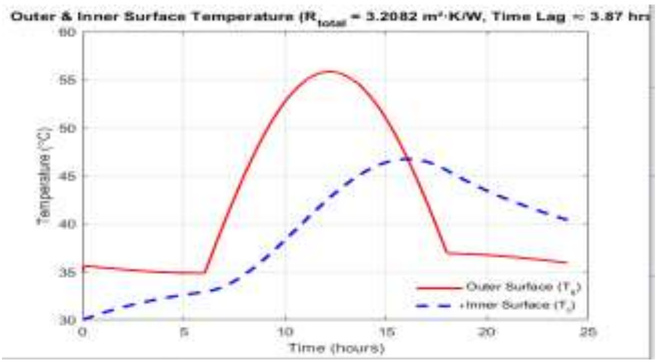


Fig 16 Dust Cool Roof Thermal Performance

Meeka tharra City, Sample 8

The study examines the thermal performance of a residential cool roof system installed in Meeka Tharra City. The roof is characterized by a thermal resistance of approximately 3.3 m²·K/W, low solar absorptivity ($\alpha = 0.25$), and high emissivity ($\varepsilon = 0.85$). Simulation results show that under clean surface conditions, the outer surface temperature peaks at 54 °C in the early afternoon, while the inner surface reaches a maximum of 45 °C. These findings are visually summarized in the corresponding figure. However, when dust accumulation was simulated resulting in increased surface absorptivity 45 the system's thermal performance deteriorated noticeably. The outer surface temperature increased to 68 °C, while the inner surface temperature rose to 54 °C, as shown in Figure 16.

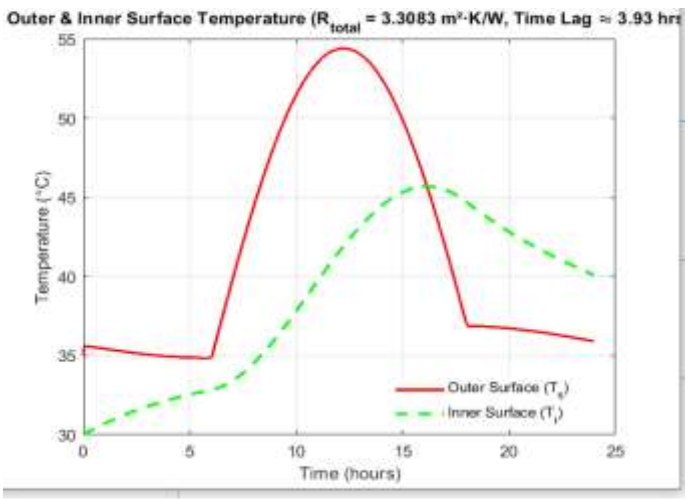


Figure 17 New cool Roof Thermal Performance

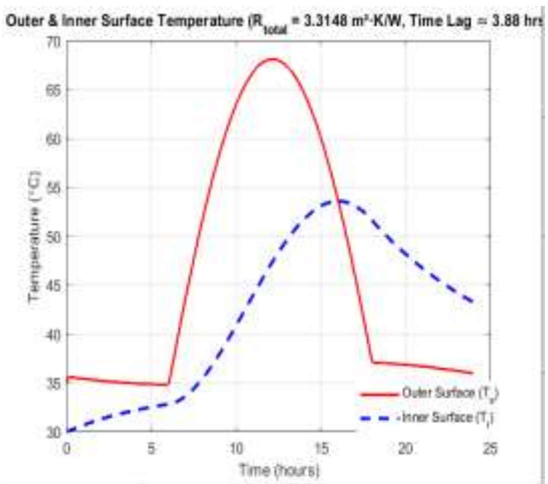


Fig 18 Dust Cool Roof Thermal Performance

Result and Discussion:

This study analyzes simulation data to assess the thermal performance of residential cool roofs in eight hot-dry cities under clean and dusty surface conditions. The investigation focuses on key parameters, including initial solar absorptivity, dust-induced absorptivity, and the resulting surface temperatures. The data reveal a strong correlation between increased total absorptivity primarily due to dust accumulation and elevated outer and inner roof temperatures.

Cities with high total absorptivity values, such as Riyadh, Alice Springs, and Meeka Tharra, experienced the greatest temperature increases, indicating a significant decline in roof cooling effectiveness. In contrast, cities with low absorptivity values like Timimoun and Mildura showed better thermal performance under similar conditions. Although Khartoum and Baghdad had identical absorptivity, minor temperature differences suggest that additional climatic factors may influence thermal behavior.

Port Augusta, despite a moderate absorptivity value, recorded higher internal temperatures, suggesting that environmental exposure also plays a critical role in thermal stress.

The study concludes that dust accumulation substantially impairs the thermal performance of cool roofs by increasing solar heat gain. It highlights the need for dust-resistant materials, maintenance practices, and climate-specific design adaptations. The findings support the revision of building codes and material standards to ensure energy efficiency and indoor comfort in arid, dust-prone environments. See table 2.

Table 2 Total Roof Absorptivity and Non-dusty roof. in different hot-dry locations using packing factor of 0.91.

Sample	Absorptivity (α)New Roof	Outer Surface Temp (°C)	Inner Surface Temp.(C)	Dust Absorptivity	Total Absorptivity	Outer Surface Temp (°C)	Inner Surface Temp.(C)
Sample 1-Khartoum	0.2	50	44	0.4	0.36	60	51
Sample 2- Riyadh	0.3	57	52	0.6	0.54	72	60
Sample 3- Baghdad	0.2	50	44	0.4	0.36	61	52
Sample 4- Timimoun	0.1	44	41	0.2	0.18	50	46
Sample 5 Alice Springs	0.3	57	46	06	0.54	74	59
Sample 6 Port Augusta	0.25	55	46	0.50	0.45	69	55
Sample 7 Mildura	0.15	47	41	0.3	0.27	56	48
Sample 8 Meeka tharra	0.25	54	45	0.5	0.45	68	54

References

[1] E. El-Desoky, etal,2015.

[2] S.ickovic, G. Kallos ,2014

[3] C. Pérez, K. Haustein, Z. Janjic, O. Jorba, N. Huneeus, J.M. Baldasano, T. Black, S. Nickovic, R.L. Miller, J.P. Perlwitz, M. Schulz, M. Thomson, Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model–Part 1: model description, annual simulations and evaluation, Atmos. Chem. Phys. 11 (24) (2011) 13001–13027.

[4] M. Sleiman, G. Ban-Weiss, H.E. Gilbert, D. Franc ¸ ois, P. Berdahl, T.W. Kirchstetter, H. Destaillats, R. Levinson, Soiling of building envelope surfaces and its effect on solar reflectance—Part I: analysis of roofing product databases, Solar Energy Mater. Solar Cells 95 (12) (2011) 3385–3399.

[5] ASHRAE Handbook—Fundamentals (2017).)

[6**]** Incropera, F. P., & DeWitt, D. P**. (2007).** *Fundamentals of Heat and Mass Transfer (6th ed.).* John Wiley & Sons. – A foundational reference for understanding conduction, convection, and radiation heat transfer, including packed bed concepts.

[7] Yagi, S., & Kunii, D. (1957). *Studies on effective thermal conductivities in packed beds.* AIChE Journal, **3**(3), 373–381. – Classical study on heat transfer in packed beds; applicable to dust layers treated as granular media.

[8] Suehrcke, H., Peterson, E., & Selby, N. (2008).*Effect of dust on solar reflectance of white roofs in Australia. Energy and Buildings*, **40**(4), 719–726. – Presents long-term data on how dust reduces solar reflectance, thus increasing surface temperature.

[9] Levinson, R., Akbari, H., & Berdahl, P. (2010). *Measuring solar reflectance—Part I: Defining a metric that accurately predicts solar heat gain. Solar Energy*, **84**(9), 1717–1744. – Defines the role of absorptivity and reflectance in thermal energy gain from solar radiation.

[10] Shao, Y., Wyrwoll, K.-H., Chappell, A., Huang, J., Lin, Z., McTainsh, G. H., ... & Zobeck, T. M. (2011).*Dust cycle: An emerging core theme in Earth system science. Aeolian Research*, **2**(4), 181–204. – Details dust particle behavior including radiation scattering and absorption, relevant for longwave interactions.

[11**]** IPCC AR5 (2013) *Climate Change 2013: The Physical Science Basis.* Cambridge University Press