Cool Roofs

Subjects: Engineering, Mechanical
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The use of white roofing material is a suggestion because of its cooling, evaporative and efficiency characteristics compared to traditional black roofing materials. Many research studies have shown that the darker roofing surfaces that are prevalent in many urban areas actually can increase temperature by 1 to 3 degrees Celsius to the environment surrounding these urban areas. Additionally, improved temperature control and heat reflection also work to reduce the energy requirements for the interior spaces of the structures that have white roofing surfaces. The white or lighter colored roofs tend to reflect a part of the solar radiation that strikes the roof's surface. Consequently, one might believe that white roofing material would be commonplace and especially so within emerging economies. Yet, this is hardly the case at all.

Keywords: cost-benefit ; energy savings ; urban heat island

1. Cool Roofs Pros and Cons and Its Relationship with the Weather

In the design stage of roofing systems, the energy savings and risk of condensation are important. The moisture-related problems can lead to deterioration of roofing materials and affect negatively the thermal performance by means of reduction in overall thermal resistance and service life of the roofing systems. This can lead as well to mold growth in those systems and affect the indoor air quality (IAQ) and the occupants' health and comfort [1][2][3][4][5][6][7][8][9].

The roof surface reflectivity can affect the quantity of the absorbed short-wave energy of the roof. Since the short-wave solar radiation has the capacity during the summer and daytime to dry out the roof, the solar reflectivity becomes an important parameter for the selection of roofing materials [1][2][10][11][12][13]. The characteristic of the cool roofs is to maintain surface temperatures lower than those from the black roof (dark) because of its low short-wave solar absorption coefficient. This may lead to moisture-related problems in cold climate zones [14] as such observed for both black and cool roofs [1][2]. Several studies have investigated the moisture-related problems due to the colour of the roofing membrane in commercial buildings with a low slope such as in [15] research. Their study was done for cold climate with the focus on single-ply roofing systems with highly reflective materials, white TPO/PVC and black membranes, where they are attached mechanically on low slope roofs (≤2:12). In this research, hygrothermal simulations were conducted for a one-year period on those roofing systems for the following cities in the USA: Boston, Albany, Chicago, Cleveland and Detroit. Two cases were studied: (i) 10% short-wave solar reflectivity for black roofs, and (ii) 70% short-wave solar reflectivity for white roofs. Since those systems are mechanically attached to the metal deck and to account for the leakage due to the attachment, the vapour permeance of metal was taken at 0.75 perms. The results showed that even there is condensation below the membrane TPO/PVC in the winter, all roofs have dried out in the summer.

Hygrothermal simulations were conducted [16] for a 5-year period. They explored the moisture accumulation in different roofing systems (i.e., white with 80% short-wave solar reflectivity and black roofs with 12%) for different cities in the USA and Germany (Phoenix, AZ, Chicago, IL, Anchorage, AK, and Holzkirchen, Germany). The results of this research showed that the white roofs have more moisture accumulation than the black ones. Three roofing systems cases, dark, bright and shaded flat roofs, have been studied by [17] for their hygrothermal performance with initial construction moisture. In the summer, the results showed that the bright roofs have the lowest surface temperatures with a smaller drying potential than the two other roofing systems. The highest surface temperature and humidity fluctuations were shown in the dark roofs with high heat fluxes. The roof with shaded surfaces has shown as well a low temperature and drying potential.

Hygrothermal simulations on white and black Modified-Bitumen (MOD-BIT) roofing systems have been conducted by [1][2]) to evaluate their energy and moisture accumulation for different climate zones in North America based on their Heating-Degree-Days (HDD) such as Toronto (ON), Montreal (QC), St. John's (NL), Saskatoon (SK), Seattle (WA), Wilmington (AZ), and Phoenix (AZ). In the cities of St. John's and Saskatoon, the white roofs showed the highest moisture accumulation over time than the black ones which could lead to moisture damage. On the contrary, there is no risk for the black roofs. The simulation results for Toronto, Montreal, Seattle, Wilmington, and Phoenix, showed that the white roofs have a low risk of experiencing moisture damage. The yearly heating loads of the white roof were slightly higher than that of the black roof. Conversely, the yearly cooling loads of the black roof were much important than the white roof. Thus, buildings with white roofs in these locations are predicted to result in net yearly energy savings compared to buildings with black roofs.

Most recently, several researchers [1][2][3][4][5][6][7][8][9][13][14][15][16][17][18][19][20][21][22][23] conducted several studies to investigate the performance of cool and black roofs in terms of energy and moisture when they were subjected to different hot and humid climates in GCC countries. These studies covered several thicknesses of roof insulation material and surface solar reflectivity. These roofing systems showed no risk of condensation, thus, no risk of mold growth and roofs with high solar reflectivity showed significant energy savings. For the Eastern Province of Saudi Arabia and Kuwait City, respectively, the highest hourly surface temperatures of the black roofs were found to be 93.2 °C and 84.0 °C compared to 65.4 °C and 61.5 °C for a white roof at no cleaning condition, and 52.7 °C and 52.6 °C for white roofs at weekly cleaning conditions. The full results of that study that include material characterizations, installing guidelines, cleaning procedures, test results, three-dimensional numerical results, etc., are available in [24][25].

2. Application and Maintenance of Cool Roofs

The application process of white roofing material requires technical knowledge as does the maintenance processes involved. Yet, the maintenance processes involved in white roofing materials must also be known from a marketing perspective. This is because emerging economies typically have limited resources available. At a granular level, however, entities that utilize white roofing materials as a means to reduce the cooling energy load of a structure, reduce environmental heat build-up and as well seek to control costs have to consider the post-application phase of the material. As mentioned, the technical application of the white roof depends upon the form of white roofing material selected. Likewise, maintenance is also dependent upon what material is selected. In effect, cost factors must also be considered with respect to ongoing maintenance of white roofs in developing markets.

The exterior surface of the roofing system is exposed to dust/dirt, rain, snow, wind, cloud index, exterior temperature and relative humidity, etc. All these external conditions as well as the roofing systems specifications (components, dimensions, etc.) could affect the roofing system's thermal and hygrothermal performance. As shown in **Figure 1**, when solar radiation hits the surface of a roofing system, a portion of this energy is reflected and the other portion is absorbed. Due to this energy absorption, the roof's surface temperature increased, thus in the summer, the cooling energy load increased and in the winter, the heating energy load decreased. On the other hand, white roofing systems use surfaces with low short-wave solar absorption coefficient to show a significant portion of the incident short-wave solar radiation, and therefore, lowers the cooling energy load and as well the roof's surface temperature compared to black roofing systems.

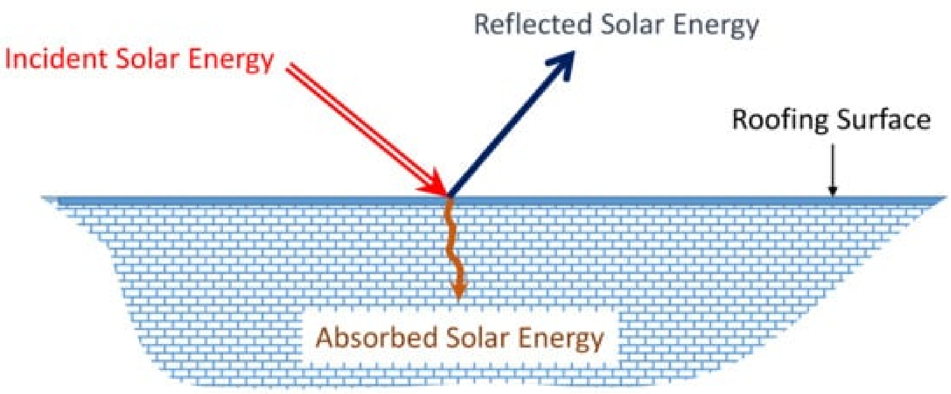

Figure 1. Schematic of roofing surface subjected to incident solar energy.

The surface solar reflectivity can be affected negatively by the accumulation of dust or dirt on those surfaces, which can result in increasing solar heat gains. Several researchers [26][27][28][29][30] have investigated the negative effect of the dust or dirt accumulation and weathering factors on the roofs' thermal properties. Additionally, several cleaning processes of dust or dirt on roofing systems' surfaces have been established to bring back roofing surfaces' solar reflectivity to its original value such as in Levinson et al. [29] studies on light-coloured roofing membranes' solar heat gain.

In the research [29], several roofing membranes with white or light gray polyvinyl chloride collected from different locations in the USA were tested. Black and inorganic carbon were found on the surface of the sample. These contaminants reduce the solar reflectivity of these membranes. To analyze the influence of several cleaning processes on the solar reflectivity values, the sample surfaces were firstly wiped to mimic the action of the wind action, then rinsed to mimic rain effect, and they were washed in the third step to simulate a homemade cleaning process using a phosphate-free dishwashing detergent. As a final step, all the surfaces were treated with sodium hydroxide and a mixture of sodium hypochlorite to mimic real cleaning processes. The outcomes of research [29] showed that after washing and rinsing processes, almost all the dirt deposited on the surface was removed except for thin layers of organic carbon and some isolated dark spots of biomass. Bleaching processes cleared these last two contaminants recovering the loss of solar reflectivity.

Akbari et al. [30] used an identical cleaning process established in [29] on unweathered (i.e., new materials) and weathered single ply roofing membranes from several North American sites. In this research, 16 types of roofing materials were tested at Lawrence Berkeley National Laboratory (LBNL), following all the cleaning processes concerning the weathered samples surface treatment, and 25 other types were tested at the National Research Council of Canada, applying just wiping processes on the surface of the roofing material. The results showed that all types of cleaning recovered near 90% of their unweathered solar reflectivity and thus, showed their effectiveness.

To the best of the researchers' knowledge, most (if not all) previous studies related to characterizing the impact of dust or dirt accumulation on the rooftops and its impact on cool roofs' energy performance were conducted in non-dusty climates. As such, a new joint research between the KSA's Jubail University College (JUC) and Kuwait Institute for Scientific Research (KISR), called "JUC-KISR project" was initiated to address this issue in a dusty climate. Several roofing materials with different emissivity are currently being tested and numerically modelled under the dusty and polluted climate of KSA's Jubail Industrial City. The objectives of JUC-KISR project include: (i) motioning the short-wave solar reflectivity's variation of the tested materials, (ii) developing a technical guide for dust and dirt cleaning processes for the tested materials, and (iii) quantification the effect of dirt and dust accumulation of on the overall roofing systems' energy and moisture performance. The developed technical guide will be proposed later to International Organizations such as ASTM or ASHRAE to develop an international standard for the cleaning procedure of different reflective materials for use in residential and commercial buildings when they are subjected to dusty and non-dusty climates.

In the JUC-KISR project, one of the reflective coating materials was characterized and tested under the highly polluted and dusty weather of Jubail Industrial City. Thereafter, this reflective coating material was used in one of the most common roofing systems in GCC countries when it was exposed to Kuwait City and Eastern Province of Saudi Arabia's environmental conditions. For Saudi Eastern Province climates, **Figure 2** shows that the yearly cooling load (EC, Y) of the conventional/black roof (1077 Wd/m2) decreased to 706 Wd/m^2 (i.e., a reduction in EC, Y by 53%) and 563 Wd/m^2 (i.e., a reduction in EC, Y by 91%) as a result of installing reflective coating material at no cleaning condition and weekly cleaning condition, respectively. Furthermore, as shown in **Figure 3** for Kuwait City climates, the yearly cooling load of the black roof (1091 Wd/m^2) decreased to 730 Wd/m^2 (i.e., a reduction in EC, Y by 49%) and 592 Wd/m^2 (i.e., a reduction in EC, Y by 84%) as a result of installing reflective cooling material at no cleaning condition and weekly cleaning condition, respectively.

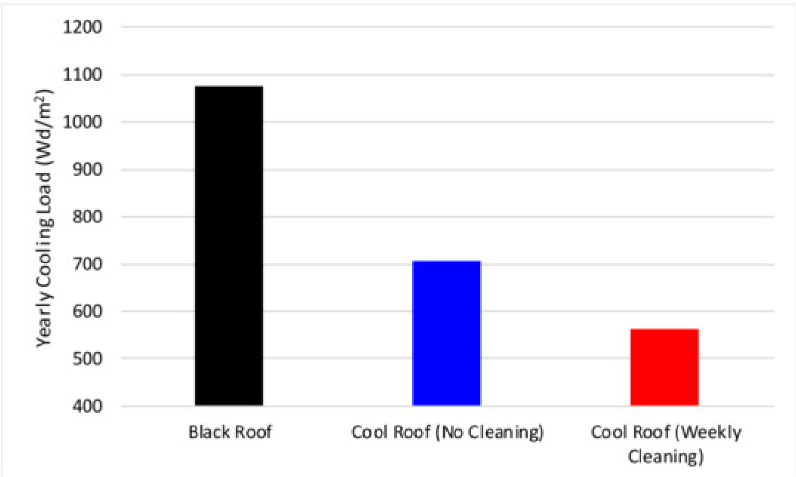

Figure 2. Comparison of the yearly cooling energy load of conventional/black roof and white roof based on no cleaning condition and weekly cleaning condition and subjected to Saudi Eastern Province climates [19][31].

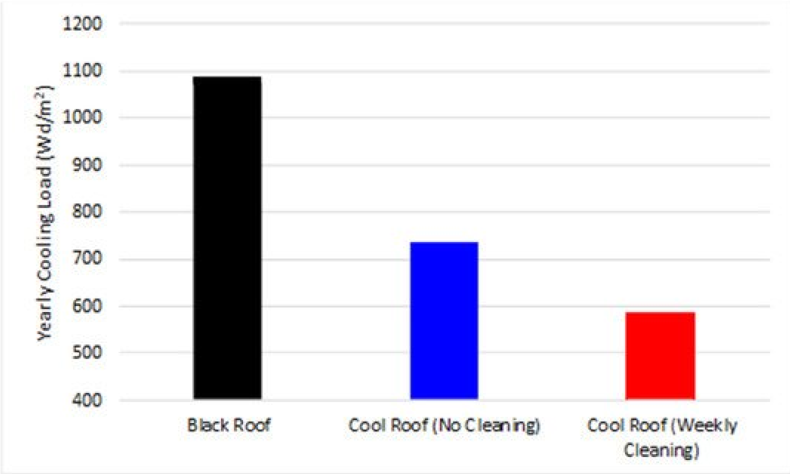

Figure 3. Comparison of the yearly cooling energy load of conventional/black roof and white roof based on no cleaning condition and weekly cleaning condition and subjected to Kuwait City climates [19][31].

For the Eastern Province of Saudi Arabia and Kuwait City's environmental conditions, respectively, the highest hourly black roofs' surface temperatures were 93.2 °C and 84.0 °C compared to 65.4 °C and 61.5 °C for white roof at no cleaning condition, and 52.7 °C and 52.6 °C for white roofs at weekly cleaning conditions. The full results of the JUC-KISR project that include material characterizations, installing guidelines, cleaning procedures, test results, three-dimensional numerical results, etc., are available in [19][31].

In summary, a logical step towards achieving energy-efficient buildings in cities with extreme climatic conditions is to design roofing systems with simultaneous energy savings, no condensation and less risk of moisture problems. The main parameters affecting the energy and moisture performance of roofing systems are a type of roof, environmental conditions, amount of insulation and the solar reflectivity of the roofing surfaces. Several cleaning processes have been used to increase the solar reflectivity to reach approximately its initial value in case there is dust/dirt accumulation on the roofing surface.

References

1. Saber, H.H.; Maref, W.; Hajiah, A.E. Hygrothermal Performance of Cool Roofs Subjected to Saudi Climates. J. Front. Energy Res. 2019, 7, 39.
2. Saber, H.H.; Maref, W. Energy Performance of Cool Roofs Followed by Development of Practical Design Tool. J. Front. Energy Res. 2019, 7, 122.
3. Miller, W.; Crompton, G.; Bell, J. Analysis of Cool Roof Coatings for Residential Demand Side Management in Tropical Australia. Energies 2015, 8, 5303–5318.
4. William, R.; Goodwell, A.; Richardson, M.; Le, P.V.; Kumar, P.; Stillwell, A.S. An environmental cost-benefit analysis of alternative green roofing strategies. Ecol. Eng. 2016, 95, 1–9.
5. Saber, H.H.; Maref, W.; Abdulghani, K. Properties and Position of Materials in the Building Envelope for Housing and Small Buildings; National Research Council of Canada: Ottawa, ON, Canada, 2014.
6. Saber, H.H.; Maref, W. Risk of condensation and mould growth in wood-frame wall systems with different exterior insulations. In Proceedings of the Building Enclosure Science & Technology Conference (BEST4 Conference), Kansas City, MO, USA, 16 April 2015.
7. Lacasse, M.A.; Saber, H.H.; Maref, W.; Ganapathy, G.; Plescia, S.; Parekh, A. Field Evaluation of Thermal and Moisture Response of Highly Insulated Wood-Frame Walls. In Proceedings of the 13th International Conference on Thermal Performance of the Exterior Envelopes of Whole, Buildings XIII, Clearwater, FL, USA, 4–8 December 2016.
8. Saber, H.H.; Lacasse, M.A.; Ganapathy, G.; Plescia, S.; Parekh, A. Risk of condensation and mould growth in highly insulated wood-frame walls. In Proceedings of the 13th International Conference on Thermal Performance of the Exterior Envelopes of Whole, Buildings XIII, Clearwater, FL, USA, 4–8 December 2016.
9. Saber, H.H.; Lacasse, M.A.; Moore, T.V. Hygrothermal performance assessment of stucco-clad wood frame walls having vented and ventilated drainage cavities. In Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations, ASTM STP1599; ASTM International: West Conshohocken, PA, USA, 2017; pp. 198–231.

10. Saber, H.H.; Hajiah, A.E.; Alshehri, S.; Hussain, H.J. Investigating the Effect of Dust Accumulation on Solar Reflectivity of Coating Materials for Cool Roof Applications. Energies 2021, 14, 445.
11. Saber, H.H.; Swinton, M.C.; Kalinger, P.; Paroli, R.M. Long-term hygrothermal performance of white and black roofs in North American climates. Build. Environ. 2012, 50, 141–154.
12. Saber, H.H.; Swinton, M.C.; Kalinger, P.; Paroli, R.M. Hygrothermal simulations of cool reflective and conventional roof s. In Proceedings of the 2011 NRCA International Roofing Symposium, Emerging Technologies and Roof System Perfo rmance, Washington, DC, USA, 7–9 September 2011.
13. Brehob, E.; Desjarlais, A.; Atchley, J. Effectiveness of cool roof coatings with ceramic particles. In Proceedings of the 2 011 International Roofing Symposium, Washington, DC, USA, 7–9 September 2011.
14. Urban, B.; Roth., K. Guidelines for Selecting Cool Roofs. Building Technologies Program; 2010. Available online: http s://www.energy.gov/sites/prod/files/2013/10/f3/coolroofguide.pdf (accessed on 1 June 2021).
15. Ennis, M.; Kehrer, M. The effects of roof membrane color on moisture accumulation in low-slope commercial roof syste ms. In Proceedings of the 2011 international roofing symposium, Oak Ridge, TN, USA, 1 January 2011.
16. Bludau, C.; Zirkelbach, D.; Kuenzel, H.M. Condensation problems in cool roofs. Interface J. RCI 2009, XXVII, 11–16.
17. Bludau, C.; Künzel, H.M.; Zirkelbach, D. Hygrothermal performance of flat roofs with construction moisture. In Proceedi ngs of the Eleventh International Conference on Thermal Performance of the Exterior Envelopes of Whole Buildings, Cl earwater, FL, USA, 4–8 December 2016.
18. Saber, H.H. Hygrothermal Performance of Cool Roofs with Reflective Coating Material Subjected to Hot, Humid and Du sty Climate. J. Build. Phys. 2021.
19. Saber, H.H.; Hajiah, A.E. 3D Numerical Modeling for Assessing the Energy Performance of Single- and Two-Zone Build ings with and without Phase Change Materials. In Proceedings of the Gulf Conference on Sustainable Built Environme nt, Kuwait City, Kuwait, 10–13 March 2019; pp. 10–13.
20. Hajiah, A.E.; Saber, H.H. Long-Term Energy and Moisture Performance of Reflective and Non-Reflective Roofing Syste ms with and without Phase Change Materials under Kuwaiti Climates. In Proceedings of the Gulf Conference on Sustai nable Built Environment, Kuwait City, Kuwait, 10–13 March 2019; pp. 10–13.
21. Green Technologies and Energy Efficiency (GTEE 2017) workshop at the King Faisal University in Saudi Arabia, 26 Apr il 2017. Available online: https://img0cf.b8cdn.com/images/course/35/68573835_1594764313.pdf (accessed on 1 June 2021).
22. Pisello, A.L.; Castaldo, V.L.; Pignatta, G.; Cotana, F.; Santamouris, M. Experimental in-lab and in-field analysis of water proof membranes for cool roof application and urban heat island mitigation. Energy Build. 2016, 114, 180–190.
23. Saber, H.H.; Alshehri, S.A.; Alnofaie, M.; Alghamdi, A.; Alraghi, S.; Hajiah, A.E. Energy Savings Due to Using Reflective Roofing Materials in Buildings of Kuwait and Saudi Arabia; Internal and Client Report (Confidenti—Part I); Kuwait Institu te for Scientific Research (KISR): Kuwait City, Kuwait, 2019; Volume 67.
24. Li, H. Evaluation of Cool Pavement Strategies for Heat Island Mitigation ; Final Research Report ; Institute of transporta tion studies, Department of Civil Environmental Engineeing, Unversity of California: Davis, CA, USA, 2012; Available on line: https://escholarship.org/content/qt6mr4k9t1/qt6mr4k9t1_noSplash_9ab61b14762e84b7d61994b7aa5e0d1b.pdf?t= pyhuvm (accessed on 1 June 2021).
25. Green Roofs. Reducing Urban Heat Islands: Compendium of Strategies: Heat IslandReduction Activities. 2018. Availabl e online: https://healthyplacesindex.org/wp-content/uploads/2018/01/epa_heat_island_reduction_activities.pdf. (access ed on 1 June 2021).
26. Berdahl, P.; Akbari, H.; Levinson, R.; Miller, W.A. Weathering of roofing materials—An overview. Constr. Build. Mater. 2 008, 22, 423–433.
27. Suehrcke, H.; Peterson, E.L.; Selby, N. Effect of roof solar reflectance on the building heat gain in a hot climate. Energy Build. 2008, 40, 2224–2235.
28. Algarni, S.; Nutter, D. Influence of dust accumulation on building roof thermal performance and radiant heat gain in hot-dry climates. Energy Build. 2015, 104, 181–190.
29. Levinson, R.; Berdahl, P.; Asefawberhe, A.; Akbari, H. Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane. Atmos. Environ. 2005, 39, 7807–7824.
30. Akbari, H.; Berhe, A.; Levinson, R.; Graveline, S.; Foley, K.; Delgado, A.H.; Paroli, R.M. Aging and Weathering of Cool Roofing Membranes. In Proceedings of the First International Conference on Passive and Low Energy Cooling for the Built Environment, Athens, Greece, 17 May 2005.

31. Saber, H.H.; Alshehri, S.A.; Alnofaie, M.; Alghamdi, A.; Alraghi, S.; Hajiah, A.E. Energy Savings Due to Using Reflective Roofing Materials in Buildings of Kuwait and Saudi Arabia. Client Report—Part II. Unpublished work. 2020.