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Università Politecnica delle Marche

Extended summary

Development of measurement procedures for the evaluation of energy performances and ageing resistance of innovative cool coloured materials

Curriculum: Ingegneria Meccanica e Gestionale

Author

Marco Emiliani

Tutors

Gian Marco Revel

Milena Martarelli

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Abstract. The objective of the present work is to define test procedures for the evaluation of energy and durability performances of innovative cool coloured products developed within COOL-Coverings project, co-funded by EU commission under FP7. These materials are spectrally selective (absorbing in the visible and reflecting in the NIR) thus combining aesthetics (colour) and cooling capabilities. Three products have been addressed: ceramic tiles and paints for façades and bituminous roof membranes. Radiative properties have been initially analysed with a spectrophotometer. To understand the impact of such technologies on buildings, a testing protocol has been defined in which cool and standard materials are applied to calibrated mock-ups and different thermal parameters are continuously monitored. Cooling energy savings have been finally estimated for different climates and applications using numerical building models validated by the experimental data collected in the demo campaign. Besides energy performances, an important issue for cool materials is represented by natural ageing that can determine a progressive reduction of radiative properties over the time. Current standards define a period of 3 years for the evaluation of ageing resistance. Such a duration is not compatible with industrial needs, while existing accelerated standards are not adequate, neglecting the soiling effect that has instead a large impact on cool performances. Part of the research was therefore dedicated to investigate ageing mechanisms identifying the main factors and quantifying the loss of reflectance on standard and cool materials. Finally, an accelerated ageing method recently proposed by the LBNL to simulate 3 year ageing in few days of lab test has been analysed. The applicability of this procedure, designed for roof and US climate, has been verified also for new products and Mediterranean climate demonstrating a correlation degree with natural testing higher than current predictive models.

Keywords. Cool material; reflectance; mock-up; ageing; accelerated test.

1 Problem statement and objectives

A cool material keeps lower surface temperature under sun exposure generating significant benefits for the building and the environment: CO_2 offset, mitigation of Urban Heat Island phenomenon, reduction of cooling energy consumption and improvement of indoor comfort for unconditioned spaces [1]-[4]. The cooling effect is determined by the capability of the surface of reflecting incident solar radiation and emitting the absorbed energy back towards the atmosphere. To date, this concept has been mainly applied to white materials, having the highest reflectance, and for roof application, that is on the components that receive the largest fraction of solar radiation. In particular the terms cool materials and cool roofs have often been associated to the same concept.

With the aim of extending the range of current cool solutions also to coloured materials and façade application, recently innovative cool products for the building envelope have been developed in COOL-Coverings project, co-funded by the EU commission under the FP7 [5]. The basic idea is to obtain spectrally selective coatings with high absorbance in the visible range (depending on the colour) and high reflectance in the NIR range where the sun emits more than 50% of its energy. Three cool products have been addressed: ceramic tiles and acrylic paints for façades and bituminous roof membranes.

The present work describes the methodology defined to evaluate thermal, energy and durability performances of these new materials.

The two radiative properties that are at the basis of a cool material are the solar reflectance and thermal emittance, both to be maximized in order to reduce surface temperature. An important additional requirement for cool materials is the durability, intended as the capability of preserving cooling properties over the time. This issue is of particular relevance since surface radiative properties can degrade not only because of common weather factors (moisture, UV radiation, temperature cycles…) but also under the effect of soiling agents (biological growths, dust and soot deposition) [6]-[8].

Current standards and rating programs (Energy Star, LEED, Title24, ASHRAE 90.1, Title 24) define minimum values of initial and aged radiative properties (i.e. solar reflectance and thermal emittance), the latter to be measured after three years of natural exposure under standard climates (CRRC-1 [9]). For a full characterization of new cool materials, however, additional studies have to be done:

- Solar reflectance and thermal emittance define surface properties while a more in depth analysis is necessary to evaluate the impact of cool materials on the thermal and energy performances of buildings. One of the most followed experimental approach consists in applying cool solutions to existing buildings and to compare thermal parameters before and after the treatment [10]-[12]. Even considering its large demonstrative impact, this method cannot accurately compare standard and cool materials since non simultaneous measurements determines differences in building operative conditions.
- Standard climates for the evaluation of ageing resistance have been defined to represent average US climatic conditions. In particular three main areas have been identified: hot/humid climate (Florida), cold/temperate climate (Ohio) and hot/dry climate (Arizona). While several studies have been carried out in the US, only few information exist in Europe where standard climates for durability assessment have not been yet identified.

- The three years defined for the evaluation of ageing resistance is not compatible with industrial needs and accelerated procedures are strictly necessary for the validation of new prototypes. Several artificial ageing methods have been defined in the past for different product classes (plastics, bituminous membranes, wood…). However none of them is suited for cool materials since they only account for UV radiation, temperature and moisture as stress factors completely neglecting the effect of soiling.

This dissertation describes the activities carried out within the COOL-Coverings project to characterize new cool coloured products tackling the abovementioned issued. In particular new experimental and numerical procedures have been developed with the following objectives:

- Accurately evaluate thermal and energy performances on real buildings. Starting from the analysis of material radiative properties at lab level, the objective is to experimentally demonstrate the effect of cool solutions in reducing solar heat gain and cooling energy demand on real buildings.
- Analyse the natural ageing mechanisms on standard and cool materials identifying main degradation factors and quantifying reflectance loss in typical Mediterranean areas.
- Contribute to the development of accelerated ageing methods in order o dramatically reduce the time required for durability assessment. In particular a procedure recently proposed by the Heat Island Group of the LBNL to simulate three year outdoor exposure in three days of lab test has been considered [13].

2 Research planning and activities

2.1 Evaluation of thermal and energy performances

The methodology adopted for the evaluation of thermal and energy performances of new cool coloured products (tiles, paints and membranes) has been subdivided into three main steps:

1) Evaluation of radiative properties at lab scale level. This activity has been focused on the analysis of reflectance spectra in the UV/VIS/NIR range (from 300 to 2500 nm) of cool and standard materials by performing spectrophotometer measurements (Figure 1) [14].

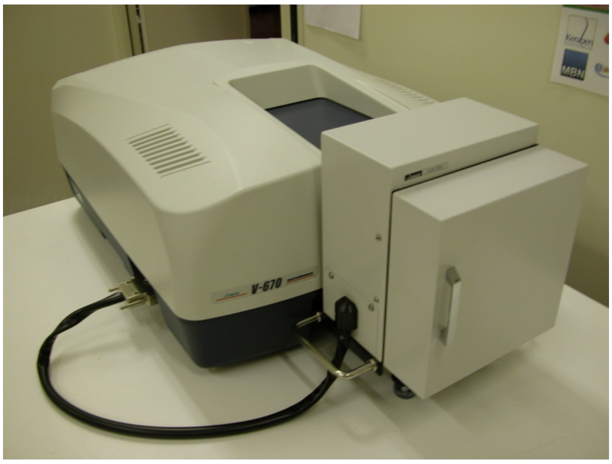

Figure 1. UV/VIS/NIR spectrophotometer used for the measurement of solar reflectance

2) Development of a dedicated measurement protocol for the evaluation of thermal performances on calibrated middle scale buildings. A dedicated Demo Park has been realized in Algete (Madrid) where 5 scaled mock-ups have been installed and fully instrumented (Figure 2). Before being covered with standard and cool coatings the units were calibrated to quantify deviations due to sensor uncertainty and human errors in construction and sensor installation. Finally different thermal parameters (wall temperatures and heat fluxes) have been continuously monitored during summer 2012 and May 2013. This activity has been performed within the E2B Nanocluster initiative.

Figure 2. Picture of Algete Demo Park

3) The following step was to estimate the energy saving potentials on real buildings under different climates taking into account not only cooling load reductions but also heating penalties during winter. Two numerical models representing potential applications of cool roof and cool façade (Figure 3) have been realized and calibrated using the experimental data of the demo park. Energy consumption under different scenarios (cool vs. standards in different localities) have been finally simulated in Energy Plus.

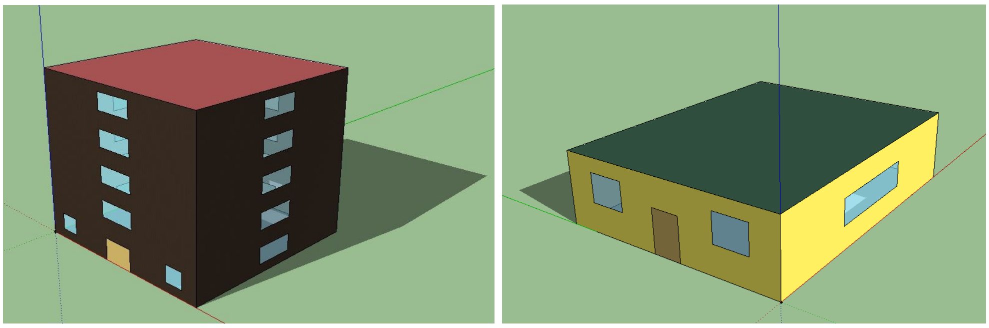

Figure 3. Numerical models used for the Energy Plus simulation

2.2 Evaluation of ageing resistance

In parallel with the evaluation of thermal and energy performances, part of the activities were dedicated to the analysis of ageing degradation phenomena and the loss of radiative properties over the time (durability assessment). The emphasis has been placed on solar reflectance considering that usually thermal emittance does not undergo significant variation on cool materials.
Two natural ageing tests have been performed on standard and cool materials (acrylic paints, ceramic tiles and bituminous membranes) by exposing samples in Ancona and measuring the progressive loss of reflectance. Different test variables (exposure angle, cleaning process, material class) have been analysed and their effect on reflectance has been quantified.

Figure 4. Standard and cool samples exposed in Ancona

The results of natural ageing tests have been then exploited to validate the accelerated test method recently proposed by the LBNL. The procedure has been developed to mimic the effect of three years of natural exposure under standard US climates in only 3 days of lab test. With respect to existing accelerated ageing standards the most innovative aspect is that it takes into account the effect of soiling by spraying on the sample a solution obtained by mixing organic and inorganic particles dispersed in the atmosphere.

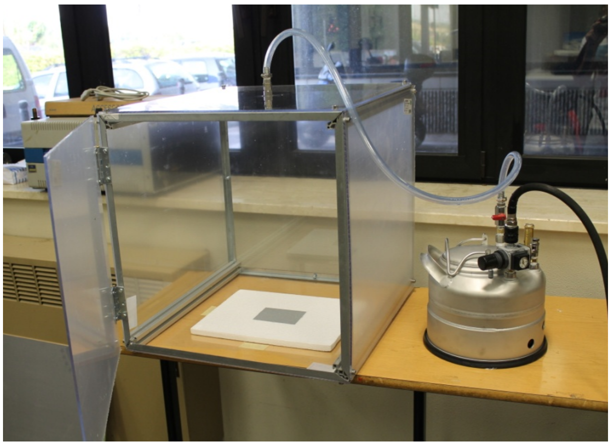

Figure 5. Soiling apparatus used for the accelerated ageing method

3 Analysis and discussion of main results

From the analysis of reflectance spectra it turns out that cool coloured materials have a similar behaviour in the visible range (up to 700 nm) but offer a definitively higher reflectance in the NIR range (Figure 6) thus maintaining the same colour and maximizing the cooling properties (NIR and solar reflectance improvements up to +0.32 and +0.17).

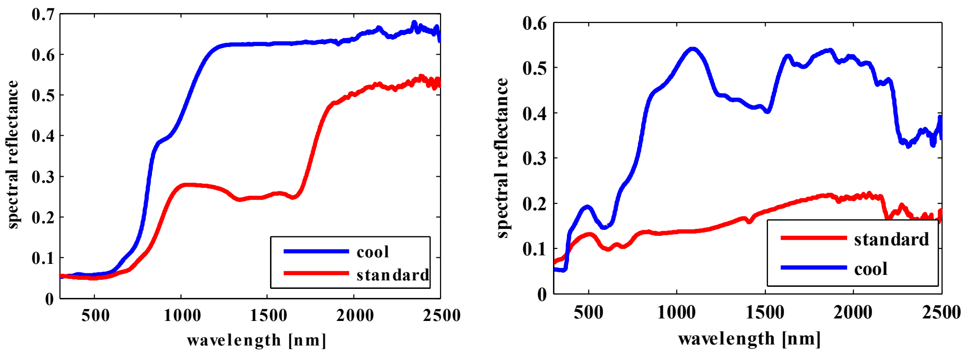

Figure 6. Reflectance spectra of cool (blue) and standard (red) materials. Left: ceramic tiles; right: bituminous membranes

When applied as coatings on the scaled mock-ups (Figure 2) new cool materials significantly reduce solar heat gain and wall temperature. In particular cool roof membranes determines a decrease of average heat flux peaks of 11.7 W/m^2 (Figure 7, right)corresponding to 24% and a reduction of external and internal wall temperature of 4.7 °C and 2.5 °C. Similar results have been obtained also by applying cool ceramic tiles and acrylic paint on façade obtaining a reduction of heat flux up to 10.2 W/ m^2 and external wall temperature up to 3.4°C.

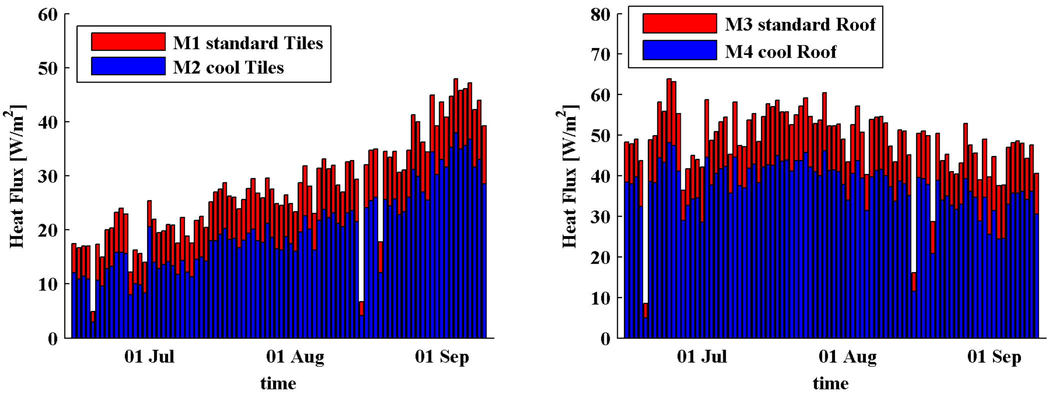

Figure 7. histograms of heat flux peaks measured on cool (blue) and standard (red) mock-ups. Left: comparison between façade tiles (South); right: case of roof membranes

In the case of real buildings, the numerical simulation demonstrated that consistent net energy savings can be obtained by replacing traditional coatings with new cool coloured ones on several tropical and temperate climate regions (Figure 8).
The largest benefits were obtained by applying cool solutions on the roof with yearly reductions of cooling loads up to 18.9 kWh/m² and energy savings up to 17%. Significant improvements, however, were obtained also considering the cool façade application with reduction of cooling loads up to 4.3 kWh/m² and net energy savings of 9.5%.

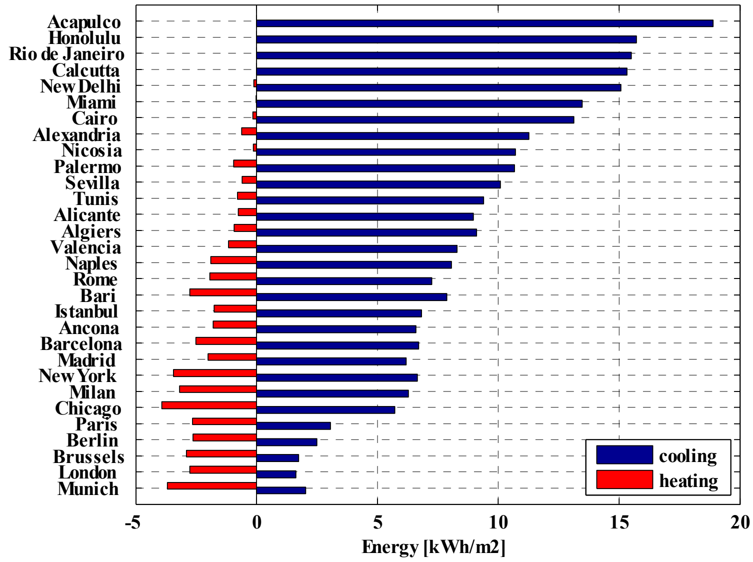

Figure 8. yearly cooling energy savings (blue) and heating penalties (red) calculated when the standard roof membrane is replaced by the cool colour matching one

In parallel with the development of procedures for thermal and energy performance evaluation, natural and accelerated ageing methods have been analysed. The two outdoor tests performed (with a duration of respectively 4 and 16 months) on standard and cool materials provided the following information:

- The largest impact on reflectance is determined by soiling, even if it has revealed in different forms: as dust and soot deposition in the first test and as mould growth in the second.
- Reflectance spectra measured on initial and aged samples show a larger decrease in the visible rather than in the NIR range (with a maximum at about 400 nm) and it can represent an advantage for cool coloured materials that are highly reflecting in this spectral region.
- The exposure angle was found to have a large effect on reflectance change. In particular ageing phenomena have a significantly lower impact on vertical surfaces where moisture, sun radiation and soiling are reduced. This aspect is of particular relevance for cool façades that would be less sensitive to ageing degradation.
- Ceramic tiles have demonstrated optimal resistance to all weathering agents and have therefore a large potential as cool solution. Improved durability has been shown also by the cool acrylic paint developed in COOL-Coverings. The use of biocides, in fact, prevents algae growth and thus helps maintaining reflectance to the original value.

Comparing the results of natural and accelerated test methods (the latter following LBNL procedure) a maximum deviation of reflectance of 5.8% (absolute difference of 0.04) has been observed. Even if designed for US climate, the accelerate method demonstrates to properly simulate ageing phenomena also for Mediterranean weather conditions. It provides a definitively better estimation of aged properties with respect to current "predictive" models (e.g. Title 24) that instead tend to overpredict ageing effects (with differences up to 16%). The accelerated method, already under consideration as an ASTM standard, can be extremely useful for industry to speed prototyping and supporting the development of new materials.

4 Conclusions

The work performed aimed at characterizing innovative cool coloured materials (ceramic tiles, acrylic paints and bituminous membranes) for the whole building envelope including both roofs and façades.
An experimental-numerical approach has been adopted to evaluate thermal and energy performances at three levels:

- Radiative properties have been initially measured at lab level with a UV/VIS/NIR spectrophotometer showing a net improvement of NIR and solar reflectance (respectively up to +0.32 and +0.17) while keeping similar colour.
- The effect on building thermal behaviour has been then experimentally demonstrated by continuously monitoring thermal parameters on calibrated mock-ups realized in a dedicated Demo Park in Algete. Results shows that cool materials applied to building envelope (both roof and façade) significantly contribute to reduce heat fluxes (up to 24%) and wall temperature peaks (up to 4.7 °C).
- Finally energy savings on real buildings have been numerically calculated for different locations worldwide. Net energy reductions up to 18.9 kWh/m^2 have been estimated by applying cool solutions both to roofs and façades.

In parallel a study on the effect of natural ageing on radiative properties has been carried out. It has been found that soiling mechanisms (that can reveal as dust/soot deposition

and/or as biological growth) can have a dramatic effect on reflectance. The test also remarked the high weather resistance of ceramics and biocide paints together with the reduced ageing on vertical components thus confirming the large potential of new cool products for cool façades.
The accelerated ageing method recently proposed by the LBNL has been then considered and analysed. Even if developed for the averaged US climate, the method has provided results in agreement with the outdoor exposure test performed in Ancona. Further studies will be necessary in the future to optimize the soiling compositions to average European climates.

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