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A review of benefits and limitations of static and switchable cool roof systems

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A R T I C L E I N F O

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A B S T R A C T

In recent years there has been a widespread adoption of high reflectance (cool) roofing materials in hot climates to reduce a building's cooling load and energy use. While a cool roof can reduce the building's cooling load during warm months, it may regrettably increase the heating load in cool months thus reducing their overall effectiveness. One potential solution to preserving high cooling load savings without accruing a large heating load penalty is to implement a switchable roof reflectance technology; allowing a low reflectance roof during the heating season and a high reflectance roof during the cooling season. This paper organizes and summarizes the literature on cool roofs and switchable roofing materials as a tool for energy savings in buildings. It presents a review of material properties and advancements, energy savings and penalties, current codes, additional benefits and limitations, and recommendations for future research. Finally, the paper summarizes comparative analysis results of the energy performance for both static and switchable cool roofs.

1. Introduction

Buildings are responsible for a significant portion of the total energy consumed worldwide. In the United States (US), commercial and residential buildings consumed 40% of the nation's total end-use energy in 2015 [1]. In particular, source energy used by US residential buildings is attributed to space heating – 28%, space cooling – 15%, and water heating – 13%. While energy consumed by US commercial buildings is mainly associated to lighting – 20%, space heating – 16%, and space cooling – 15% [2]. Building envelope components are estimated to be the main sources of heating thermal loads for both commercial and residential buildings with roofs responsible for 12%. Even though cooling thermal loads are dominated by internal heat gains from lighting, equipment, solar radiation through glazing, and occupants, roofs can contribute 14% especially for low-rise buildings [3].

One approach to reduce cooling load due to heat gains through roofs is to consider cool roofs with high solar reflectance coatings. Indeed, high reflectance roofs typically lower outdoor roof surface temperatures reducing heat flows from outdoors to building indoors and thus decreasing the thermal cooling loads. However, the same cool roofs with high solar reflectance can also increase thermal heating loads and building energy use during heating seasons especially in colder climates [4]. As alternative to static cool roofs characterized by constant solar reflectance properties through the seasons, switchable roof coatings have been proposed and have shown to be more beneficial to a wide range of climates with the potential to decrease thermal cooling loads without increasing building space heating energy consumption. Switchable cool roofs are particularly beneficial in climates with similar length of heating and cooling periods as well as for climates with extreme temperature swings throughout the year with long heating seasons and short cooling seasons.

This review paper summarizes the existing literature on static and switchable cool roofs and roofing materials as passive systems to reduce energy consumption and improve indoor thermal comfort in buildings. In particular, the review encompasses advances in cool roof coating properties, their energy savings and potential penalties, applicable current codes, and recommendations for future research. In addition, the paper summarizes comparative analysis results of the performance for both static and switchable cool roof systems when applied to residential and commercial buildings in select US climates.

2. Cool roof properties

Cool roofs have exterior surfaces or coatings that minimize solar absorption and maximize thermal emittance. They maintain lower surface temperatures and reduce heat flows into the building [4,5]. In particular, solar absorption is minimized by increasing roof solar reflectance, defined as the fraction of the solar radiation that is diffusely reflected away by the surface. Lighter surfaces have higher reflectance

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values than dark surfaces. Specifically, solar reflectance is close to 0 for black surfaces and close to 1 for white surfaces. In addition to color, surface roughness and presence of impurities can also affect roof solar reflectance [6]. Roof thermal emittance measures the surface's ability to radiate any absorbed solar energy. The higher their thermal emittance is, the more rapidly roofs can cool [7]. Cool roofs can also increase their thermal resistance since the thermal conductivity of insulation layers typically rises with temperature [4,8].

The majority of buildings in the US have relatively dark roofs. For instance, aerial photos of Chicago, Philadelphia, and Washington DC have indicated that buildings roofs in these cities have an average solar reflectance of 0.25 [3]. According to a survey conducted for ASHRAE in 1998, it is found that standard shingles have a solar reflectance ranging from 0.03 to 0.26, with most values between 0.10 and 0.15. Moreover, non-white roofing membranes, such as single-ply roofing materials, smooth bitumen, and granule-surface bitumen have a solar reflectance value that ranges from 0.06 to 0.26. Similarly, gravel roofs have low solar reflectance values varying from 0.12 to 0.34.

Commercial roof products that qualify as cool roofs fall into three categories: single ply, liquid applied coating, and white finished metal panels [7]. A freshly applied white elastomeric coating has a solar reflectance value that ranges from 0.60 to 0.85. Solar reflectance of new white single-ply roofing membranes typically exceeds 0.70 [6,9]. Thermal emittance value of non-metallic surfaces is generally between 0.80 and 0.90. Shiny metal roofs can have a relatively high solar reflectance, upwards of 0.60, but they tend to have low thermal emittance making them as hot as dark roofs. Therefore, they would not be good materials for cool roofs [9]. One method to quantify the properties of cool roofs is the estimation of their Solar Reflectance Index (SRI). SRI is calculated by using solar reflectance and thermal emittance values adjusted with wind coefficients. The higher the SRI value of a roof is, the lower is its surface temperature and thus the lower is the heat gain into the building. SRI is defined to be zero for a clean black roof (with a solar reflectance of 0.05 and a thermal emittance of 0.90) and 100 for a clean white roof (with a solar reflectance of 0.80 and a thermal emittance of 0.90) [10]. The SRI can be determined by the following equations:

$$SRI = 123.97 - 141.35(x) + 9.655(x^2) \quad (1)$$

With,

$$x = \frac{20.979*\alpha - 0.603*\varepsilon}{9.5205*\varepsilon + 12.0} \quad (2)$$

Where, α is the absorption and ε is the emissivity of the roof surface.

By definition, cool roofs should have an initial SRI value that exceeds 78 [7]. Table 1 shows typical roofing materials with their solar reflectance, infrared emittance, temperature rise, and SRI [10].

The properties provided in Table 1 are specific for newly installed roofs. Over time, the solar reflectance of cool roofs is likely to decrease over time because of surface dirt accumulations and material degradations. The emittance, however, would not decrease significantly [11]. Indeed, soiling and accumulation of soot particles can reduce roof surface solar reflectance by about 0.15 with most of the degradation occurring during the first year [11,12]. Standard maintenance and washing of roof surfaces can restore some of their original solar reflectance properties depending on the washing method. Akbari et al. found in a study on aging that the solar reflectance of 5–8 year aged cool roofs dropped from 0.80 to 0.50. However, they found that simply washing the roof surfaces with water could restore their solar reflectance to 70–100% of the original values [13].

Table 1
Typical roofing material properties.

Product	Solar reflectance	Infrared emittance	Temperature rise	SRI
Smooth Bitumen	0.06	0.86	83	−1
Generic Black Shingle	0.05	0.91	82	1
Gray EPDM	0.23	0.87	68	21
Shasta White Shingle	0.26	0.91	64	27
Light Gravel	0.34	0.90	57	37
Aluminum	0.61	0.25	48	56
White EPDM	0.69	0.87	25	84
White Coating on Shingle	0.71	0.91	23	87
White PVC (Sarnafil)	0.83	0.92	11	104

2.1. Cool roof impact on energy consumption

Several field studies have monitored and documented cooling energy savings and cooling peak demand reductions from cool roofs in warm climates including California, Florida, and Nevada. Early case studies focused on residential buildings, while the majority of recent studies has focused on commercial buildings. The reported studies have discussed the impacts of cool roofs on air-conditioning electricity use, roof surface temperatures, plenum, indoor, and outdoor air temperatures, and insulation levels. In particular, Parker et al. [14] monitored peak power demand and cooling energy use of residential buildings with increased roof solar reflectance for 11 Florida homes during summer months. The daily electricity savings for individual homes were found to range from 5.4 to 138 W h/m^2 (2–45%) and peak power demand were reduced from 1.5 to 7.8 W/m^2 (12–23%). The study of Parker et al. has indicated that energy use savings from cool roofs correlate inversely with the ceiling insulation level and the location of the duct system. Specifically, large energy savings were obtained for homes with poor insulated levels and duct systems located in the attic space [14]. Similarly, Akbari et al. [15] monitored peak power demand and cooling energy use savings from high reflective coatings installed on roofs for one house and two school bungalows in Sacramento, California. The measurements revealed that increasing roof solar reflectance for the house by 0.55 resulted in a daily cooling energy use reduction of 14 W h/m^2 and a peak demand reduction of 3.55 W/m^2. Seasonal cooling energy use savings and peak demand reductions were estimated to be 80% and 17%, respectively. Comparative analysis of measurements obtained from the two school bungalows revealed that a white roof bungalow used 52 W h/m^2 less energy than a bungalow with a metal roof, and 42 W h/m^2 less energy than a bungalow with a brown roof. The peak load was found to be 6.78 W/m^2 lower for the white roof. The seasonal cooling energy and peak demand savings for the school bungalow were estimated to be 35% and 32%, respectively [15].

Recently, several studies have been carried out to assess the performance of cool roofs when applied to commercial buildings. Hildebrandt et al. [16] have measured that daily cooling energy use savings associated with cool roofs for an office building, museum, and hospice in Sacramento, California are 10, 20, and 11 W h/m^2 (17%, 26%, and 39%), respectively. All three monitored buildings were retrofitted with high reflective roofs so the increase in the solar reflectance was approximately 0.40 [16]. Parker et al. [17] monitored seven retail stores within a strip mall in Cocoa Beach, Florida before and after applying high reflective coatings. The roofs were metal corrugated and had an initial value for the solar reflectance of 0.29 for the first half of the summer and a value of approximately 0.75 for the second half of the summer. The measurements showed an average reduction in daily cooling energy use of 62 W h/m^2 (25% savings) with a range of 5–137 W h/m^2 (2– 3% savings). The average peak-demand savings were 5.9 W (40% savings) [17]. Konopacki et al. [18] measured summer daily cooling energy use savings from high reflective coatings for three commercial buildings in California: two medical office buildings in Gilroy and Davis and a retail store in San Jose. The