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RESEARCH ARTICLE

COOLING THE BUILDING USING PASSIVE STRATEGIES BY IMPLEMENTING REFLECTIVE MATERIAL TO REDUCE COOLING LOAD

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ABSTRACT

Reflective coating applied to building envelopes are becoming increasingly important because of their benefits in terms of internal cooling and energy savings. Because of their optical properties, reflective materials stay cooler than standard materials under the same conditions; therefore, they are also known as cool materials. This paper presents a review on the application of reflective materials on buildings' walls, fenestration and roof. The thermal performance of these materials has been analyzed using different methodologies. Thus, the reported studies can be classified into five categories: envelope components, test cells, computational fluid dynamics, building simulation, monitored buildings,. The paper describes the results obtained by means of these methodologies, the main characteristics of the models and, when available, the optical properties of the standard and cool materials. The temperature of cities continues to increase because of the heat island phenomenon due to undeniable climatic change. The observed high building temperatures intensify the energy problem in buildings, deteriorates thermal comfort conditions, and increases cooling load. To counterbalance the phenomenon, important mitigation technologies have been developed and proposed. Among them, technologies aiming to increase the albedo of cities and use of insulators appear to be very promising, presenting relatively high building temperature mitigation potential. This paper aims to present the affect of, when applied in the building, the reduction in temperature was found up to 12 C and 40% saving in energy were achieved.

INTRODUCTION

Solar radiation incident on building envelope can be absorbed, reflected and transmitted and it influences interior and exterior surface temperatures, heat flow entering the building, and hence indoor thermal environment. Increasing the envelope reflection coefficient (exterior surface reflectivity weighted by the spectral energy distribution and integrated over the solar spectrum) results in reduced absorbed solar radiation and reduced surface temperatures, which allow reduction of conduction heat transfer to the building interior. Utilization of solar reflective coatings has shown great potential to reduce solar heat gain, cooling loads and peak power loads while improving indoor thermal conditions. One way to reduce the influence of the roof into the heat gains is to implement passive measures. Important research has been conducted in the field of passive cooling for roofs. According to Sanjai and Chand (2008), the passive cooling techniques can be classified in architectural methods and non-architectural methods. The architectural methods are related to the configuration and the roof geometry that contribute to the reduction of heat gains. These methods are usually applied in the construction stage of the buildings. For example, the domed roofs are popular in the vernacular architecture of the Middle East and Africa due to their thermal advantages; the thermal radiation over the inhabitants tends to be diminished, and if they have an opening at the crown of the dome, it permits the escape of heated air causing buoyancy-induced ventilation (Taha *et al*., 1992). On the other hand, the non-architectural methods can be used independently of the roof geometry. These passive techniques are becoming important since they can be implemented in existing buildings. The transmission barriers are materials that prevent the inward of heat flow of the roof due to its low thermal conductivity. These materials are installed in either the interior or the exterior of the roofs; in addition, they can be used in walls. The wetted roofs use the evaporative cooling to diminish the surface temper-atures. A wetted roof can have a layer of accumulated water or it can be sprayed continuously, another type is the use of wetted gunny bags (Cheng *et al*., 2004). A reflective or cool roof is a conventional roof with a solar reflective material on the exterior surface. The high solar

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reflectance and thermal emittance (ε) of the coating conserve the surface cooler (with a lower temperature) than conventional roofs under the same conditions. This measure is the easiest to apply since the optical properties can be controlled just by acting on the surface of the roof, generally changing the color or by using high reflective materials (cool materials) (Regan, 1997).

The following sections present a short literature review on previous studies with reflective coatings

Previous experimental studies—the impact of reflective coatings on surface and indoor air temperature:

A number of studies on reflective coatings have been carried out, commonly focused on warm climates and summer conditions. Most studies on this topic are experimental and contain measurements of reduction in interior and exterior surface temperatures and their impact on room air temperature. Givoni and Hoffman (1968) com-pared the resulting indoor temperature for unventilated buildings in Israel and they reported that it could be 3 C cooler in the summer when the buildings were painted white compared with when painted grey. Synnefa *et al*. (2006) reported "cool materials" for buildings and other urban surfaces application, and measured a surface temperature reduction of 4 C for white concrete tile when painted with reflective coatings. Cheng *et al*. (2005) performed experiments with test cells to investigate the influence of envelope color on indoor temperatures under hot and humid weather condition. They showed that the maximum difference of inside air temperature between a black and a white cell was about 12 C for lightweight construction. Taha *et al*. (1992) measured the reflectivity and surface temperatures of various materials used in urban surfaces and found that white electrometric coatings with a reflectivity of over 0.72 could be as high as 45 C cooler than black coatings with a reflectivity of 0.08. Bansal *et al*. (1992) performed experiments under different conditions and found that black painted envelopes resulted in up to 7 C (per unit volume of interior space) higher temperature than the corresponding white painted envelopes. Uemoto *et al*. (2010) showed that cool colored paint formulations produced significantly higher near infrared radiation reflectance than conventional paints of similar colors, and measured a more than 10 C reduction in surface temperatures when exposed to infrared radiation. Reagan and Acklam (1997) calculated the total building heat gain reduction when roof surface reflectivity increased from 0.35 to 0.75. In July, the reductions were 6.4% and 4.8% in Tucson, Arizona with ceiling thermal resistances of 2.5 and 5.88 m^2 K/W respectively. Griggs *et al*. (1998) found up to 65% reduction in heat flux through a white roof compared to black roof with the same thermal resistances of 1.32 m^2 K/W1.2. Experimental studies—the impact of reflective coatings on energy consumption and peak demand. Akbari *et al*. (1997) compared cooling energy and peak power consumption of two identical school bungalows with different roof reflectivity and found a 3.1 kWh (35%) savings in cooling energy as well as 0.6 kW peak demand savings with reflective roofs. They also concluded in (1998) that increasing the roof reflectance of commercial buildings in California from about 20% to 60% decreased the roof temperature on hot summer afternoons by 7.2 C. In another study (2003), they reported electricity savings of 0.5 kWh/day (or 33 Wh/m^2/day) by increasing roof reflectivity from 26% to 72%, which translates into annual energy savings of about 125 kWh. For the same location, Hildebrandt *et al*. (1998) measured daily air-conditioning savings of 17%, 26% and 39% in an office, a museum and a hospital with high reflectivity roofs. Parker *et al*. (1994) monitored six homes in Florida before and after application of high-albedo coatings on their roofs. Reduction in air-conditioning electricity consumption was measured between 11% and 43% with an average saving of 9.2 kWh/day, and reduction in peak power demand (occurs between 5 and 6 pm) was 0.4–1.0 kW with an aver-age reduction of 0.7 kW. They also monitored seven retail stores within a strip mall in Florida. After applying a reflective roof coat-ing, a 7.5 Wh/m^2 (25%) drop in daily summertime cooling-energy use and a 0.65 W/m^2 (29%) decrease in demand were realized (1997). Akridge (1998) reported daily savings of 75 Wh/m^2 (28%) for an edu-cation building in Georgia by painting the galvanized roof with white acrylic coating. The same researcher (1998) also measured a reduction of 33 C in peak roof temperature of a single storey building after application of a thermal control coating. In Nevada, Akbari and Rainer (2000) measured daily air-conditioning energy savings of 33 Wh/m^2 (only 1%) in two telecommunication regen-eration buildings. In Texas, Konopacki and Akbari (2001) measured daily energy savings of 39 Wh/m^2 (11%) and peak-power reduction of 3.8 W/m^2 (14%) in a large retail store when a reflective membrane was used. Energy savings in an office building in Mississippi reached 22% after application of a reflective roof coating. In Hong Kong, Cheung *et al*. (2005) showed that 30% reduction in solar absorptance can achieve 12% saving in annual required cooling energy.

Computational studies on reflective coatings by increasing albedo of roofing material

Other studies employed modeling to calculate the potential benefits of reflective materials. Taha *et al*. (1988) performed simulations and predicted a cooling load reduction of 18.9% for summer days in California when the roof and walls reflectivity was increased from 0.30 to 0.90. The simulated ceiling and wall thermal resistances were 5.28 and 3.35 m^2 K/W respectively. Anderson (1989) found similar reductions for a flat concrete roof of a simple single room. Konopacki *et al*. (1997) simulated the direct energy savings from high reflective roofs in 11 US metropolitan areas, and computed the annual electricity savings in old residences, new residences and old/new office buildings to be 55%, 15% and 25% respectively. A simulation study by Shariah *et al*. (1998) for two mild and hot climates, showed that, as the reflectance increases from 0 to 1, the total energy load decreases by 32% and 47% for non-insulated buildings and by 26% and 32% for insulated buildings. Wang *et al*. (2008) developed a dynamic model and compared the annual cooling load, heating load and electricity consumption of a retail shed coated with solar reflective materials for six locations around the world. Other studies also used computer simulations to estimate the effect of reflective roofs (1998). Finally, Tang and Zhou (2008) analyzed the relationship between outdoor sol-air temperature and solar radiation absorptance and investigated the influence of wall reflectance on annual building energy consumption for three Chinese cities representing hot summer and cold winter zone. Akbari and Levinson (2008) reviewed and compared the technical development of cool-roof provisions in the ASHRAE Standards (2007), and California Title 24 Standards and discussed the treatment of cool roofs in other standards and energy efficiency programs.

Methodologies applied

This article presents the state of the art of the research car-ried out internationally with regard to the thermal performance of reflective materials applied to building components. Different methodologies have been used to study the potential of reflective materials to improve thermal comfort and to reduce energy consumption in buildings. Therefore, the review is divided into five sections: component of envelope, test cells, computational fluid dynamics, building simulation, monitored buildings, calibrated simulation, and mesoscale modeling. In each section, a summary table describes the results, the characteristics of the models, the location of the study and, when available, the optical properties of the standard and cool materials are also presented.

Components of envelope

A proper architectural design of a building envelope can significantly lower the energy usage through daylighting, reduced HVAC loads, etc. Innovations such as the self-shading envelopes are being explored by researchers. A nomogram simulation of a solar collection envelope (SCE) was discussed by using a computer modeling tool called SustArc (1997). The SCE concept is used to generate self-shading envelopes. In efficient self-shading envelope designs, the summer sun is blocked while the winter sun is permitted. The most important building envelope components and their latest developments are discussed in the following sections.

Roof as a single component

The studies presented in the following section consider the roof as a single component. We present theoretical and experimental works where the roof heat transfer is analyzed. Theoretical studies are based on either steady state or transient models. Experimental studies are carried out outdoors or indoors. In the first case, the samples are exposed to the sunlight, while in the second, halogen lamps are used instead.

Stationary methods were used to estimate the total heat gain of roofs during a day. Reagan and Acklam (1979) reported one of the first studies. They calculated the daily average heat gain using the Total Equivalent Temperature Difference (TETD) method for a roof in Tucson, Arizona. When the roof color was changed from dark to light, the heat gain was reduced up to 50% for poorly and well insulated roofs. Assem (2011) estimated the thermal transmittance (U-value) of walls and roofs typically used in Kuwait with the TETD method. A series of correlations based on the solar reflectance were developed. When the roof reflectance was increased, the daily heat gain was reduced up to 42%. Another analysis was presented by Suehrcke *et al.* (2008). The authors derived an equation to estimate the heat gain of dark and light colored roofs. For north Australia, the derived equation suggested that a light-colored roof had about 30% lower daily heat gain than a dark-colored one. Four dynamic analyses of the transient heat transfer in roofs were performed. In these studies, the climatic data were time varying and the interior air temperature was considered constant as a result of using an air conditioner. For instance, Granja and Labaki (2003) studied the influence of the external color in a flat roof for a summer design day of Campinas, Brazil. They used Fourier analysis to solve the heat conduction equation. When the roof had a low thermal resistance (thickness), the change of color from gray to white caused a heat flux reduction up to 74 W/m^2. In contrast, for thicknesses greater than 15 cm, the roof was not influenced for the change of the color. A numerical study conducted by Oliveira *et al.* (2009) estimated the heat flow in a concrete roof. Low and high solar reflectance conditions were evaluated for 14 cities in Brazil. Compared to the conventional roof, the reflective roof resulted in a 61% reduction of annual heat gains in sub-tropical areas. Ahmad (28) evaluated a concrete roof with thermal insulation and a reflective coating in Rawalpindi, Pakistan. The heat gain contribution of the bare concrete roof was 55% of the total gain in a building. The heat gain after the installation of the insulation and the coatings was just 6%. Brito Filho *et al.* (2011) analyzed the application of selective coatings on roofs with and without thermal insulation using climatic data of São Paulo, Brazil. To calculate the heat fluxes, the authors used an energy balance. A white paint had a more significant effect on the roof without insulation; it decreased the peak heat flux from 225 W/m^2 to 50 W/m^2. As the reflective roofs maintain lower temperatures than dark roofs, they may provide less heat to dry out moisture. Two studies aiming to investigate the hygrothermal performance of roofs are available (2012). Saber (2012) simulated the hygrothermal performance of roofing systems under different North American climates. They found that black roofs always performed with lower moisture than white roofs. For a 5 year period, the white roofs could lead to long-term moisture-related problems in the cities with cold climate, where the moisture content exceeded the acceptable limit of 19%. Ahrab and Akbari (2013) made simulations of several roof-ing systems in North American climates. During a period of 5 years, moisture performances of white roofs were similar to the dark roofs in hot climates. Typical white roofing experienced moisture prob-lems in cold cities. Adding a ventilated air space along with a smart vapor retarder eliminated the risk of moisture accumulation.

In other studies, the roof model was validated with experimental data by comparing the roof surface temperatures (2010). Moujares and Brickman (2003) developed a model that uses temperature nodes and the energy balance equations to describe the roof heat transfer. An 11% reduction in the daily heat transfer was achieved when applying a reflective paint to the roof located in Las Vegas, US. Using the same methodology, Ray and Glicksman (2010) developed a roof model to analyze the heat transfer. This model was validated for concrete roof and cool roof cases. The white coating was able to reduce the surface temperature around 10 C. To obtain energy savings, the model was incorporated into the MIT Design Advisor, an existing simulation tool; the cool roof would save 11% annually. Research carried out by Han *et al.* (2009) investigated the thermal performance of lightweight roofing systems in Hong Kong. A model for analyzing the transient heat transfer through the roofs was solved numerically. The total daily heat gain was reduced up to 20% using a lightweight roof with polyurethane insulation and a white painted surface. Recently, Tong *et al.* (2014) studied the thermal performance of unventilated and ventilated concrete-based roofs during a typical weather day in Singapore. The authors carried out a field experiment to validate the roof models. Compared with the roofs with reflectance of 0.1, every 0.1 increase in the reflectance cut down the daily heat gain by 11% in the unventilated and ventilated roofs. The application of cool paint reduced the daily heat gain by 234 and 135 Wh/m^2 in the unventilated and ventilated roof, respectively. In addition, they indicated that compared with unventilated roofs (either reflective or not reflective), the individual uses of roof ventilation and 2.5 cm of expanded polystyrene (EPS) insulation reduced the daily roof heat gain by 42% and 68% respectively, and these reductions increased to 73% and 84% in the ventilated roofs with 2.5 cm EPS and radiant barrier respectively. Experimental studies were performed either indoors or out-doors. In both cases, the temperature and heat flux reductions have been analyzed when using reflective materials. With regard to the indoor studies, two studies are available (2009). Uemoto *et al.* (2010) analyzed cool colored acrylic paints applied on roofs. When the cool paints were exposed to infrared radiation, the surface tem-perature remained about 10 C lower than the conventional paints. With respect to the untreated roof, the cool paints reduced the heat flux between 26 and 37%. In the other indoor study, Alvarado *et al.* (2009) tested a passive cooling system for concrete roofs. The sys-tem consisted in a metal sheet and thermal insulation underneath. Compared to the control prototype, the passive system led to reduc-tions in heat conduction between 65 and 88%. On the other hand, at the outdoors of Chihuahua, México, Martin-Dominguez *et al.* (2011) measured the heat flux through several slabs with different coatings. The temperature of the slab with a white coating was 13 C lower than the bare slab. Thus, the maximum heat flux reduced from 180 W/m^2 to 80 W/m^2. By integrating the heat flux curves, they found that the white coating reduced 58.3% of the diurnal heat gain. Details of all studies presented in this section are outlined in Table 1.

Wall as a single component

An air gap between two layers of masonry wall braced with metal ties constitutes a ventilated or double skin wall. Ciampi *et al.* (2003) developed a mathematical model to evaluate the energy performance of a ventilated wall. They validated this model for 6 different ventilated wall designs. Although, energy savings for all the wall designs increase with the increase in width of the air gap, however, further increase over 0.15 m yielded only diminishing returns. A typical summer cooling energy savings of 40% can be achieved with a care-fully designed ventilated wall. Athienitis *et al.* compared phase change material (PCM) based and non-PCM based gypsum board for inside wall lining and concluded that the PCM based wall lining lowered the maximum room temperature by 4 C and reduces the heating demand during night. In a more conduction-based type (uncontrollable) of solar wall such as Trombe wall or unventilated solar wall is preferable in regions with longer heating seasons. However, the problem of overheating in summer can be prevented through the use of solar shields (2002). Jie *et al.* (2007) have proposed an innovative design of PV integrated Trombe wall. In this design, PV cells are affixed on the back of the transparent glass cover of a normal Trombe wall. Both the heat rejected by the PV cells and the heat absorbed by the thermal mass of Trombe wall are used for space heating. A theoretical analysis on a Trombe wall with fin-type structured outer wall surface design suppresses the convective and infrared (IR) radiation heat losses from the wall's outer face to the glass cover thereby encouraging the conduction through the wall along with convective and radiative heat exchange to the inside of the room (1986). Phase change material (PCM) based Trombe walls have been reviewed (2007). Experimental results suggest that PCM Trombe walls were thinner and also performed better than concrete walls. A novel concept of fluidized Trombe wall system (as shown in Fig. 1) where the gap between the Trombe wall and the glass cover is flu-idized with highly absorbing, low-density particles is introduced (1991).

Fenestration (windows and doors) as a single component

A simulation study was carried out on 10 different glazing types applied to five different climatic zones in India (2009). It was observed that the annual energy savings by a window is dependent on not just the thermal conductivity (U-value) and the solar heat gain coefficient (SHGC or g-value) of the window but also on its orientation, climatic conditions and building parameters such as insulation level, floor area, etc. The visible transmittance of a low-e tin oxide-based glazing is increased by antireflection treatment with silicon dioxide (SiO_2). The measured percentage increase of integrated visible transmittance was 9.8% and a transmittance value of 0.915 was achieved (2003) An exhaustive study is presented on the processes and the costs involved in the fabrication of vacuum glazing (1995). Also a comparison between the vacuum and argon filled double glazing is discussed. Heat transfer through evacuated triple glazing, a prospective glazing technology, was investigated by using analytical thermal network modeling and numerical finite element modeling (2006). The findings suggested that a triple vacuum glazing with a center-of-glazing thermal transmittance of less than 0.2 W/m^2 K is achievable.

Test cells

The following section describes the studies developed using test cells. Among researchers, this approach has been broadly used to assess reflective materials in terms of thermal comfort and energy consumption. Two or more identical units are used, one is the ref-erence and the others are altered by applying reflective materials either in the roof or in the whole envelope. In most cases, these cells are constructed without windows or doors to only determine the influence of the reflective coating. Thus, the measurements are carried out simultaneously and mainly under outdoor conditions. Because the inside air temperature is the most direct representation of thermal comfort conditions (2008), this variable is used to compare the behavior of test cells in free floating conditions. White materials are the most commonly evaluated. Several studies have been conducted over the years to study thermal comfort. For instance, Bansal *et al.* (1992) used two wood enclosures, one painted black and the other painted white to measure the inside air temper-ature. During hours with maximum solar radiation in New Delhi, India, the black enclosure recorded 7 C higher air temperatures than the white enclosure. In the research carried out by Cheng *et al.* (2005) in the hot humid climate of Hong Kong, the maximum air tempera-ture inside the black test cell was higher by about 6 or 12 C than the white one depending on the thermal mass. Winandy and Beaumont performed experiments using five outdoor chambers during a three year period in Madison, US. The chamber covered with black shingles was 5 C–8 C warmer than the white shingled chamber. In the same way, Nahar *et al.* (1999) fabricated several test structures for studying passive techniques for arid areas.

Table 1. Characteristics the studies that consider the roof as a single component

Reference	Climatic data	Model(s)	Method	Case of study	Results
Reagan and Acklam (1979)	Tucson, US	Flat built-up gravel roof with U = 0.4 W/m2 K or U = 0.17 W/m2 K	TETD method	1) Dark color, ρ = 0.35 2) Light color, ρ = 0.75	The light roof reduced 50% of the heat gain
Granja and Labaki (2003)	Campinas, Brazil	Flat solid concrete roof with two thicknesses: 5 cm and 40 cm	Fourier analysis	1) Gray color, ρ = 0.39 2) White color ρ = 0.74	The white coating reduced the heat flux by 74 W/m2 in the roof of 5 cm
Moujares and Brickman (2010)	Las Vegas, US	Concrete tile roof with a thickness of 1.75–2.0 cm	Energy balance	1) Concrete color 2) Reflective paint, ρ = 0.8, ε = 0.8	The reflective paint reduced up to 11% of the daily heat transfer
Suehrcke et al. (2008)	Northern, Australia	Low thermal mass roof	Energy balance	1) Average color, ρ = 0.3 2) Reflective white paint, ρ = 0.65	A light-colored roof had 30% less daily heat gain
Alvarado et al. (2009)	Indoor tests	Eight roof prototypes made of 101 mm concrete and 19 mm of insulation plus metal sheet	Indoor measurements	1) Control case 2) Galvanized steel, ρ = 0.6 3) Aluminum, ρ = 0.9	The passive system reduced the heat conduction between 65 and 88%
Han et al. (2009)	Hong Kong, China	Metal sheet roof made of 1 mm metal deck,150 mm polyurethane and 1 mm metal deck	Finite volume method	1) Black paint, ρ = 0.25 2) White paint, ρ = 0.52	Light painted roof reduced 9.3% the heat gain, when polyurethane was added it reduced 20%
Oliveira et al. (2009)	Several cities of Brazil	Concrete slab with a thickness of 100 mm and 20 mm of cotton wool insulation underneath	Finite difference method	1) Control case, ρ = 0.35 2)Reflective coating, ρ = 0.8	The highly reflective roof reduced 61% the annual heat gain
Ray and Glicksman (2010)	Orlando, Florida	15 cm thick concrete slab with insulation on top of or beneath the slab	Nodal energy balance	1) Concrete roof 2) Cool roof, ρ = 0.7, ε = 0.75	The cool roof saved 11% annually on cooling energy
Ahmad (2010)	Rawalpindi, Pakistan	Concrete slab with a thickness of 15 cm ,U = 3.3 W/m2 K or U = 0.54 W/m2 K when insulated	OPAQUE software	1) Concrete roof 2) White insulated roof	The white insulated roof reduced the heat gain from 66% to 5%
Uemoto et al. (2010)	Indoor tests	Fiber cement roofing	Indoor measurements	1) Unpainted roof 2) Cool white, ρ = 0.78 3) Cool brown, ρ = 0.23 4) Cool yellow, ρ = 0.58	The cool white paint was the most effective in reducing heat flux, Up to 37%.

Table 2. Characteristics of the studies of reflective materials using test cells

Reference	Study location	Characteristics of the models	Cases of study	Results
Bansal et al. (1992	New Delhi, India	Two enclosures made of 25 mm thick plywood board (walls and roof) and 90 cm × 90 cm × 60 cm in dimensions.	Two envelope colors: 1)Black painted, = 0.3 2)White painted = 0.8	The light roof reduced 50% of the heat gain
Winandy and Beaumont (1995)	Madison, US	Five field exposure chambers 3.7 m wide × 4.9 m long with Teed XT-25 fiberglass roofing shingles	Two roof colors: 1) Black shingled 2) White shingled	The white shingles decreased the air temperature between 5 C and 8 C
Simpson and McPherson (1997)	Tucson, US	Three 1/4-scale models with plywood walls. The pitched roofs (18) covered with asphalt shingles, U = 1.78 W/m2 K. The ceiling with two layers of fiberglass insulation, U = 0.2 W/m2 K	Three roof coatings: 1) Gray, ρ = 0.3, ε = 0.94 2) Silver, ρ = 0.49, ε = 0.7 3) White, ρ = 0.75, ε = 0.98	The model with white roof used 5% less daily electricity than silver or gray roof models
Nahar et al. (1999)	Jodhpur, India	Two test cells with walls and roofs of galvanized steel sheet (20 gauge). The cells have dimensions of 1200 mm × 600 mm × 910 mm	Two roof colors: 1) Bare steel 2) White paint	The white paint diminished the indoor air temperature 7 C gain

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Nahar et al. (2010)	Jodhpur, India	Three test cells with galvanized steel walls and concrete slab roof (100 mm thick). The cells have dimensions of 1280 mm × 610 mm ×1100 mm	Two roof surfaces: 1) Bare concrete 2) Pieces of white tiles 3) White cement	The white cement and white tiles reduced the air temperature 5.4 C and 11.0 C, respectively
Suman and Verma (2008)	Roorkee, India	Two test rooms with 10 cm thick reinforced concrete roof and 5.8 m × 3.66 m × 3.25 m size	Two roof colors: 1) Concrete 2) White coating, ρ = 0.9	The white coating reduced 2.8 C the indoor air temperature
Cheng et al. (2005)	Hong Kong, China	Two test rooms,2.7 m×2.7 m×2.7 m with asbestos cement (6 mm thick) or galvanized iron sheet roof (3 mm thick)	Three roof surfaces: 1) Bare asbestos 2) Bare iron 3) White coating, ρ = 0.9	The reflective roof decreased 1.5 C the air temperatures
Amer (2006)	Menofiya, Egypt	Two test cells built with 20 mm thick waterproof plywood, with Styrofoam 25 mm thick. With dimensions of 1 m× 1 m × 1 m	Two envelope colors: 1)Matt-black paint, ρ = 0.2 2)Matt-white paint, ρ = 0.75	The white envelope decreased the air temperature 5 C and 12 C depending on the thermal mass

Table 3. Characteristics of the studies of reflective materials by using CFD

Reference	Tool	Model	Cases of study	Results
Xamán et al. (2010)	Fortran code	2D square cavity, 5 m size;	Black roof ρ = 0.05, ε = 0.89	The white roof cavity had an average decrease of air temperature of 4.2 C
Sekar et al. (2012)	FLUENT software	3D closed cavity with a roof area of 25 m2	1) Standard roof 2) Reflective roof, ρ = 0.86, ε = 0.94	The reflective roof brought down 7.0 C the air temperature
Azemati et al. (2013)	FLUENT software	2D square closed cavity 1 m size. The roof is made up of nine solid layers; it has a thickness of 350 mm	1) Bare roof 2) Roof with acrylic paint, ρ = 0.75 3) Roof with ceramic coating, ρ = 0.81	The average air temperature was reduced 4.5 C by the ceramic coating
Borge-Diez et al. (2013)	Design Builder CFD software	3D open room with concrete roof with a thickness of 120 mm	1) Reference case 2) Cool roof (ρ = 0.92) with several ventilation strategies	The combined use of a cool roof and a roof opening led to reductions of 2.83 C
Revel et al. (2014)	Star CCM+ Code	3D closed room, 2.4 m×3 m×2.4 m. Walls and roof made of plasterboard (1.2 cm), air gap (7.5 cm) and OSB exterior layer (2.5 cm)	1) Black standard tiles, ρ = 0.14, ρ = 0.82 2) Black cool tiles, ρ = 0.26, ε = 0.82 3) Gray standard membranes, ρ = 0.13, ε = 0.82 4) Gray cool membrane, ρ = 0.30, ε = 0.78	The cool façade tiles and cool roof membrane reduced the indoor air temperature by 0.9 C and 0.7 C, respectively

Among the measures, they considered painting the metal roof with a white paint. In Jodhpur, India, the drops in roof surface temperature and ambient temperature inside the white roof structure averaged 22 C and 7 C, respectively. In a similar study, but developed in Egypt, Amer found an inside air temperature reduction of 6.5 C in a cabinet with a white painted metal roof. Like in their previous study, Nahar *et al.* (2003) developed a series of experiments, but now they considered passive cooling techniques for concrete roofs. The cell that incorporated pieces of white glazed tiles on the roof reduced the air temperature by 11 C. The cell painted with white cement on the roof reduced the temperature 5.4 C. Similarly, Hamdan *et al.* (2010) demonstrated that white glazed tiles were more effective than white cement for cooling the environment inside test cells with concrete roofs in Amman, Jordan. Suman and Verma (2003) examined a reflective coating on different types of roofs using experimental rooms in Roorkee, India. In the rooms with asbestos and galvanized roof, the air temperature difference was about 1.5 C between the room with reflective roof and the reference room. Meanwhile, the reflective coating on a reinforced concrete roof led to a reduction of 2.8 C indoor air temperature. In another study of test cells, Yu *et al.* (2008) evaluated the influence of different coatings on the walls of two masonry models located at Xi'an Jiaotong University. When the reflectance of the walls increased, the maximum decrease of the indoor air temperature was 4.67 C with an average diurnal temperature decrease of 3.53 C. Herrmanns *et al.* (2010) conducted experiments in two small cells with pitched roofs. One roof had dark asphalt shingles, and the other was coated with a white reflective layer. The roof surface temperatures and internal air were lower in the cell with white coating, up to 17 C and 14 C, respectively. Guo *et al.* (2012) performed indoor tests using three boxes to assess white coatings. In this experiment, infrared heat lamps were used to simulate the sunlight. The white reflective coating decreased the surface wall temperature by 4.5 C, whereas the ordinary white coating reduced it by 3.7 C. Recently, Yew *et al.* (2013) carried out indoor tests in four scale prototypes with different roof configuration using halogen light bulbs. Three metal roofs were covered with a white reflective coating and one was used as reference. The test cell that incorporated both reflective coating and ventilation on the roof had a reduction of up to 13 C in the air temperature compared to the conventional roof system. Details of the studies presented above are outlined in Table 2.

Computational fluid dynamics (CFD)

The CFD method is the most complete theoretical approach to analyze heat and mass transfer in buildings; it can be able to provide a detailed information of air temperature, air velocity, contaminant concentration once the mathematical model and its boundary con-ditions are solved (2013). In this section are presented the existing works of reflective components developed with CFD. These studies focus on the thermal comfort improvements as a result of using reflective materials on the roof or the walls. Four of the building models analyzed are closed cavities (2014). However, a study considering a model with openings for ventilation is available (2013). Research carried out by Xamán and Mejía (2010) has investigated the impact of diverse types of coatings on the temperature distribution inside a cavity. With the heat transfer analysis, it was obtained that the difference in the air average temperature between the cavities with black and white roof was 4 C. In addition, a compound roof (concrete-expanded polystyrene) with a white coating showed the minimum heat fluxes to the inside of the cavity. Sekar *et al.* (2012) analyzed the influence of a reflective roof on the thermal comfort in a three-dimensional model. The solar reflective paint brought down the average air temperature in the cavity by about 7 C. In the same way, Azemati *et al.* (2013) simulated a two-dimensional model. It was observed that using a reflective coating on the roof led to a 17% decrease in energy gains causing the room temperature to be close to the comfort temperature. Recently, Revel *et al.* (2014) evaluated the effect of colored reflective materials on the indoor thermal conditions in a room model. Using CFD, the authors analyzed two cases and compared the results with those provided by standard materials. The first case was black cool tiles applied on the façade and the second cool membranes applied to the roof. In terms of indoor temperature, reductions of 0.9 C and 0.7 C at the center of the air volume were obtained using respectively cool facade tiles and cool roof membranes. On the other hand, Borge-Diez *et al.* (2013) studied the combined effect of cool roof and natural ventilation in a building model. The combination of passive techniques provided eight cases of study. Using a cool roof and roof opening had the best performance; this combination improved the air circulation and heat evacuation being able to increase thermal comfort up to 16%. Table 2 summarizes the characteristics of the foregoing studies

Buildings simulation

Dynamic simulation programs have been accepted as powerful tools for analyzing thermal performance of buildings (2001). This technique has the ability to describe the behavior of a multiple zone building on a large time scale with a small computational time (2013). In this section are presented the studies developed using building simulation. Energy consumption and/or the space-averaged temperature in the rooms are estimated for cases, using conventional surfaces and using reflective materials. Several studies have analyzed the change of reflectance in the whole envelope or in the walls. Taha *et al.* (1988) presented one of the first simulation studies. They analyzed the potential energy savings from whitewashing the envelope of buildings located in four US cities. This measure resulted in savings up to 14% and 19% on cooling peak power and electrical cooling energy, respectively. Shariah *et al.* (1998) simulated the effect of wall and roof reflectance on heating and cooling loads for residential buildings in mild and hot climates of Jordan. The roof and the four external walls were evaluated individually having a low and high solar reflectance. The effect of the reflectance of the sidewalls on the total energy load was almost negligible. In contrast, the reflectance of the roof had a great effect on the total energy load; it could be reduced between 31 and 66%. Balaras *et al.* (2000) found that light-colored roof and external walls reduced the annual cooling load in apartment buildings located in the three climate zones of Greece. The energy consumption of light-colored buildings was 2–4% less than in dark colored buildings. Hatamipour *et al.* (2007) estimated the cooling load for a hospital and an office building during the summer in the hot and humid areas of Iran. According to the simulations, a light colored roof reduced the cooling load by 10% for both, the hospital and the office building. On the other hand, light colored walls reduced the cooling load by 10.4%

and 11.8% in the hospital and the office building, respectively. Eskin and Türkmen (2008) examined the effect of external walls' color on annual energy requirements for an office building in the four major climatic zones in Turkey. In hot and humid climate zones, it was possible to obtain 9.5% and 10% saving in annual energy requirements by choosing light colors on external walls, whereas these values drop 2% and 3.6% in cold and mild climate regions, respectively. By develop-ing a dynamic model for a retail shed, Wang *et al*. (2008) compared the electricity consumption of the shed with different coatings for six locations around the world. The highly reflective coatings significantly reduced the energy consumption in hot climates in a range of 25–38%. In another simulation study, Yu *et al*. (2008) analyzed several design envelope strategies to save air conditioning energy in rooms in hot summer and cold winter zone of Chang-sha, China. One of the strategies consisted in increasing the solar reflectance of external walls. Compared with the base case, there was a decrease of 9% in the cooling energy consumption, an increase of 4% in heating energy consumption, and a decrease of 4.3% in total annual energy consumption. Zinzi *et al*. (2008) simulated several roof and facade reflectances in a building located in different Mediterranean localities. When the reflectance was increased, savings up to 25% of the energy for cooling were reached.

Ascione *et al*. (2010) performed a series of simulations for 20 cities around the world. From the results, they proposed a simple index called surface factor (SF) to identify the best external coating for walls from an energy point of view. For cities with high irradiation and/or low winter degree-days (SF > 0.65), cool paints were more suit-able, while the opposite results were obtained for cold climates (SF < 0.4). In another study, Shi and Zhang (2011) studied the variation of the annual air-conditioning loads due to changes in the solar reflectance and emissivity of building envelopes in various climates around the world. In tropical and subtropical climates, the high solar reflectance and the high long wave emissivity exterior surface were the most favorable to building energy-saving. In the mountain plateau climates and the subarctic climates, the low reflectance and the low emissivity of exterior surface were suitable. In the temperate continental climates and the temperate maritime climates, the medium reflectance and the low emissivity fitted the energy-saving requirements. Feng and Jun (2013) analyzed the effect of a reflective material on the energy consumption of a high-rise build-ing under the different climatic zones in China. The cooling energy consumption decreased between 7 and 15% and the heating energy consumption increased between 4 and 23%. The reflective materials were more effective in zones with lower latitudes in reducing energy consumption. The reflective material was not applicable in severe cold regions since it increased heating energy consumption. Retrofitting methods for external walls in high rise buildings were investigated by Huang *et al*. (2013). Their results indicated that in cooling-dominant cities, employing high reflective coating reduced cooling load between18 and 23%. Dias *et al*. (2014) assessed the impact of cool paints applied to both the roof and facades surfaces of residential buildings located in Portugal. The results of annual energy demand for heating showed a maximum penalty of about 30% when using cool paints. However, it was demonstrated that the cooling demand almost vanishes, eliminating the need to install air-conditioning devices.

Other simulation studies have considered the influence of the roof reflectance on the cooling and heating loads. For instance, Synnefa *et al*. (2007) estimated the impact of using cool roof coatings on the cooling of residential buildings in 27 cities around the world representing different climatic conditions. The results showed that increasing the roof solar reflectance reduces cooling loads by 18–93% and peak cooling demand in air-conditioned buildings by 11–27%. The authors concluded that increasing the reflectance of the roof resulted more beneficial for lower or no roof insulation levels. Sabouni *et al*. (2011) explored the influence of various energy saving alternatives in a bungalow house located in Malaysia. One of the alternatives considered was the replacement of the concrete tile roof with a white painted steel roof. This modification saved 5.8% annually more cooling energy rather than the base case model. Table 3 summarizes the characteristics of all studies presented in this section.

Experimental Studies on existing buildings

In the following section are presented the experimental studies performed in existing buildings. Energy savings and thermal comfort improvements have been measured due to the use of cool roofs. Either residential or non-residential buildings were monitored. Such monitoring process is carried out in two stages, in the first the building remains with the regular roof and in the second a reflective coating is applied to the roof. Several studies have measured the energy savings. For example, Akbari *et al*. (1997) monitored peak power and cooling energy savings from reflective roofs at one house and two bungalows in Sacramento, California. Applying a high reflective coating to the house resulted in savings of 2.2 kWh/day (80% of base case use), and peak demand reductions of 0.6 kW. In the bungalows, cool-ing energy was reduced by 3.1 kWh/day (35%). Parker and Barkazi (1997) performed a series of tests in nine occupied houses in Florida. Cool roofs provided average cooling electricity savings of 19%, and coincident peak savings of 22%. In the same city, Parker *et al*. (1997) conducted tests in seven retail shops to examine how roof whiten-ing impacted cooling energy consumption. The results showed a 25.3% average reduction (8.6 kWh/day) in summer space cool-ing energy (34.1 kWh/day to 25.5 kWh/day) in the shops with a range of savings of 13–48%. During the summer of 2000, Akbari (2003) monitored the energy in two small non-residential buildings located in Nevada, US. The author demonstrated that savings from a white reflective roof were about 0.5 kWh/day (1%). The relative benefits of the cool roof were not clear because the buildings had high internal loads. In another study, Akbari *et al*. (2005) monitored the effects of cool roofs on energy use in commercial buildings at three different sites of California. For a building in Sacramento, the savings of cooling energy averaged 70 Wh/m^2 /day (52%). On the other hand, for a building in San Marcos, the savings were about 42–48 Wh/m^2 /day (17–18%). Finally, for a facility in Reedley, the savings were 57–81 Wh/m^2 /day (3–4%). Xu *et al*. (2012) quantified the cooling energy savings from the installation of cool roofs in commercial buildings in India. The annual energy savings from roof whitening of previously black roofs ranged from 20 to 22 kWh/m^2 of roof area, corresponding to a cooling energy use reduction of 14–26%. The application of white coatings to uncoated concrete roofs resulted in annual savings of 13–14 kWh/m^2 of roof area, corresponding to cooling energy savings of 10–19%. The annual direct CO_2 reductions associated with the reduced cooling energy use were estimated to be 11–12 kg CO_2 /m^2 of flat roof area. During the summer 2012, Pisello *et al.* (2013) monitored an office building located in Rome, Italy. They investigated the contribution of a cool roof to the decrease of the energy required for cooling. The cool roof reduced the energy consumed by the air conditioner by about 34% during the day. Rosado *et al.* (2014) measured the energy use in two identical homes in Fresno, US. One of the homes had a dark asphalt shingle roof, whereas the other had a reflective concrete tile roof. The house with reflective roof had an annual space conditioning (heating + cooling) source energy savings were 10.7 kWh/m^2 (15%). Three studies show the influence of cool roofs in the thermal comfort of residential buildings (2013). In Rome, Italy, Zinzi and Fasano (2009) monitored a house to analyze the potential of a reflective roof to improve the indoor comfort conditions. With respect to the original materials, the room with white-coated roof had a reduction of indoor air temperature between 1 C and 2 C. Pisello and Cotana (2014) monitored a residential building located in Peru-gia, Italy. They indicated that the cool roof produced a maximum effect of decreasing summer peak indoor overheating of the attic by 4.7 C. The corresponding winter maximum over cooling reduction was 1.2 C. Finally, Pisello *et al.* (2013) measured the temperatures of the indoor air in the office mentioned in the previous paragraph, but under free-floating conditions. The cool roof was able to decrease the air temperature around 2–4 C.

DISCUSSION AND CONCLUSION

Building type has its role in determining the effectiveness of envelope thermal insulation on the thermal performance of buildings. The use of more thermal insulation is more critical in the envelope-load dominated buildings compared to those buildings with more internal-load dominance. Although wall and roof insulation are important, roof insulation is generally more critical than walls as it is continuously exposed to the direct summer solar radiation during daylight hours. This paper presented an overview of the performance characteristics and the main features of common building thermal insulating materials and their applications into concrete building structures in a comprehensive and practical way for the practicing engineer and/or building owner. The recommendations can be summarized as follows:

1. Proper treatment of building envelopes can significantly improve thermal performance especially for envelope-load dominated buildings, such as residences. Therefore, the proper selection and treatment of the building envelope components can significantly improve its thermal performance.
2. Wall and roof insulation are recommended for buildings in all climates for more thermally comfortable space and, therefore, less energy requirements. Insulation helps in reducing conduction losses through all components of the building envelope. However, roof insulation is generally more critical than walls and should be given more attention.
3. Moisture penetration and condensation could cause a lot of physical damage and health problems. It could also deteriorate the performance of thermal insulation over time. Therefore, it is important to control moisture in buildings through adequate ventilation, infiltration control and the proper use and location of moister retarders in the building envelope.
4. Infiltration is the most difficult variable to measure and its losses are the most difficult to control. Additionally, due to frequent opening of doors and windows in residences, infiltration rates are expected to be generally higher than anticipated. Therefore, careful treatment of cracks and leaks should be implemented.
5. It is important to provide adequate ventilation in order to insure proper indoor air quality and moisture control, especially in well-insulated tight buildings.

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