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Józsefné Mara , Attila-Ede Bodnár , László Trif , Judit Telegdi *

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Article

Infrared Reflective Coatings

Józsefné Mara [1], Attila-Ede Bodnár [1], László Trif [2] and Judit Telegdi [1,2,3,*]

[1] EGROKORR LTD, Fehérvári út 63-65. 2030 Érd, Hungary; maram@egrokorr.hu; bodnara@egrokorr.hu
[2] Research Centre for Natural Sciences, Magyar tudósok körútja 2, 1117 Budapest, Hungary; trif.laszlo@ttk.hu
[3] Óbuda University, Faculty of Light Industry and Environmental Engineering, Doberdó u. 6, 1034 Budapest, Hungary
* Correspondence: telegdi.judit@ttk.hu

Featured Application: This infrared reflective coatings could be used on top of vehicles and cool roofs in order to save energy.

Abstract: The adsorption of surfaces exposed to sunlight results in increased temperature that can cause physical damage and increase in energy consumption. The infrared reflective coatings that keep objects cooler have significant benefits in a wide variety of application by reflecting the infrared lights, reducing the operating costs, improving energy efficiency of buildings and vehicles (roofs, walls and windows), extend the objects' lifespan. Our research focused on the elaboration of coatings with minimum adsorption in the infrared wavelength range. This was achieved by production of coatings that have infrared transparent and infrared reflective ability. The infrared reflection and surface warm up was investigated in the function of concentration and composition of pigments in the coatings. With investigation of different coating compositions the pigments and the binding systems were optimized. The coatings with different compositions were characterized by total solar reflection in the UV, visible and infrared wavelength range as well as by infrared reflection. Different coatings were produced in RAL7016 anthracite green color but with much better infrared reflectance, transparency as well as with heat reflectance.

Keywords: infrared reflection; infrared reflective pigments and coatings; total solar reflection; infrared solar reflection; refractive index; chromatic properties; heat reflection

1. Introduction

In case of surfaces exposed to sunlight the solar energy can be transmitted, reflected and absorbed. At absorption the photon energy is converted into thermal energy. More absorbed solar energy needs more cooling in the interior. Solar irradiation contains three regions: ultraviolet (280-400 nm, only 5% of the sun energy), visible (400-700 nm, 43% of the sun energy) and near infrared region (700-2500 nm, 52% of the sun energy) [1]. The near infrared light plays important role in the heat generation [2].

Sunlight, which is not reflected, is absorbed by objects (buildings, cars, solar panels, textiles, etc) and heats it. The heating, ventilation and air conditioning [3] consume about 40% of building energy [4].

After long stay in sun the heated objects could be physically damaged and can lose their strength. This is the problem of the dark-colored objects as they are too hot and are not only untouchable but could be deteriorated, too.

The energy consumption could be diminished by air conditioning as well as by use of special coatings with infrared reflecting pigments that are able to reflect the radiation in the near-infrared spectrum. When the solar reflectance increases, the surface temperature diminishes; the solar radiation is rather reflected than absorbed. The consequence in an object is a more comfortable thermal condition without air conditioning [5,6].

When we want to compare the importance of infrared reflective coatings with the traditional coatings, the first we have to emphasize is that the traditional ones (paints, varnishes) are mainly

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used to increase the aesthetic properties and it is not important whether they have infrared reflective characteristics or not. On the contrary, coatings with infrared reflective property are used because of their ability to reflect the infrared light, to reduce the heat absorption and increasing the energy efficiency. Of course, the aesthetic appearance is also important.

Most of the infrared reflective coatings can reduce the cooling loads in buildings and improve the indoor comfort. Ideal durable infrared reflective coatings with high reflectivity in infrared band are used as cool roof coatings of high total reflectance, taking into account the total solar reflectance of low and high slope roofs. In order to choose the best combination of substrate and application parameters it needs careful analysis of the requirements. The problem is that only after long, systematic screening (research on the refractive index, transparency, electric resistance, thermal conductivity, etc.) is possible to state that this or that pigment has good effective infrared reflectivity or not.

The use of color pigments goes back to the antiquity; they formed the basic part of all paints, decoration [7-9]. The pigments should be stable and chemically inert in order to withstand to aggressive environment and be able to retain their color.

Generally the inorganic pigments are small particles that are insoluble in solvents and binders [10].

In summary: the benefits to use infrared reflecting coatings are the follows: longer life cycle; less degradation due to the lower temperature; less heat transfer into the objects; decreased energy demand for air conditioning; cooler touch of the objects.

A lot of color pigments (e.g. white, blue, yellow, that are responsible to give color to objects because they partly selectively absorb the visible light and reflect the others corresponding to their colors) are good in near infrared reflection. The black pigments absorb and store heat not only in the visible but also in the near infrared light, too [11].

The mostly used infrared reflecting coatings are the follows:

Metals: gold, silver, aluminum, aluminum foil, metallized thin films;

Metal oxides: TiO_2, ZnO, CuO; [12,13];

Infrared inorganic pigments [14];

Infrared reflecting organic pigments and fillers

Black pigments (perylene black that does not absorb in near infrared wave range)

Composites: oxide-metal-oxides: TiO_2/Ag/TiO_2, ZnS/Ag/ZnS (nanomesh patterned [15];

Single layer and stacked polar dielectrics: SiC, GaN [16];

Single and multilayered Ag-doped hafnium nitride;

Small spheres of glass, glitter, crystals [12,17,18].

The coatings of metals (silver, aluminum, gold) are very useful because of their high reflectivity in the infrared region; they are mainly used for windows. Metal oxides (TiO_2, ZnO) act in very thin polymer films blended with other materials; the use of pigments and metals of different types in alternative layers are important as one of them has high, the others low reflectivity in the infrared region. The application decides the choice of materials. The compatibility and durability are important factors in selection of materials [19].

Some literatures that discussed the above mentioned infrared reflective pigments are the follows:

The TiO_2 (rutile, anatase) is mainly applied in white pigments [20,21].

In some cases the TiO_2 was applied together with other pigments that could enhance the infrared reflective efficacy [22,23].

The usefulness and effectiveness of zinc oxide [24], the importance of the bismuth vanadate [25], bismuth titanate [26,27], as well as of the rare earths [28,29] were also demonstrated. It is important to mention a very useful review on optical properties of near infrared reflective inorganic pigments of Jose et al., publishes in 2019 [7]. In another publication Levinson et al. described and grouped (according to their color) the most important pigments active in the near infrared light region [30].

Though the organic pigments are brighter and more transparent than inorganic ones, their light resistance is much less, they could be solved and migrate in thermoplastics.

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In order to compare the usefulness of the infrared reflective coatings with other coating resolutions that also can reduce heat absorption and improve the energy efficiency, we have to mention other possibilities like:

1. Low-emissivity coatings: they can reflect and absorb infrared and block UV radiation. They effectively control the heat exchange between the interior and exterior of buildings; but the infrared reflective coatings reduce the heat absorption.
2. Thermochromic coatings: they change their color and/or their opacity due to the altered temperature; on this way they control the amount of heat that enters buildings. But, as mentioned in the previous case, the infrared reflective coatings reduce the heat absorption significantly.
3. Phase-change materials: when they turn into liquid or into solid, they absorb or release heat. This phase-change allows to regulate the temperature and to reduce the energy consumption in a building. Though the final impact of the effect of this material and the infrared reflective coatings are similar, the mechanisms they act and where they could be used are different. The application of the infrared reflective coatings is more extensive.

Some words about the factors that affect the infrared reflectivity: after a systematic screening it is necessary to find the best pigment with high reflectivity in the near infrared region; the pigments should be compatible with any other ingredients; it is necessary to hark to the combination of different pigments; the infrared reflective pigments could have visible opacity; the particle size of the pigments has important impact on the refractive activity (reflecting in the infrared light region: the size of the particles should be more than half of the wave length of the reflected light, i.e. they must be in the range of 0.35 and 0.55 μm).

Factors that determine which infrared reflecting pigment will be applied are the follows: cost, compatibility, performance, aesthetics as well as the environmental impact and the energy efficiency.

The infrared reflective pigment could have the following arrangements:

1. one-layer system: the coating is applied directly onto the solid substrate that contributes to the increase of the refractivity of the coating;
2. two-layer system: this is commonly used technique; the solid substrate is first covered by a primer and then comes the second layer, the top coat, which contains the proper pigment. This upper layer gets in touch directly with the sun radiation;
3. multilayer structure: multiple layers with different refractive properties are deposited onto each other. The interference effect between the layers increases the reflective property. Important is to take into consideration not only the chemical properties but also the thickness of each layer.

The lifespan of infrared reflective coating depends on different factors like UV radiation, surface preparation, moisture, chemical resistance, etc. The proper selection of pigments and ingredients can enhance the lifespan of the coated surfaces and decrease the energy consumption.

High reflectivity, optical clarity, durability, adhesion and ease of application can characterize a high quality infrared reflective coating.

In the present work cost effective coatings with high infrared reflection and transparency and good UV resistance were elaborated in RAL7016 color. This color is often selected to the top of vehicles that are under the influence of sun and the energy used for air condition inside the vehicles increases significantly. In order to demonstrate that not only the white color but other colors, too, can reflect sunlight, seven colored coatings were formulated in RAL7016 color. Previously the pigments used in these experiments were systematically investigated from the point of view of infrared reflection, transmission, chemical composition and concentration as well as of film thickness. The traditional pigments were replaced by other ones that have similar color but much higher infrared reflection. After selection of proper ingredients, the pigments were applied in water-based coatings developed on two primers. The influence of the pigments and other components in the coatings were characterized and compared in order to select the most effective infrared reflecting ones. We had to carefully control each steps to achieve the desired level of coating performance.

2. Materials and Methods

2.1. Composition of the Paints

In all these compositions the applied pigments produced the anthracite grey color of RAL7016. These pigments were either inorganic or organic ones and in some cases composition of two pigments. In all cases they were mixed with TiO_2 to produce the anthracite grey color.

The surface coatings with pigments were produced on primers (white or black). The top coatings made of Metallux Aqua 2k (which is a two-component, water soluble polyurethane system with high UV- and chemical resistance and excellent mechanical properties) combined with different pigments, fillers and binders. TiO_2 helped to produce the proper grey color.

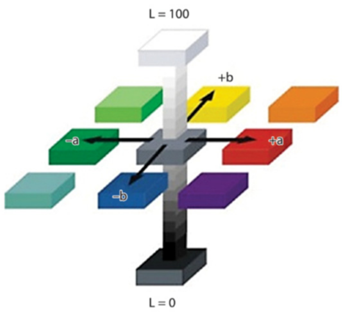
Coating samples under investigation:
Metallux Aqua 2k SZ RAL7016 L95/CR28 (L95/CR28): infrared reflective, covering inorganic black pigment;
Metallux Aqua 2k SZ RAL7016 S84/CR28 (S84/CR28): infrared transparent black pigment;
Metallux Aqua 2k SZ RAL7016 S84/CR28lcquer (S84/CR28/Lacquer): infrared transparent black pigment at optimal concentration;
Metallux Aqua 2k SZ RAL7016 TR RU/ZD (TR RU/ZD): infrared transparent, two-component pigment;
Metallux Aqua 2k SZ RAL7016 PS/ZD (PS/ZD): another infrared transparent, two-component pigment;
Metallux Aqua 2k SZ RAL7016 S84/A80 (S84/A80): infrared transparent organic pigment as well as infrared transparent filler;
Metallux Aqua 2k SZ RAL7016 (Traditional): traditional, not infrared reflective pigment.

2.2. Characterization of coatings with infrared transparent pigments

Refractive index: this is an important parameter of pigments. It measures the reflectivity of coatings either at a given wavelength or in a range of the wavelength. The reflection of all coated samples was measured in the 335 and 2500 nm wavelength range (Surface Optics SOC410). The total solar reflection (TSR) and the infrared solar reflection (IR-SR: 700-2500 nm) vales are summarized in tables and demonstrated in figures.

***Characterization of chromatic properties*:** To the chromatic characterization of all coatings RAL7016 color card was used. The brightness was measured by Konica Minolta CM-25cG instrument.

The colors of samples were determined according to the CIE (Commision Intenationale de l'Eclairage) [31].



Colorimetric coordinates, CIE color system L*, a*, b*.

L*: it represents the differences between the light (100%) and the dark (0%)

a*: it displays the difference between red (+a*) and green (-a*)

b*: it corresponds to the difference between yellow (+b*) and blue (-b*)

The color differences (ΔE*) between two color point are calculated according to the distance between their location in the three-dimensional space [32].

Measured ΔE* $_{a,b}$	Visual observation
ΔE*< 1.5	not observable
1.5 < ΔE* < 3	observable
3 < ΔE* < 6	well observable
6 < ΔE*	significant

Heat camera: this instrument can evaluate the temperature and show the change in temperatures caused by the infrared reflection coatings. It can display the thermal image over and under the coated surfaces and it compares the measured values to the ambient temperature. The instrument type is: GUIDE PS610.

3. Results and Discussion

3.1. Chromatic Parameters.

Before evaluation of the colorimetric and brightness data summarized in Table 1 please, remember that the L^*, a^* and the b^* values are used to identify colors.

Table 1. The colorimetric and brightness values measured on coatings applied on two different substrates (i.e. on the top of white and black primers).

Name of the coating	substrate	ΔE*	Δa*	Δb*	ΔL*	brightness %
Traditional	white	0,560	0,440	0,270	-0,230	84,990
	black	0,500	0,400	0,290	-0,080	84,750
L95/CR28	white	1,300	1,050	0,020	-0,760	84,750
	black	1,420	1,100	0,020	-0,900	84,090
S84/CR28	white	0,750	-0,340	-0,350	-0,570	49,810
	black	0,880	-0,410	-0,360	-0,690	67,760
TR RU/ZD	white	1,580	-1,260	0,110	0,940	88,190
	black	1,320	-1,180	0,070	0,590	89,960
S84/CR28/Lacquer	white	1,940	0,000	0,290	-1,920	89,270
	black	2,010	-0,270	0,210	-1,980	89,230
PS/ZD	white	2,150	-0,180	-1,990	-0,810	89,520
	black	2,110	-0,160	-1,980	-0,700	88,450
S84/A80	white	2,530	-0,410	-0,390	-2,470	89,210
	black	2,660	-0,480	-0,370	-2,590	89,350

The chromatic parameters listed in Table 1 show clearly that there are not significant differences between the color and brightness values weather the coating was applied on white or black substrates. The aim to investigate the coatings on white and black background was first to prove that on both, significantly different colors these coatings can cover properly the substrate; there are not significant differences in colors. On the other hand, with the investigation of black and white background beneath the coatings we wanted to see which composition is the best or worst. The behavior of coatings (primer plus enamel) in the 335 and 2500 nm spectrum range are demonstrated in Table 2 and in Figures 1 and 2. By using black background we wanted to demonstrate the influence of a primer with very infrared absorptive (low total solar reflectance) characteristic, on the other hand, the white primer has a good infrared reflective (high total solar reflective) characteristic i.e. in this case the solid warms up much less than in case of the black primer.

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Table 2. Reflection behavior of coatings deposited either on white or on black background, measured in large wavelength range (UV: 335-380 nm; visible: 400-720 nm; near infrared: 700-2500 nm).

Name of the coating	substrate	Reflection values measured at different wavelength [nm]						
		335-380	400-540	480-600	590-720	700-1100	1000-1700	1700-2500
		1	2	3	4	5	6	7
Traditional	white	0,061	0,085	0,082	0,075	0,067	0,062	0,062
	black	0,059	0,085	0,082	0,075	0,067	0,063	0,062
L95/CR28	white	0,063	0,119	0,097	0,099	0,283	0,730	0,635
	black	0,063	0,115	0,095	0,097	0,258	0,438	0,324
S84/CR28	white	0,067	0,2	0,137	0,175	0,810	0,813	0,564
	black	0,066	0,147	0,113	0,142	0,489	0,331	0,136
TR RU/ZD	white	0,058	0,170	0,122	0,113	0,544	0,795	0,589
	black	0,060	0,147	0,111	0,103	0,401	0,395	0,169
S84/CR28/LAKK	white	0,070	0,192	0,134	0,180	0,809	0,795	0,553
	black	0,068	0,119	0,100	0,124	0,334	0,197	0,085
PS/ZD	white	0,064	0,167	0,118	0,104	0,533	0,790	0,586
	black	0,060	0,134	0,103	0,090	0,318	0,281	0,112
S84/A80	white	0,057	0,184	0,125	0,135	0,723	0,788	0,602
	black	0,056	0,120	0,096	0,100	0,332	0,311	0,223

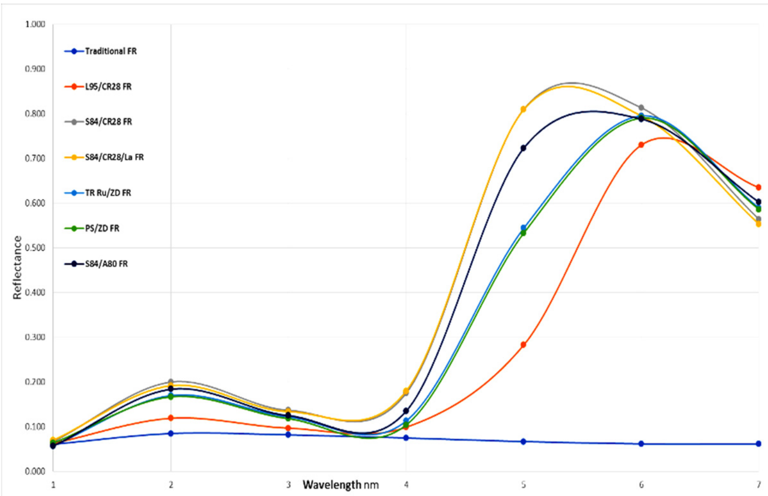

Figure 1. Reflection behavior of different coatings deposited on white background.

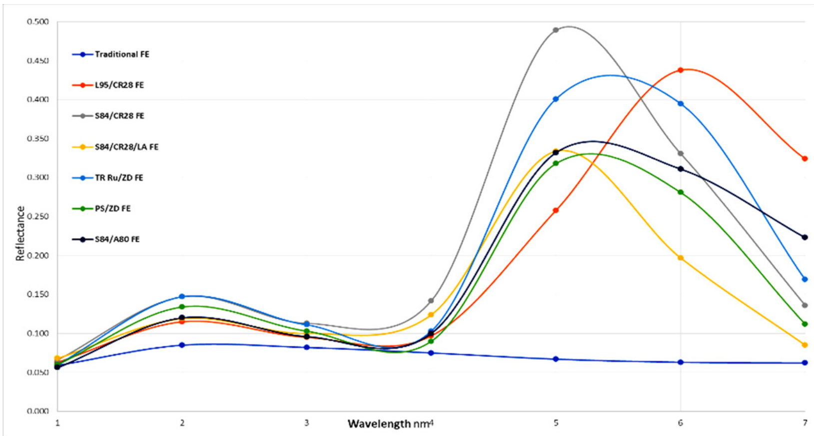

Figure 2. Reflection behavior of different coatings developed on black background.

3.2. Reflection Behavior of the Coatings.

The Figure 1 demonstrates the influence of different coatings developed on white substrate on the reflection.

Figure 1. clearly demonstrates that the traditional coating with traditionally used pigment, is the worst. The best results were got by the coatings named S84/CR28 and the S84/CR28/Lacquer. Similarly good result was obtained in the presence of S84/A80 coating. With other words, the best results were provided by the coatings with infrared transparent pigments. Those coatings that were formulated by top infrared reflective pigments are less acceptable.

As the results summarized in Figure 2 prove, those coatings developed on black background show the best results that contain infrared transparent pigments. These were followed by coatings that contained top infrared pigments. The worst result was measured on the coating with traditional pigment.

On the basis of results measured on white and black background it is clear that compositions on white primer show always higher reflectance than on black. The only exceptions are coatings with traditional pigments when there is not any difference caused by the different color of the primers. In order to get a coating with desired total infrared reflective ability the use of white primer with high total reflectance pigment is advisable.

3.3. Total Solar Reflectance And Infrared Solar Reflectance Parameters

Other parameters i.e. the total solar reflectance and the infrared solar reflectance involved in the same diagram (Figure 3) allow a better comparison of the usefulness of coatings. In the case of the developed coatings with RAL7016 grey color there are significant differences between the infrared solar reflectance and the total solar reflectance (Figure 3).

According to measured values as Figure 3 show the worst results were got with coating built of traditional pigments. Those coatings that contained covering infrared reflective pigments showed better results. The best examples are those that were built of infrared transparent pigments represented by the L95/CR28, S84/A80, S84/CR28 and S84/CR28/lacquer compositions. Data involved into Figure 3 show that the white primer is beneficial when a coating with high total solar reflection is required. In all cases the infrared solar reflection values are higher than the total solar reflection ones. It means that the coatings under investigation in the wavelength range of 700 and 2500 nm show better reflection than in the full spectrum (330-2500 nm) that contains the absorption in the UV and visible lights.

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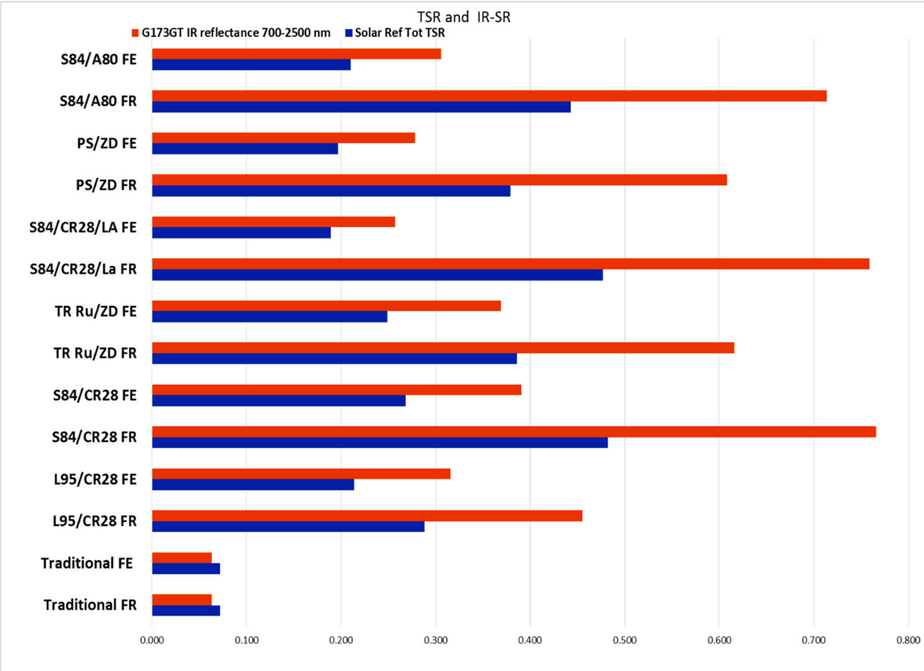

Figure 3. Diagram summarizing the total solar reflectance and the infrared solar reflectance values measured on the developed coatings (FE: black; FR: white).

To demonstrate more clearly the differences between the total solar reflection and infrared solar reflection values, data are summarized in the Table 3.

Table 3. The TSR and IR-SR values measured on different coatings.

Name of the coating	substrate	TSR %	IR-SR %
traditional	white	7.2	6.3
	black	7.2	6.3
L95/CR28	white	28.8	45.5
	black	21.4	31.6
S84/CR28	white	48.2	76.6
	black	26.8	39.1
TR RU/ZD	white	38.6	61.6
	black	24.9	36.9
S84/CR28/Lacquer	white	47.7	75.9
	black	18.9	25.7
PS/ZD	white	37.9	60.8
	black	19.7	27.8
S84/A80	white	44.3	71.4
	black	21.0	30.6

As all coatings had anthracite grey color (RAL7016) there are not allowed to be differences in the visible wave length but in the infrared range. High reflection value (near to 100) means significant light reflection, which means that the surface does not really absorb the infrared light and that's why it is much less warm. We could reach this aim with coatings of S84/CR28 (TSR: 48.2%; IR-SR: 76.6%) and of S84/CR28/lacquer on white primer (TSR: 47.7%; IR-SR: 75.9%); on the other hand these coatings

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on black primer less effective. The worst results were observed on the traditional coatings (TSR: 7.3%, IR-SR: 6.3%).

3.4. Evaluation of Heat Reflection

In order to demonstrate the influence of coatings on temperature, these samples were placed on racks outside and exposed to sun. The coated panels' temperatures were measured by heat camera and the measured values were analyzed by the instrument' software (Table 4).

Table 4. Temperature measured by heat camera on the coatings under investigation.

Name of the coating	substrate	Temperature [°C]		
		min	max	average
Traditional	white	64,5	61,7	60,0
	black	64,2	52,4	60,4
L95/CR28	white	59,3	48,6	54,5
	black	61,5	51,6	57,1
S84/CR28	white	52,2	44,3	**48,5**
	black	59,6	50,9	55,5
TR RU/ZD	white	57,4	48,0	53,2
	black	61,4	51,7	57,3
S84/CR28/lacquer	white	54,2	45,2	**49,8**
	black	61,7	52,4	58,3
PS/ZD	white	55,5	47,2	53,0
	black	61,0	51,7	57,6
S84/A80	white	52,3	46,2	**49,8**
	black	59,4	51,4	56,0

Values involved into Table 4 allow the comparison of the effectiveness of coatings from the point of view of efficiency in the heat reflection. As the blue-marked numbers show, coatings **S84/CR28, S84/CR/Lacquer** and **S84/A80** developed on white primer resulted in the best heat reflective character**.** Comparing the temperature values with that one measured on traditional coating, the highest difference achieved was **11.5 °C**, which is a significant difference! Those temperature differences measured on the good samples (1.3 °C) are in the range of the accuracy of the measurement, with other word their effectiveness as infrared reflective coatings are similar.

4. Conclusions

The worst infrared reflection was measured on the traditional coating, the best one on coating with infrared transparent pigment.

If high reflection and total solar reflection is waited from the coating the white primer is the good resolution. On black primer those coatings are the most effective that contain infrared transparent pigment. The traditional coating is the worst on both primers.

Important observation is that all coatings under investigation (except the traditional one) proved to be more effective in the infrared solar reflection than in total solar reflection. The best example is the S84/CR28 lacquer coatings with TSR 48.2% and IR-SR 75.9%.

The best infrared reflective results were got in the case of the S84/CR28 and the S84/CR28 lacquer coatings that differ in the organic black pigment concentration (the S84/CR28 lacquer contains much less pigment).

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The reflective characters of the S84/A80 coating that contains a special infrared transparent binder are similar to the S84/CR/lacquer and, but the production procedure is much more difficult and the cost of the paint is not competitive with the other ones.

Summarizing results demonstrated before the most promising coatings are the S84/CR28 and the S84/CR28/lacquer as in case of its application about 11 ^{o}C reductions in the surface temperature could be achieve. It is important to emphasize that even 1 ^{o}C decrease can save 2% in energy (e.g. in air conditioning, cooling).

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References

1. Liu, L.; Han, A.; Ye, M.; Feng, W. The Evaluation of Thermal Performance of Cool Coatings Colored with High Near-Infrared Reflective Nano-Brown Inorganic Pigments: Magnesium Doped $ZnFe_2O_4$ Compounds. *Sol. Energy* **2015**, *113*, 48–56. https://doi.org/10.1016/j.solener.2014.12.034.
2. Kaur, B.; Quazi, N.; Ivanov, I.; Bhattacharya, S. N. Near-Infrared Reflective Properties of Perylene Derivatives. *Dyes Pigments* **2012**, *92* (3), 1108–1113. https://doi.org/10.1016/j.dyepig.2011.06.011.
3. Kolås, T.; Røyset, A.; Grandcolas, M.; Cate, M. Ten; Lacau, A. Cool Coatings with High near Infrared Transmittance for Coil Coated Aluminium. *Sol. Energy Mater. Sol. Cells* **2019**, *196*, 94–104. https://doi.org/10.1016/j.solmat.2019.03.021.
4. Jazaeri, J.; Gordon, R. L.; Alpcan, T. Influence of Building Envelopes, Climates, and Occupancy Patterns on Residential HVAC Demand. *J. Build. Eng.* **2019**, *22*, 33–47. https://doi.org/10.1016/j.jobe.2018.11.011.
5. Levinson, R.; Akbari, H.; Berdahl, P. Measuring Solar Reflectance—Part I: Defining a Metric That Accurately Predicts Solar Heat Gain. *Sol. Energy - Sol. ENERG* **2010**, *84*, 1717–1744. https://doi.org/10.1016/j.solener.2010.04.018.
6. Zinzi, M.; Carnielo, E.; Agnoli, S. Characterization and Assessment of Cool Coloured Solar Protection Devices for Mediterranean Residential Buildings Application. *Energy Build.* **2012**, *50*, 111–119. https://doi.org/10.1016/j.enbuild.2012.03.031.
7. Jose, S.; Joshy, D.; Narendranath, S. B.; Periyat, P. Recent Advances in Infrared Reflective Inorganic Pigments. *Sol. Energy Mater. Sol. Cells* **2019**, *194*, 7–27. https://doi.org/10.1016/j.solmat.2019.01.037.
8. *The Pigment Compendium: A Dictionary of Historical Pigments*; Eastaugh, N., Ed.; Elsevier Butterworth-Heinemann: Amsterdam ; Boston, 2004.
9. Orna, M. Historic Mineral Pigments: Colorful Benchmarks of Ancient Civilizations; 2015; pp 17–69. https://doi.org/10.1021/bk-2015-1211.ch002.
10. Hund, F. Inorganic Pigments: Bases for Colored, Uncolored, and Transparent Products. *Angew. Chem. Int. Ed. Engl.* **1981**, *20* (9), 723–730. https://doi.org/10.1002/anie.198107231.
11. Levinson, R.; Berdahl, P.; Akbari, H.; Miller, W.; Joedicke, I.; Reilly, J.; Suzuki, Y.; Vondran, M. Methods of Creating Solar-Reflective Nonwhite Surfaces and Their Application to Residential Roofing Materials. *Sol. Energy Mater. Sol. Cells* **2007**, *91* (4), 304–314. https://doi.org/10.1016/j.solmat.2006.06.062.
12. Lu, D.; Gao, Q.; Wu, X.; Fan, Y. ZnO Nanostructures Decorated Hollow Glass Microspheres as near Infrared Reflective Pigment. *Ceram. Int.* **2017**, *43*. https://doi.org/10.1016/j.ceramint.2017.04.067.
13. You, Z.; Zhang, M.; Wang, J.; Pei, W.; Li, G. Experimental Study of Optical and Cooling Performances of CuO and TiO2 Near-Infrared Reflective Blending Coatings. *Sol. Energy* **2021**, *225*, 19–32. https://doi.org/10.1016/j.solener.2021.06.061.
14. Bendiganavale, A.; Malshe, V. Infrared Reflective Inorganic Pigments. *Recent Pat. Chem. Eng.* **2010**, *1*. https://doi.org/10.2174/1874478810801010067.
15. Woo, H. K.; Zhou, K.; Kim, S.-K.; Manjarrez, A.; Hoque, M. J.; Seong, T.-Y.; Cai, L. Visibly Transparent and Infrared Reflective Coatings for Personal Thermal Management and Thermal Camouflage. *Adv. Funct. Mater.* **2022**, *32* (38), 2201432. https://doi.org/10.1002/adfm.202201432.
16. Hou, C.-C.; Chen, H.-M.; Zhang, J.-C.; Zhuo, N.; Huang, Y.-Q.; Hogg, R. A.; Childs, D. T.; Ning, J.-Q.; Wang, Z.-G.; Liu, F.-Q.; Zhang, Z.-Y. Near-Infrared and Mid-Infrared Semiconductor Broadband Light Emitters. *Light Sci. Appl.* **2018**, *7*, 17170. https://doi.org/10.1038/lsa.2017.170.
17. Shi, Y.; Zhong, M.; Zhang, Z.; Wang, D. Crystal Structure and Near-Infrared Reflective Properties of Fe3+ Doped AlPO4 Pigments. *Ceram. Int.* **2017**, *43* (8), 5979–5983. https://doi.org/10.1016/j.ceramint.2017.01.131.
18. Gao, Q.; Wu, X.; Fan, Y.; Meng, Q. Novel near Infrared Reflective Pigments Based on Hollow Glass Microsphere/BiOCl1-xIx Composites: Optical Property and Superhydrophobicity. *Sol. Energy Mater. Sol. Cells* **2018**, *180* (Complete), 138–147. https://doi.org/10.1016/j.solmat.2018.02.033.
19. Rosati, A.; Fedel, M.; Rossi, S. NIR Reflective Pigments for Cool Roof Applications: A Comprehensive Review. *J. Clean. Prod.* **2021**, *313*, 127826. https://doi.org/10.1016/j.jclepro.2021.127826.

20. Mastai, Y.; Diamant, Y.; Aruna, S.; Zaban, A. TiO2 Nanocrystalline Pigmented Polyethylene Foils for Radiative Cooling Applications: Synthesis and Characterization. *Langmuir* **2001**, *17* (22), 7118–7123. https://doi.org/10.1021/la010370g.
21. Wang, S.; Zhang, J. Effect of Titanium Dioxide (TiO2) on Largely Improving Solar Reflectance and Cooling Property of High Density Polyethylene (HDPE) by Influencing Its Crystallization Behavior. *J. Alloys Compd.* **2014**, *617*, 163–169. https://doi.org/10.1016/j.jallcom.2014.07.191.
22. Yuan, L.; Han, A.; Ye, M.; Chen, X.; Ding, C.; Yao, L. Synthesis and Characterization of Novel Nontoxic BiFe1−xAlxO3/Mica-Titania Pigments with High NIR Reflectance. *Ceram. Int.* **2017**, *43* (18), 16488–16494. https://doi.org/10.1016/j.ceramint.2017.09.032.
23. Zou, J.; Zheng, W. TiO2@CoTiO3 Complex Green Pigments with Low Cobalt Content and Tunable Color Properties. *Ceram. Int.* **2016**, *42* (7), 8198–8205. https://doi.org/10.1016/j.ceramint.2016.02.029.
24. Kiomarsipour, N.; Razavi, R.; Ghani, K.; Kioumarsipour, M. Evaluation of Shape and Size Effects on Optical Properties of ZnO Pigment. *Appl. Surf. Sci.* **2013**, *270*, 33–38. https://doi.org/10.1016/j.apsusc.2012.11.167.
25. Kumari, S.; Rao, P.; Narayana, A.; Radhakrishnan, P.; James, V.; S, S.; Koshy, P. Brilliant Yellow Color and Enhanced NIR Reflectance of Monoclinic BiVO4 through Distortion in VO43− Tetrahedra. *Sol. Energy Mater. Sol. Cells* **2013**, *112*. https://doi.org/10.1016/j.solmat.2013.01.022.
26. Xiao, J.; Pan, Z.; Zhang, T.; Lu, Y.; Wang, Y. Preparation of High Near-Infrared Reflectance Mica/(Ni, Sb)-Co-Doped Rutile Yellow Composite Pigment via Mechanochemical Pretreatment and Sintering. *Ceram. Int.* **2023**, *49* (4), 6015–6029. https://doi.org/10.1016/j.ceramint.2022.10.099.
27. Meenakshi, P.; Selvaraj, M. Bismuth Titanate as an Infrared Reflective Pigment for Cool Roof Coating. *Sol. Energy Mater. Sol. Cells* **2018**, *174*, 530–537. https://doi.org/10.1016/j.solmat.2017.09.048.
28. Radhika, S. P.; Sreeram, K. J.; Nair, B. U. Rare Earth Doped Cobalt Aluminate Blue as an Environmentally Benign Colorant. *J. Adv. Ceram.* **2012**, *1* (4), 301–309. https://doi.org/10.1007/s40145-012-0029-6.
29. Jose, S.; Jayaprakash, A.; Laha, S.; Natarajan, S.; Nishanth, K. G.; Reddy, M. L. P. YIn0.9Mn0.1O3–ZnO Nano-Pigment Exhibiting Intense Blue Color with Impressive Solar Reflectance. *Dyes Pigments* **2016**, *124*, 120–129. https://doi.org/10.1016/j.dyepig.2015.09.014.
30. Levinson, R.; Berdahl, P.; Akbari, H. Solar Spectral Optical Properties of Pigments—Part II: Survey of Common Colorants. *Sol. Energy Mater. Sol. Cells* **2005**, *89* (4), 351–389. https://doi.org/10.1016/j.solmat.2004.11.013.
31. Khan, M.; Ueno, K.; Horimoto, S.; Komai, F.; Someya, T.; Inoue, K.; Tanaka, K.; Ono, Y. CIELAB Color Variables as Indicators of Compost Stability. *Waste Manag.* **2009**, *29*, 2969–2975. https://doi.org/10.1016/j.wasman.2009.06.021.
32. García-Marino, M.; Escudero-Gilete, M. L.; Heredia, F. J.; Escribano, T.; Rivas-Gonzalo, J. Color-Copigmentation Study by Tristimulus Colorimetry (CIELAB) in Red Wines Obtained from Tempranillo and Graciano Varieties. *Food Res. Int.* **2013**, *51*, 123–131. https://doi.org/10.1016/j.foodres.2012.11.035.