ADVANCED ROOF COATINGS: MATERIALS AND THEIR APPLICATIONS

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Abstract

The use of low emittance and high solar reflectance coatings is widespread in window glazings, wall and roof materials as methods of thermal control of buildings. However in hot climates, the use of high emittance coatings has the advantage of increasing the loss of heat from a material. In most cases the low emittance is accompanied by an increase in absorption of solar radiation within the building (either in the glazing or in the interior), and this usually leads to an increase in heat load on the building. High emittance materials, on the other hand, will lose heat readily by radiation and have a cooling effect on the building. Commonly high emittance materials are dark in colour and absorb significant solar radiation, which offsets this cooling benefit.

In this paper we describe the properties of a paint which has a high emittance (approximately 94%), and low solar absorptance paint (approximately 15%), and also describe the impacts of this paint on the cooling of a building through modelling of the thermal performance. It is shown that the benefits of this type of coating can be significant, reducing the heat load on the building substantially and reducing the requirement for airconditioning. Results of laboratory tests on the coating, modelling of a commercial building and actual comparative performance of two buildings (one with the coating and one without), are presented. The results show that there are significant gains from the use of this type of paint, especially in reducing cooling load, but at the expense of an increase in heating load in winter.

Keywords: thermal emittance, roof coating, heat load, radiative cooling, modelling

Symbols

G	incident solar irradiance, W/m^2
α	solar absorptance (dimensionless)
h_{in} (h_{out})	internal (external) heat transfer coefficient, $W/(m^2K)$
T	roof temperature (external surface) , °C
T_{in}	interior temperature (just under internal roof surface), °C
T_a'	ambient temperature, °C

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1. Introduction

A key issue in achieving sustainability in the built environment is reducing the rapidly growing demand for airconditioning of buildings, which is in turn increasing the already large greenhouse gas emissions generated by cooling of buildings. In Australia, the cooling of commercial buildings accounts for 28% of commercial building energy use (AGO, 1999[1]), or approximately 72PJ per annum, corresponding to approximately 13 MT CO_2 emissions (1998 figures).

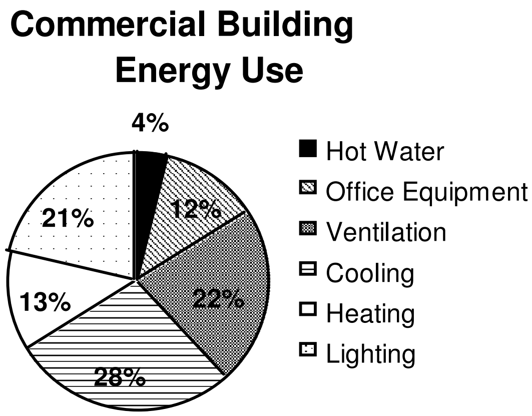

Figure 1. The breakdown of energy use in commercial buildings in Australia in 1998 (source: AGO Commercial Building Energy Baseline Study, 1999)

In addition, while domestic energy use for heating and cooling is large (125PJ per annum in 1998[2]), the greenhouse emissions are significantly lower ($8MTCO_2$) than the emissions from commercial buildings, owing to the large proportion of gas and wood heating in southern Australia, and the relatively low penetration of domestic airconditioning. However the rate of increase in the domestic airconditioning market is enormous, with an anticipated increase in electricity demand in South-East Queensland of 5% per annum due to domestic airconditioning[3]. Therefore there are significant opportunities to use improved design and smarter materials to reduce the long term greenhouse emissions, particularly those generated by cooling demand.

Heat transfer through walls and roofs contributes a major component of the heating and cooling load in many buildings, with the internal loads (including occupants) contributing a heating load to be removed from the building. Most high rise office buildings are internal load dominated, while most houses are façade dominated (ie the heating and cooling load is dominated by the heat transfers to the environment through the building shell. Typical design approaches to controlling the heating and cooling load are to increase the level of insulation in the walls and in particular the roof, and to use light colour external materials to reduce the absorption of solar radiation.

For buildings which have significant internal loads, however, or with large roof areas relative to walls, insulation of the roof and the use of light colour roofing materials can lead to situations where heat is trapped inside the building and can only be removed by mechanical airconditioning. In these cases, using radiation from the roof to assist in cooling can be a very effective means of reducing the cooling load.

In this paper, results of measurements on, and performance modeling of, several different roofing materials have been made to compare the properties of a high reflectance and high emittance coating, which has the trade name SkyCool. SkyCool exhibits very high solar reflectance (above 85%) and thermal emittance over 94% and is a practical adherent painting mix with high pigment levels that can expand and contract without delamination. Granqvist and Eriksson[4] reviewed the long history of the field of radiative cooling over a decade ago, with both paints and pigmented foils being studied. TiO_2 [5] and ZnS[6] pigments have both been used with partial success, but achievement of the combination of properties exhibited by SkyCool on large areas has been elusive.

Modelling of whole buildings has also been undertaken to assess the impacts on energy use, greenhouse gas emissions, and operating cost of the building when the coating is applied to the roof. The results indicate that for appropriate buildings, the use of this type of coating can lead to triple-bottom line benefits, with reduced operating costs, reduced environmental impacts, and improved indoor environment, with increased thermal comfort inside the buildings resulting from lower roof temperatures. The next section describes the basics of heat transfer through roofs, and this is followed by a discussion of the roof coating key characteristics, its performance in laboratory trials in comparison to other roof materials, and finally its performance in a whole building.

2. Heat transfer through a roof

As shown in condensed form in equation (1) the energy balance of a roof is made up of the incoming solar energy, the reflected solar energy, the absorbed solar energy and heat transfer via radiation, convection and conduction, as shown in figure 2. In addition, there is heat flow through the roof depending on the roof structure (insulations, air spaces etc) and the interior and exterior temperatures.

Under steady state conditions with fixed solar flux G on the roof plane , coating solar absorptance α and roof metal temperature T the complex coupled heat flow system can be condensed into the single equation

$$\alpha G = h_{in}(T - T_{in}) + h_{out}(T - T_a') \quad (1)$$

h_{in} and h_{out} represent heat conductances at temperature T in and out from the roof sheet at temperature T. T_{in} is the temperature just under the roof or roof insulation and T_a' is the ambient temperature which can be modified to reflect the sky temperature impact or can be left as actual ambient with a modified effective h_{out} to take account of enhanced cooling to the sky. The interior heat flow can be lowered by either lowering the internal heat transfer by using insulation or lowering the roof surface temperature (T) through a combination of a low solar absorptance and enhanced external heat transfer.

The solar absorptance α of a roof is a key factor in determining the thermal performance, as a high absorptance (or low reflectivity) means the roof absorbs significant energy from solar radiation, and some of this will be transferred into the building, depending on the level of insulation of the roof. The proportion of heat which is transferred inwards depends on the external conditions (sky temperature, wind speed), but also on the ***emisivity or thermal emittance*** of the roof material. For a low thermal emittance material, little heat is reradiated (h_{out} is low), while for a high thermal emittance material, significant heat can be lost by radiation (radiative cooling, h_{out} increases), reducing the internal load, and also the roof temperature.

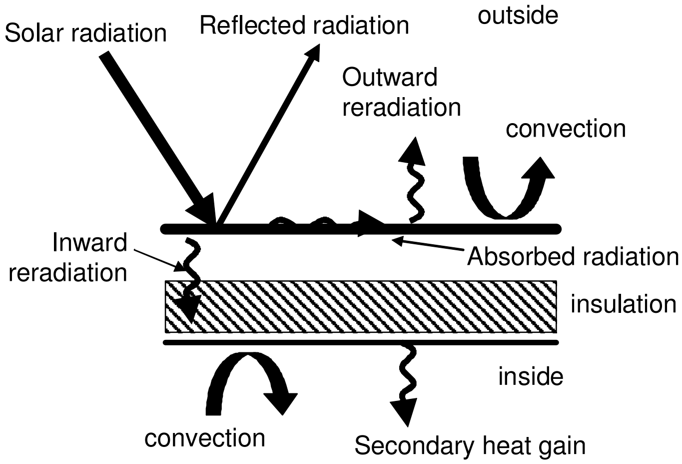

Figure 2. The components of heat transfer for a roof.

In addition, the thermal emittance can affect the heat loss from the interior of the building. A low thermal emittance will reduce the heat loss through the roof, while a high thermal emittance will increase the heat loss through the roof. This is affected by the level of insulation in the roof.

3. Laboratory Tests

Four large steel metal boxes open at one end, and one of the same size constructed of off-white Colorbond steel, were used in the tests. With the open end down (box inverted) the base then became the "roof' for the purposes of irradiation and night cooling testing. The walls of each box were lined with R 1.5 insulating batts. The four cases studied are detailed in Table 1.

Table 1. Laboratory Test Cases

Box	Exposed Roof Material	Roof Insulation	Solar Absorptance
A	Steel	-	0.49
B	Steel	R1.5	0.49
C	Steel-SkyCool (0.7mm)	-	0.15
D	Steel-SkyCool (0.7mm)	R1.5	0.15
E	Colorbond	R1.5	0.50

Temperatures were recorded with calibrated chromel-alumel thermocouples. Global solar radiation incident on each roof, was recorded in outdoor work at the same frequency as temperature data.

Both indoor and outdoor tests were performed. Indoor irradiation using simulated sun from an array of four lamps positioned centrally above each box. The boxes were illuminated until steady state temperatures had been achieved at each location. The lamps were then turned off and the cooling curves recorded. Temperatures were monitored for the roof itself and three positions at different heights within each space, just under the roof or insulation, in the middle and near the base.

For outdoor tests, all boxes were run simultaneously. To accommodate all data channels on the computer, including the ambient shade temperature and solar radiation data, only the roof and central internal temperature were recorded for each box. Temperature stratification profiles can be estimated approximately from the indoor results. Data was obtained on different days with clear skies and on one day with an intermittent mixture of clear and cloudy conditions. To avoid heat gains through the walls from their direct solar heating and to confine other heat flows of consequence to the roof, reflective insulation was applied to the outside of all walls.

The results for the outdoor and indoor tests are quite consistent, allowing for the extra modes of heat transfer in the two situations. The results for one test (outdoor, solar irradiance 1062W/m^2) are shown in Table 2 below. The energy balance described in Table 2 is derived from the near steady state conditions in the results during outdoor exposure, together with knowledge of the optical properties of the materials. The energy balance of each roof is made up of the incoming solar energy, the reflected solar energy, and the absorbed solar energy. The absorbed solar energy heats the roof and raises its temperature so the SkyCool-coated roofs (C&D) stay cooler primarily because they reflect most of the incident solar energy

Table 2. Results for Outdoor Tests with Solar Radiation of 1062W/m^2

Sample	Solar Energy Reflected **Wm^{-2}**	Heat Lost to Ambient and sky from roof* **Wm^{-2}**	Roof Temperature* **°C**	Interior Temperature* **°C**
A	542	498	56	41
B	542	500	61	35
C	894	188*	33	27.5
D	894	170*	32	27.5

* These are values determined from quasi-equilibrium values – the temperatures had become approximately constant

4. A whole building

A large Australia Post depot, with a floor area of 23,000m^2 was simulated using the GSL simulation software (ref), both with and without SkyCool coating. The software allows the roof material to be specified to allow for varying thermal emittance. The building has significant internal loads, but has few windows. A comparison of the annual heating and cooling loads between a colorbond roof and SkyCool coating (see Figures 3) shows significant savings in total energy usage. Similar reductions in peak energy demand are observed.

The savings in operating costs and greenhouse emissions in this case are substantial, despite an increased heating load in winter as a result of the cooling properties of SkyCool. Even with this additional heating load and cost, the operational cost savings are approximately $85,000 per annum (assuming an energy cost of $0.10 per kWhr), and a greenhouse gas emission reduction of 875 tonnes CO_2. In addition, the reduction in peak cooling load is approximately 30%. Savings in installed plant capacity could significantly add to the overall cost savings for this installation.

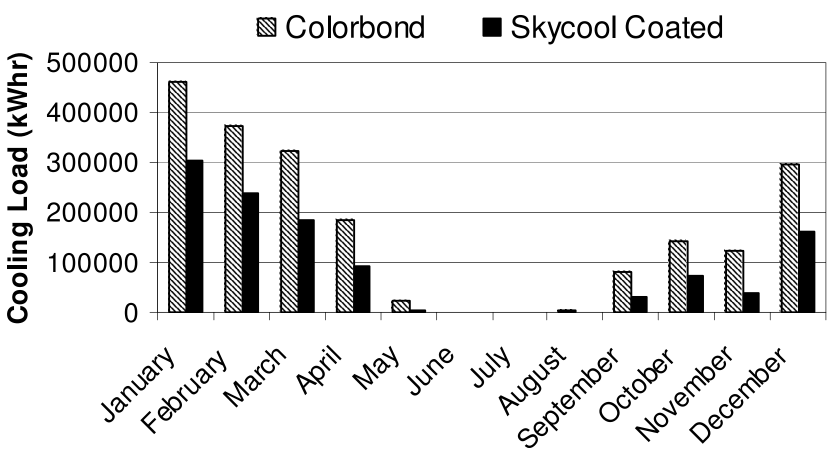

Figure 3. Monthly values of TOTAL energy use for the Australia Post building with a Colorbond roof and Colorbond coated with SkyCool

It is significant to note that there is an increase in heating load in this building in winter. This is consistent with the laboratory results which indicates that the SkyCool coating, even with insulation present, give a net cooling effect. The extent of the increase in heating load in winter does depend on the amount of insulation in the roof, but as the amount of insulation increases, the benefit in reduction of cooling load reduces.

5. Case Study – a comparison of supermarkets

Some buildings have been treated with the SkyCool product. These include a supermarket (large floor area, low rise) on the Sunshine Coast in Queensland. A similar supermarket in Chancellor, also on the Sunshine Coast (and therefore subject to similar climate) has been compared with the trial building, and the impact on total energy use has been monitored over an entire year. The results are shown in Figure 4 .

6. Discussion & Conclusions

Something unusual and special happens under bright sun and clear sky with the SkyCool coating on the roof. The SkyCool roof over insulation is always slightly cooler under a clear sunny sky than its uninsulated counterpart. Normally insulation is expected to make a roof metal hotter as losses to the outside must increase (see equation (1): as h_{in} decreases, $h_{out}(T-T_a^{'})$ must increase). If the roof temperature decreases, then radiative cooling from the roof must be greater than absorbed solar energy. The uninsulated roof stays warmer because it is **gaining** heat from the interior and is thus unable to cool to the extent of its insulated counterpart.. At night with no solar gain this radiative cooling can pump much heat from the interior as roof temperature falls significantly.

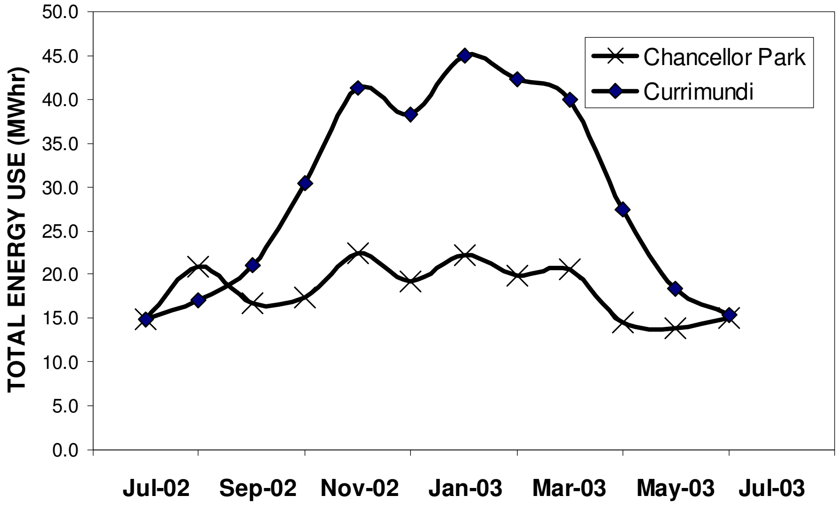

Figure 4. The total energy use over a 12 month period for similar supermarkets in Chancellor Park (coated) and Currimundi (uncoated).

The benefits of this type of cooling on building energy use, and internal comfort (which results from both reduced airconditioning and lower roof temperatures), can be substantial. Clearly this type of coating works most effectively where the building has a large floor plate (and roof area) and is low rise, so the maximum benefit from cooling via the roof is possible. Under these circumstances siginificant savings in operating energy costs and also potential reductions in plant size, and peak energy demand are added benefits.

7. References

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