Paper No 314: Optical properties and influence of reflective coatings on the energy demand and thermal comfort in dwellings at Mediterranean latitudes

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Abstract

Climatic conditions affect shape, colour, geometry and lay-out of buildings. The vernacular Mediterranean architecture was characterised, among other passive techniques, by light colours to minimise solar gains through the opaque components of the building envelope. Actual building design and construction often forget such old bioclimatic approaches, delegating the comfort conditions to artificial systems. The energy consumption increase in the residential sector witnesses this problem, due to the high penetration of air conditioning systems. Ancient concepts, merged with innovative technologies, are hence necessary today. Reflective coatings can reduce the cooling loads with an effective solar control on the building envelope. Photometric analyses were carried out the measure the optical properties of a sustainable light coloured cool paint. Dynamic energy simulations were run for different Mediterranean localities (Rome, Palermo, Seville, Athens, Tripoli), buildings geometry (stand alone and row house), different thermo-physical properties of the opaque envelope (solar reflectance, U-value, thermal capacity) and of the whole building (natural ventilation rates and shading of glazing systems). The influence of reflective materials was assessed respect to the cooling and overall energy demand. The same simulations were repeated considering not cooled dwellings and the related thermal comfort conditions.

Keywords: cool materials, solar properties, energy demand, energy comfort,

1. Introduction

The use of light colours for painting the building envelope is a trademark of the vernacular Mediterranean architecture. This solution, together with other strategies, was effective in reducing the cooling demand and ensuring the thermal comfort conditions in the built environment. The modern architecture often does not take into account these concepts and it is today experimented the dramatic increase of cooling loads in residential and commercial buildings, as well as the thermal discomfort conditions for occupants. Old concepts merged with new technologies can improve the energy performance of buildings at the Mediterranean latitudes.

The influence of solar gains through the opaque components of building is nowadays practically neglected, without taking into account the consequences of this strategy. High reflective coatings and paintings, also identified as cool materials, can be useful for the building envelope, to reduce cooling loads and energy consumptions. This applies especially for the roof, exposed to severe solar gains in summertime. Many theoretical studies and monitoring campaigns witness this opportunity [1, 2, 3, 4, 5, 6]. Some characteristics are required: high reflectance over the solar spectrum, easy to clean, high durability in maintaining the original colour and resisting to ageing phenomena.

Residential buildings reach the energy peak late in the evening, when the absorbed heat during the daytime is released to the built environment. This situation is particularly critical in the mild Mediterranean climates. Minimising such gains has two positive influence for the building:

- Reduce the energy demand and peaks in cooled dwellings.
- Reduce the numbers of thermal discomfort hours in not cooled buildings

Cool materials also improve the quality of outdoor urban spaces, more and more affected by the phenomenon known as “heat island effect”. This phenomenon is the increase of air temperatures in cities respect to the surrounding countryside due to the high construction density, the limited green area, waste of public and private transport, waste of air conditioning systems and others cause

Monitoring campaigns found that the temperature of suburban areas can be 1-1.5 degrees higher respect to the country side, and the difference rises up to 4 degrees in city centres. Green area and high albedo of cities, using construction and road paving materials able to reflect the solar radiation, can improve the climate conditions in urban areas.

This first part of the paper deals with the optical characterisation of white and coloured paints to be used both, on the building roof and façades. Also the comparison of the colouration depth and the white colour base effect were investigated. The second part is dedicated to a detailed parametric analysis to assess how the solar behaviour of the opaque building envelope affect the energy performances and the thermal comfort levels in residential buildings scattered in the Mediterranean area.

2. Experimental

This section is dedicated to the optical characterisation of a cool material obtained by an natural organic based paint. The product used in this experimental campaign, produced by Laboratori Ecobios (www.ecobios-solaria.it), was selected because of its sustainability criteria. This is in fact a multi-mineral hydro-painting based on a mixture of milk and vinegar, obtained by Mediterranean grapes. Among the several uses it was produced for, the high solar reflectance and the possibility of being applied practically on almost all the construction (wood, concrete, plaster, metal, glass and so on) make this product suitable for the experiment.

The high solar reflectance of the white coatings in the near infrared range was tested in previous analyses [7]. Two more objectives were fixed in this study.

The first objective was to assess the properties of the coloured coating using the milk and vinegar base. Several coloured samples were tested in this experimental campaign and the results are summarised in Table 1. Two colour depths were chosen for each pigment, indicated as light and dark in the table.

The next step was comparing to paints having the same chromatic appearance (same specific percentage of coloured pigments) but different basic compositions: the ecological and a conventional white base were respectively used. The aim was to check the improvement achievable using a coating with high reflectance in the near infrared respect to usual paints

Photometric measurements were carried to investigate the reflectance properties of the selected samples.

2.1 Measurement of the solar reflectance

The main parameter to characterise construction materials under the solar radiation is the solar reflectance ρe. The optical measurements were performed by means of an automatic registration double ray spectrophotometer Perkin Elmer Lambda 9. The instrument covers the UV, visible and near infrared range using an integer time of 0.56 seconds (corresponding to a scan speed of 100 nanometres per minute). The resolution step was 1 nm in the UV, visible and near infrared range. Being the sample diffusing, the spectrophotometer is equipped with a small integrating sphere.

The global reflectance curves (direct + diffuse) were corrected using a white diffusing ceramic reference standard.

The spectral reflectance of the sample is obtained applying the following equation:

Error!

where:

λ wavelength

ρx,ass() absolute reflectance of the sample

ρx,mis() measured reflectance of the sample

ρstd,mis) measured reflectance of the standard

ρstd,ass() absolute reflectance of the standard

2.2 Results of the coloured samples

Table 1 summarises the solar reflectance of the selected samples and the results are interesting. According to the table, it can be inferred that a reflectance higher than 80% was measured for three samples (white, yellow and green). The rose sample showed a solar reflectance higher than 75% and only the grey showed a lower value (62%), even if more than acceptable for façade applications.

Good results were obtained for the deep coloured samples too. The dark grey is slightly higher than 50%, the other samples s have solar reflectances values between 71 and 77%. The relative decrease respect to the light colours is between 4 and 12%, except the for grey sample, where the measured difference reaches 18%.

The spectral curves for the two colouration levels are in figure 1 and 2 for the light and dark colours respectively.

Table 1: Solar reflectance of the selected samples

Sample	**Light** ρ_e**(%)**	**Dark** ρ_e**(%)**
White	85.9	
Red	75.2	69.4
Yellow	80.6	77.7
Rose	69.3	61.7
Green	82.6	76.4
Grey	62.0	51.8

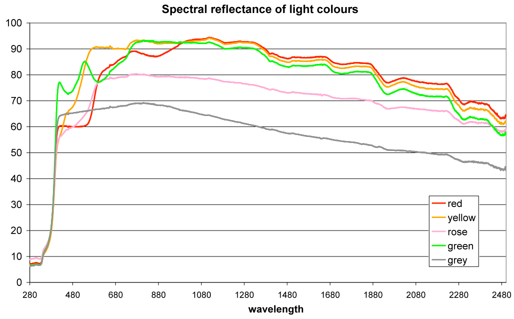

Fig 2. Solar reflectance of the light coloured samples

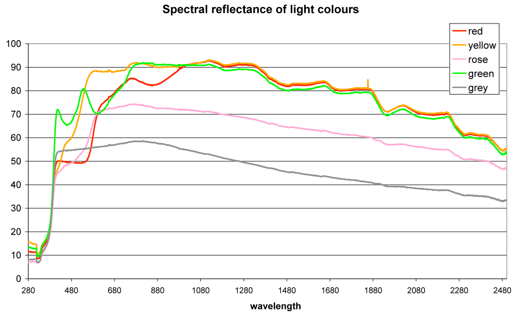

Fig 3. Solar reflectance of the dark coloured samples

Table 2 shows the comparison of green and red paints obtained using the milk/vinegar and a conventional base respectively. No special attention was paid on the colouration depth, since only the different behaviour was aimed to. The spectral comparison is presented in figure 3.

This analysis did not lead to the expected results. The two coating curves have almost the same profile in the visible range, according to the same chromatic appearance. The ecological paint has better performances than the conventional one in the near infrared range, but these differences lead to relative improvements of 8.8 and 10% for the green and the red colours respectively.

The result is not encouraging compared versus other studies [8], where definitely better performances are obtained using same bases but cool coloured pigments instead of conventional ones.

Table 2: Solar reflectance of the coloured samples obtained with different white bases

Colour Base	Milk/vinegar ρ_e(%)	Conventional ρ_e(%)
Red	44.2	40.2
Green	55.9	51.4

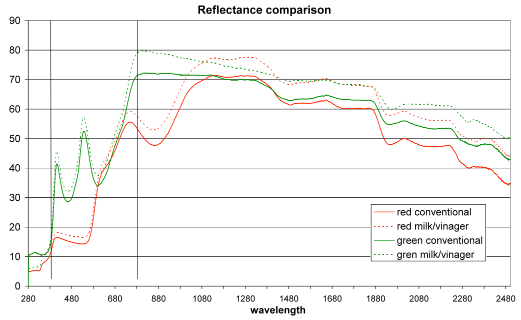

Fig 3. Solar reflectance of the green and red samples obtained by ecological and conventional paints

3. Parametric numerical analysis

Once evaluated the properties of white and coloured paintings, the second part of the research aimed at demonstrating the influence of such materials in reducing the energy consumption during the cooling season and during the whole year. Reducing solar gains implies both, the reduction of the cooling demand as well as the increase of the heating demand, because of the reduced solar gains through the building envelope. It is correct using the primary energy as indicator, in terms of annual energy balance, passing through the efficiency of the energy systems installed in the buildings.

The effect of such materials was considered in not cooled building too. Comfort temperature levels were calculated, in order to evaluate the number of discomfort hours in the reference building.

TRNSYS 16, a well known and tested dynamic simulation tool, was used to carry on this parametric study based on the definition of a reference residential building and on the following parameters:

- Location
- Solar reflectance of the roof
- Insulation level
- Orientation
- Thermal mass

3.1 Climatic zones

The study was addressed to the Mediterranean area, where the cooling energy consumption in the residential buildings is rapidly increasing and where the thermal comfort in the built environment is critical. The mix of air temperature and solar radiation suggests that coherent design and construction technologies might avoid the cooling system installation or, at least, reduce the number of working hours per year. Table 3 and 4 summarise the climatic data of the selected zone:

- Rome
- Palermo
- Seville
- Athens
- Tripoli

The first and last cities represent the cold and hot extreme of the Mediterranean zone where the cooling demand is more critical.

The weather data are the monthly integration of hourly data taken from Meteonorm, a global climatic database whose data are also used in TRNSYS.

Table 3: Monthly mean air temperature in the selected localities

	Tm [°C]				
	Rome	**Palermo**	**Athens**	**Seville**	**Tripoli**
Jan	8.0	12.8	9.2	10.6	12.1
Feb	8.8	13.0	9.7	11.9	13.2
Mar	10.8	13.8	11.8	14.0	15.4
Apr	13.2	15.5	15.3	15.7	18.3
May	17.3	18.7	22.2	19.6	22.3
Jun	21.0	22.4	24.3	23.1	25.8
Jul	24.1	25.6	27.0	26.8	27.1
Aug	23.9	26.2	26.7	27.0	27.9
Sep	20.6	23.9	23.0	24.1	25.8
Oct	19.6	22.9	21.7	22.8	24.9
Nov	12.1	16.3	14.2	14.1	17.4
Dec	9.3	14.1	11.2	11.1	13.3

Table 4: Monthly horizontal solar radiation in the selected localities

	Ho [MJ/m2]				
	Rome	**Palermo**	**Athens**	**Seville**	**Tripoli**
Jan	207	227	238	280	395
Feb	262	295	268	329	363
Mar	440	472	374	524	565
Apr	554	605	526	578	750
May	690	727	652	738	824
Jun	729	789	719	777	839
Jul	777	787	764	846	881
Aug	681	690	717	725	775
Sep	511	539	556	580	605
Oct	363	400	381	431	457
Nov	227	254	238	269	375
Dec	178	206	190	241	375

3.2 Reference building and variant solutions

The selected building is a one floor single family house, representing a significant portion of the building types present at Mediterranean latitudes. The layout of the building, whose net area is 108 square meters and net volume is 292 cube meters, is in figure 4. Two thermal zones were defined: night and day, respectively 63 and 45 square meters. The global external surface on global volume ratio is 0.98, while the roof accounts the 31% of the global external area of the building.

The night zone has a facade facing north and part of the east and west facades. The window distribution is practically homogeneous for the four façade, as it can be inferred from the picture.

The thermal properties of the building enveloper were defined according to the relevant national standards in the three European countries. Practical approach was followed to define the building characteristics in Tripoli. The windows were also defined according to standards, but inputted through glazing and frame properties, hence not reported in the text. Table 5 summarises the main envelope data.

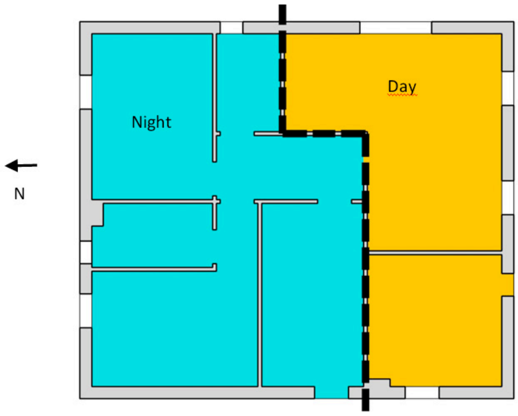

Fig 4. Layout of the reference building

Table 5: Main building envelope characteristics

Locality	wall	floor U [kw/m2°K]	roof
Rome	0.40	0.40	0.35
Palermo	0.54	0.54	0.42
Athens	0.70	1.00	0.50
Seville	0.82	0.52	0.45
Tripoli	1.00	1.00	0.80

Table 6: Main building operational data

Operational parameter	Set point	Unit
T set-point heat	20	°C
T set-point cool	26	°C
Power	unlimited	W
Heat efficiency primary	80	%
Cool efficiency primary	97	%
Shading winter	0	%
Shading summer	75 external	%
Ventilation winter	0.3	1/n
Ventilation summer	0.3 + 1 night	1/n

The thermal mass of the building was defined according to the technological solutions used in Italian construction.

Preliminary analyses were run to assess the final configuration in terms of natural ventilation and solar control strategies. The final configurations are defined in Table 6.

Temperature set points were 20 and 26°C for heating and cooling. The heating and cooling was considered continuous and the power unlimited. Once calculated the energy demand, the primary energy consumption was determined applying seasonal efficiencies to the energy systems. The operative parameters are summarised in Table 6.

The analysis was run according to the following envelope variation:

- Roof/façade solar reflectance: 02-04, 05-04, 08-04, 08-07.
- Thermal insulation: U (Table 5 values), U1 (20% less of the Table 5 value), U0 (no insulation).
- Frontal mass: 186, 296, 366 kg/m^2. This data affect the thermal capacity of the structure, small variation were obtained as a function of the climatic zone. The difference depends on the used brick type, respectively mixed hollow and massive, only hollow, only massive

3.3 Results: energy consumption

The first result to present is the influence of the building orientation. According to the building shape and windows distribution it was found that the orientation does not particularly affect the final energy demand. The test was run in Rome, where four different orientations were considered. Relative differences of the global energy demand as a function of the orientation were lower than 5% respect to the average value. This result was obtained for the four solar reflectance configurations, as defined in the previous paragraph.

Another set of simulation was run to assess the influence of the thermal mass on the energy balance of the building. The calculation was performed for Palermo. According to the envelope characteristics and the building use, the influence of the thermal mass is almost negligible. Maximum global energy savings are lower than 2% for the heavier structure and higher reflectance.

The parametric analysis is hence presented as a function of the locality, the insulation level (except Tripoli, where only an insulation level was defined) and the solar reflectance of the envelope. The selected orientation is the north/south reference and the thermal mass is186 kg/m^2.

The left column of Figure 6 shows the results obtained for the five localities. The histograms reports the specific primary energy consumption for space heating and cooling, expressed in kWh/m^2 per year, calculated for the three insulation levels and for the four solar reflectance configurations. The insulation configurations are different according to the country and this makes the comparison more complex.

The main outcome is the reduction of the primary energy consumption increasing the insulation level and the albedo of the envelope. Minor advantages come from the use of cool materials for wall, respect to the roof.

In poor insulated buildings, the heating consumption is predominant and reducing the solar absorption through the envelope leads to an increase of heating demand and primary energy consumption. This is critical in Rome, the coldest among the selected cities, where the primary energy raises by a factor three, when reducing the insulation levels.

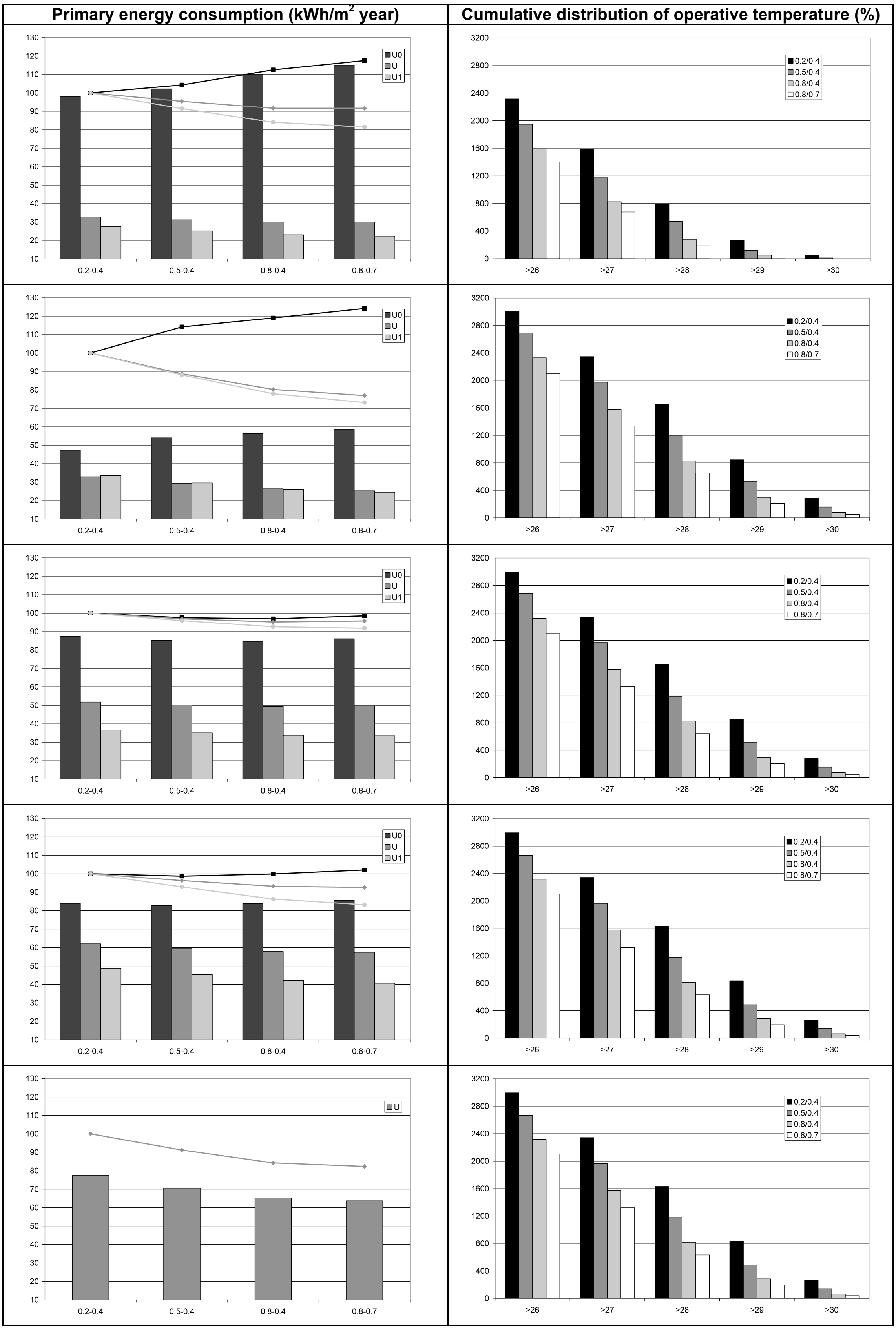

Fig 6. Left column: primary energy consumption in kW/m2 per year as a function of the city, solar reflectance of the envelope and thermal insulation, and relative energy reduction. Right column: cumulative distribution of the number of hours with average operative temperature higher than reference values in the built environment. Localities from above: Rome, Palermo, Athens, Seville, Tripoli

The other two configuration levels show the benefits of cool materials, since the influence of the cooling demand is as important the heating demand in acceptable insulated building. To be noted that the Italian standard are quite strict in terms of U-values, in fact the energy consumptions does not differ significantly between U0 and u1 configurations.

This implies that the percentage reduction can be very high in Italy, where values up to 25% can be reached. In fact once, the heating performance is optimised, the reduction of cooling demand is obtained using cool materials.

Seville and Athens have moderate performances, depending on the fact that poor insulation levels partially reduce the influence of the heating demand, and the balance between cold and hot season is not optimised.

Tripoli is the most extreme climate and even non insulated building benefits of cool materials.

3.4 Results: thermal comfort

The right column in figure 6 presents the cumulative distribution of the number of hours, when the operative temperature is higher of assigned reference values. The temperature is the average of the values calculated in the two thermal zones, the building is divided in. This analysis refers to not cooled dwellings, the energy behaviour in the winter season is not considered, since the aim of the study was the improvement of thermal comfort in the cooling season.

High temperatures are reached at each latitude, but cool materials are very effective. The numbers of hours with operative temperature higher than 27°C decrease by 50% in Rome and Tripoli when switching from the most absorbing configuration to the most reflective. In Palermo, Athens and Seville this percentage decrease to 35%. The peaks are reduced in all the cases. Few hours with temperature higher than 30°C are calculated in Palermo, Athens and Seville, and none in Rome.

To be noted that the influence of the vertical walls is not negligible when evaluating the performance of cool materials in terms of thermal comfort. The number of hours with temperatures higher than 29°C is reduced by one third, when high albedo walls are used in combination with cool roofs.

4. Conclusion

This paper presented part of a larger study aimed at evaluating the solar properties of ecological cool coatings and the benefit achievable for building applications.

The tested material showed good performances across the whole solar spectrum. The white paint base, on the contrary, does not significantly improve the solar behaviour of coloured pigments respect to conventional coatings.

The calculation analysis showed the influence of cool materials on the energy performance of residential buildings. Benefits are achievable in all the selected zones, especially in Italy where higher insulation levels coupled with solar control lead to strong energy reductions.

The operative temperature profiles receive significant advantages from the application of cool materials on the roof, as well as on the façade, with consequent improvement of thermal conditions inside the built environment.

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