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A FIELD TEST TO DEMONSTRATE THE BENEFIT OF COOL ROOF PAINTS IN A TEMPERATE CLIMATE

CHRISTOPHER JENSEN, DOMINIQUE HES and LU AYE
The University of Melbourne, Melbourne, Australia
{cjensen, dhes, lua}@unimelb.edu.au

Abstract. Roof albedo has been demonstrated to be a successful tool in the pursuit of reduced energy loads in buildings, as well as providing other benefits, such as reduced urban heat island effect and benefiting micro-climates. The monitoring of three 11m^2 buildings shows that there are significant heat load reductions; internally of up to 5°C and externally the high albedo roofs being up to 30°C cooler. Further data on reflectivity from the high albedo roofs show a threefold increase in reflection of the sun's energy. All these findings confirm that using high albedo paint on corrugated roofs with no insulation in Melbourne will reduce cooling requirements and reduce contribution to the Urban Heat Island effect of these roofs by up to 4.2 MJ/m^2

Keywords. Albedo; cool roofs; solar thermal load; energy efficiency; urban heat island effect.

1. Introduction

This research was conducted on behalf of the City of Melbourne in order to develop a *Cool Roof Guideline* to demonstrate the benefits of high albedo paints to building owners (City of Melbourne 2011).

1.1. COOL ROOF STUDIES AND MEASUREMENTS

There have been several documented studies using both field measurement and computer simulations that document the energy savings from increasing the solar reflectance properties of buildings, combined with an increased thermal emittance. These show that the higher reflectivity a roof colour is, the lower solar energy is absorbed and the lower surface temperature will be (Kiehl and Trenberth 2010).

Akbari and Konopacki (2005) used modelling to calculate the cooling energy savings due to the application of heat island mitigation strategies (application of cool materials and increase in vegetation cover) for 240 regions in the United States. They found that for residential buildings the cooling energy savings vary between 12% and 25%, for office buildings between 5% and 18%, and for commercial (retail stores) buildings between 7% and 17%.

In a 2001 study by Konopacki and Akbari, the Lawrence Berkeley National Laboratory (LBNL) measured and calculated the reduction in peak energy demand associated with a cool roof's surface reflectivity. They found that, compared to the original black rubber roofing membrane on the Texas retail building studied, a retrofitted vinyl membrane delivered an average decrease of 24 °C in surface temperature, an 11 percent decrease in aggregate air conditioning energy consumption, and a corresponding 14 percent drop in peak demand. The average daily summertime temperature of the black roof surface was 75 °C, but once retrofitted it measured 52 °C. Without considering any tax benefits or other utility charges, annual energy expenditure was reduced by $7,200 or $0.75 per m/2.

Other relevant field studies in California and Florida have demonstrated direct cooling-energy savings in excess of 20% upon raising the solar reflectance of a roof to 0.6 (e.g. medium - light) from a prior value of between 0.1 and 0.2 (e.g. black) Energy savings are particularly pronounced in older houses that have little or no attic insulation, especially if the attic contains air distribution ducts for ducted heating and cooling. Further, Akbari et al (1997) observed cooling-energy savings of 46% and peak power savings of 20% achieved by increasing the roof reflectance of two identical portable classrooms in Sacramento, California. Konopacki et al (1998) documented measured energy savings of 12-18% in two commercial buildings in California. Finally, in a large retail store in Austin, Texas, Konopacki and Akbari (2001) documented measured energy savings of 12%.

1.2. URBAN HEAT ISLAND

The Urban Heat Island (UHI) effect refers to the phenomenon of a metropolitan or built up area that is significantly warmer than its surrounding areas. Internationally, it can cause average urban daytime air temperatures to be up to 5.6°C higher than the surrounding rural areas in summer (Akbari et al, 2009), for Melbourne this effect is up to 4°C (Coutts et al, 2008). When looking over the long term, downtown Los Angeles has been measured to be 2.5° Kelvin warmer than in the 1930's, which equates to 1 – 1.5 GWe more electricity to cool in summer, costing an extra $100 Million per year (Akbari, 2008). Surface air temperatures elevated by at least 1°C compared with surrounding areas have been observed in New York City for more than a century (Gaffin et al, 2008).

The Urban Heat Island effect can be detected throughout the year, but it is of particular public policy concern during the summer. The higher surface and air temperature is associated with increases in electricity demand for air conditioning, air pollution, and heat stress-related mortality and illness (Rosenfeld et al, 1995; Nowak et al, 2000; Sailor et al, 2002; Hogrefe et al, 2004). According to the U.S. Centre for Disease Control and Prevention, over the past 20 years, more Americans were killed by heat than by the combined impact of hurricanes, lightning, tornadoes, floods, and earthquakes. Within a five-day period, the 1995 Chicago heat wave killed between 525 and 726 people (Akbari, 2008). As such, the Urban Heat Island effect is a very real and serious problem facing developed areas.

In areas that suffer from the UHI effect, the temperature difference is usually larger at night than during the day. It is most apparent when there is little wind as materials hold onto the heat of the day. Specifically, the material that the city is built of such as the roads, concrete bricks and other construction materials. These materials often also have a low albedo, being a dark colour, and therefore absorb more heat to add to this thermal lag.

The UHI effect decreases air quality by increasing the production of pollutants such as ozone (Taha et al, 1994). Further, the UHI has been linked to changes to local weather patterns including rainfall and pressure systems, resulting in a reduced removal of these pollutants. For example, rainfall is greater downwind of cities, partially due to the UHI.

Mitigation of the UHI effect can be accomplished through the use of green roofs and the use of high albedo or lighter surfaces in urban areas (Synnefa et al, 2008). The green roofs absorb solar energy and evapotraspirate while the high albedo surfaces reflect more of the sun energy and absorb less heat. Despite concerns raised about its possible contribution to global warming, comparisons between urban and rural areas show that the urban heat island effect has little influence on global mean temperature trends (Peterson, 1999).

In terms of a solution increased vegetation, higher albedo surfaces and higher albedo pavements are cited as the main opportunities. Rosenzweig et al (2009) found that the influence of vegetation on urban climate is more important than the influence of the albedo of built surfaces, but that planting street trees citywide has only half the impact of high-albedo surfaces. Yet both solutions need to be applied as they are cumulative and vegetation cannot be used in every situation.

1.3. LOCAL THERMAL EFFECTS – MICRO HEAT ISLANDS

During a typical sunny day, approximately 1 kW/m^2 of solar radiation hits a roof's surface. Of this between 20 percent and 95 percent is absorbed based depending on the roof's colours (Suehrcke et al, 2008). This heat load affects the microclimate around the building and the city. This heat load is influenced by the incident solar radiation on the building envelope as well as the level of vegetation in the area. The thermal or long wave radiation re-radiated from building surfaces affects air temperature, relative humidity and wind speed (Prado and Ferraira, 2004).

Based on the literature, this research project described in this paper was developed to test the benefits of high albedo roofing treatments, green roofs and urban trees at the University of Melbourne. This paper outlines the high albedo outcomes on the corrugated iron roofed buildings. The results were of interest for the City of Melbourne (CoM) who want to develop a policy for the retrofit of many of their existing buildings and are interested in reducing Melbourne's UHI.

2. Method

The CoM guideline was based on two concurrent testing methodologies. The first, which is the focus of this paper is a full-scale installation of three single room buildings (and one 1/3 scale building) at the University of Melbourne's Burnley campus in Melbourne, Australia. Two of the full-scale buildings and the 1/3 scale building are painted with proprietary reflective, high albedo, white cool roof paint (CRP), and the third building was left unpainted as a control.

Concurrently, computer simulation of the physical experiment using the TRNSYS software package was carried out. This allowed the research team to translate the results of the actual experiment to different buildings and to carry out sensitivity analyses. Precedent studies by Akbari et al (1997) suggest that simulated and measured data is not likely to be directly relative but rather implicit of trends and indications. Therefore the computer model was calibrated with our actual results establishing an effective predictive model. The modelling component of the research was used in CoM guidelines to extend upon the outcomes of the physical modelling, but does not form a focus for this paper.

The site for this was study located in Eastern metropolitan Melbourne at coordinates 37°48′49″S, 144°57′47″E. The moderate oceanic climate results in significant residential heating and cooling loads throughout the year and is an ideal climate for the application of passive design principles. Among the simplest of these principles is the use of roof surface albedo that has the potential to provide significant reductions in cooling energy demand and corresponding peak loads.

The test buildings were of a lightweight construction typical of Australian housing. Insulation levels were indicative of the 1991 minimum building standards (approx. R1.0 walls (US R5.67) and R0.82 (US R4.65) which would have been in place at the time of construction. The un-insulated timber floors and the absence of weather strips to doors resulted in an infiltration rate of approximately 2 air changes per hour (ACH). The doors and windows were kept closed with the exception of those times access was required for the installation and maintenance of equipment. North facing windows had internal venetian blinds in order to mitigate misleading sensor output affected by glare and direct solar gain.

2.1. STUDY LIMITATIONS

This study is limited in scope as follows:

- The study was conducted in a year that was cooler than average with less sunshine hours.
- The studied buildings were small single zone structures and therefore had a relatively high wall to roof ratio, meaning increased heat transfer.
- The study tested three proprietary products in the field with one additional product in the computer modelling.
- Computer modelling (used in the is inherently limited to specific assumptions about internal gains, occupancy profiles and other variables that were required to be fixed as static. The impact of this was minimised through the calibration with actual results.

2.2. SITE MEASUREMENTS

The field study of the products was conducted at the Melbourne University Burnley Horticultural campus where three “full sized” (10.43 m^2) buildings, (1 control and 2 retrofitted with high albedo paint) were monitored along with a scale model building (approx 3 m^2) built to 2010 code requirements. This building allowed the team to test soiling, weathering, angle and so forth without needing to climb 3.5 metres.

Data collected included:

- heat flux through the ceiling
- ambient temperature (dry bulb and wet bulb) humidity,
- radiant temperature
- air movement and

- Incoming and reflected surface radiation from the roof in the horizontal and vertical plane

The data collected was extensive and on-going and extends beyond that required for this paper, it is hoped that this will facilitate a more longitudinal study of the effect of the retrofits to these buildings. Further, this extended data collection provided an opportunity to collect thorough surface property and environmental data over an extended period of time and was useful in verifying results and identifying anomalies in data or building performance.

Two means of data collection were used: a DataTaker DT85 data logger with two CEM20 expansion modules, and a Hobo weather station. The bulk of the data was recorded using the DT85 data logger, which was logging continuously at 20-second intervals. The data logger was located in the control building (building B) for part of the field test but was relocated to a nearby building in order to eliminate the need for regular access to building B which would influence results. The primary data collection was of the indoor and outdoor temperatures, roof surface temperatures and reflection both in the horizontal and vertical planes. Additional data was logged including the solar radiation received.

Once the data logging was stable there were no changes to the test buildings or the logging equipment for the duration of the study.

2.3. COMPUTER MODELLING

The field data was used to verify the computer model for the benefit of extending the results to commercial and industrial buildings with different heating and cooling requirements, and allowed for sensitivity analysis to be undertaken of the test building specifically looking at the impact of roof paint properties, levels of insulation, percentage shading and pitch (Table 1).

Table 1. Modelling parameters tested

Option	**Sensitivity range**	**Factor**
Roof paint colour	based on available products	Total energy use based on properties
Insulation levels	R1.5/R2.5/R3.5/R4/R4.5/R5	Heat transfer through the roof
Percentage of shading	0%-20%-50%-70%-100%	Percentage shaded
Pitch	5%, 20%	Percentage of incident

TRNSYS 16 (Klein et al, 2006) was used for all the simulations. Typical Metrological Year data for Melbourne developed by Morrison and Litvak (1999) was used. The simulated hourly internal temperatures and roof tem-

peratures were compared with the experimental data to validate the model developed for this study.

3. Results

The results of the onsite measurements conducted between December 2010 and July 2011 (on-going) have been summarised into summer (January 1 – 14) and winter (April 23 – 8th May) data sets, with specific days used (7th Jan and 28th April) for 24 hour data results presentation.

3.1. INDOOR TEMPERATURES – SUMMER RESULTS

The summer indoor temperature profiles suggest that the high albedo test buildings maintained up to 2 to 3 °C lower internal temperatures compared with the control building at the warmest part of the day in summer (Figure 1). This effect was consistent across a 24 hour period rather than restricted to daylight hours.

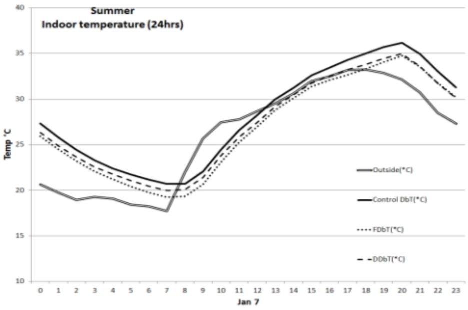

Figure 1. Summer indoor temperatures over 24 hrs.

3.2. INDOOR TEMPERATURES – WINTER RESULTS

The daytime winter indoor temperature profiles for the test buildings do not show any significant difference to the control building. This is most likely due to the lower solar radiation at this time, and therefore conducted heat gains and losses are a more significant factor in determining indoor temperatures.

The night-time temperatures of the test buildings show a lower temperature reading through the night (see Figure 2).

This supports the notion that these products assist with the extraction of heat from within the building to the atmosphere (related to the thermal emittance of the materials).

Both the computer simulations and the field results support the idea that the insulation used in the ceiling / roof cavity is negating the majority of the effect on indoor temperature of these products in the field study. As such, a building that does not have bulk insulation would get a greater benefit from the use of these products.

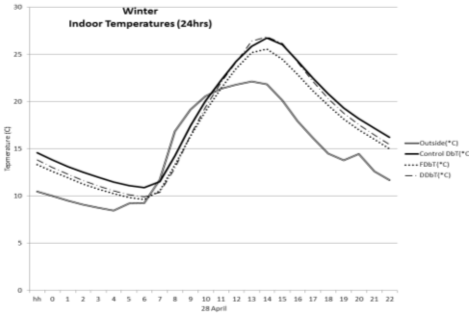

Figure 2. Winter indoor temperatures over 24 hrs.

3.3. ROOF SURFACE TEMPERATURES (EXTERNAL)

The roof temperatures results refer to the outside temperature of the roof surface. The results show that high albedo paints significantly reduce the surface temperature (Figure 3).

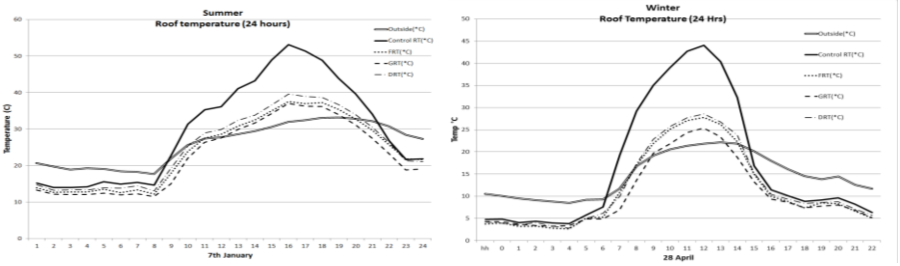

Figure 3 & 4. Summer roof temperature over 24 hrs. & Winter roof temperature over 24 hrs.

The summer roof temperature data shows a difference of up to 30 degrees with the highest recorded temperature of 68° C, whilst the coolest treated roof is 35° C – this supports the suggestion that a “normal” (zincalume) roof is too hot to touch whilst the high albedo roofs, independent of product type were consistent below 40° C.

The winter roof temperature results (Figure 4) demonstrate a similar temperature reduction as the summer results, suggesting that although the roof surface temperatures are lower in general, the high albedo roofs still provide a temperature reduction that is comparable with the summer results. Yet as shown in Figure 3 the reduced surface temperature from the treated roof does not affect internal temperatures for Melbourne’s mild winter conditions.

3.4. ROOF REFLECTIVITY

Both horizontal and vertical roof radiation was measured; the results showed that due to the low angle of the roofs only the horizontal measurement could be used to represent radiation off the roof. The three treated roofs functioned very similarly as such, only one of the roofs is shown below compared to the control (see Figure 5 and 6).

The summer results for reflectivity demonstrate a 3 fold increase in reflectance from the high albedo treated roofs.

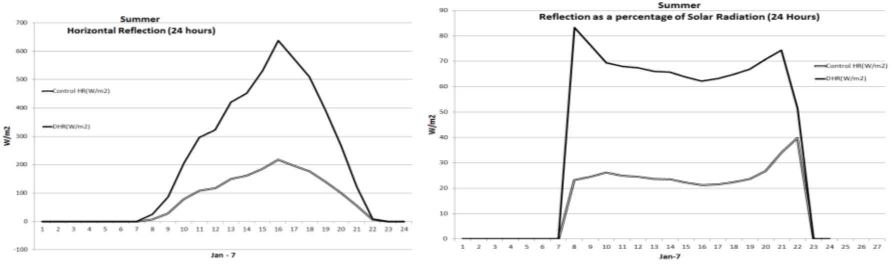

Figure 5 & 6. Summer horizontal reflectivity over 24 hrs. & Summer horizontal reflection as a percentage of radiation received over 24 hrs.

5. Conclusion

The field test results presented here have demonstrated that high albedo roofs are highly effective at reflecting solar radiation and lowering roof surface temperatures, when compared with a standard metal roof material, and also have demonstrated that the products reduce indoor temperatures of the test buildings both during the day and at night-time. This supports the claims of manufacturers that the products are effective at reflecting radiation AND emitting heat at night time. Furthermore, these results are fairly consistent between the summer and winter seasons. These results indicate that the high albedo roofs are likely to contribute to a reduced UHI effect due to lower roof surface temperatures.

Despite the suitability of these products for retrofitting residential and commercial buildings, the single drawback of these products has been shown to be the potential negative effect on heating load – which is a significant proportion in a cool temperate climate such as Melbourne. Consideration of the balance between the heating and cooling load would be critical in deciding to use these cool roof paints.

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