CERAMIC TILE SOLAR REFLECTANCE INDEX. INFLUENCE OF SOME VARIABLES

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ABSTRACT

The "heat island effect" is the rise in temperature in urban areas, relative to the surrounding area, associated with human activity. To mitigate this effect, "cool materials" with high solar reflectance are being increasingly used. However, not only high solar reflectance, but also high emissivity is required to avoid heating a surface exposed to the surrounding environment. These two magnitudes are combined, together with environmental conditions such as air and sky temperature, wind speed, and maximum solar irradiation, in the solar reflectance index (SRI).

The SRI is a magnitude that is used to compare the thermal performance of roofs and floors regarding their ability to return incident radiation to the atmosphere. A material with a high SRI indicates a significant ability not to absorb radiation solar and, in façades and roofs, prevents building interiors from heating up. On the other hand, in countries where people tend to walk barefoot, a courtyard paved with materials having a high SRI lowers flooring temperature, facilitating walking without getting burnt.

In this study, the SRI of floor tiles with a white glaze was determined, and the influence of the composition, roughness, and microstructure on the SRI was studied. The conclusions enabled design of glazed tiles with a high SRI, adding value to typical white tiles.

1. INTRODUCTION

Solar absorption of radiation by roofs, walls, and floors in urban areas has led to the so-called heat island effect, materialising in a 4–6ºC temperature rise in cities, relative to temperatures of the surrounding areas[1]. To mitigate this effect, many construction materials have been designed to minimise absorption of solar radiation. Such "cool materials" exhibit high reflectance and high thermal emissivity, while maintaining the desired aesthetic specifications[2]. Solar reflectance expresses the ability of a surface to reflect incident solar radiation, while thermal emissivity expresses the ability to emit the heat absorbed by a surface[3].

To evaluate a material's thermal performance regarding solar irradiation, it is of interest to determine its solar reflectance index (SRI), as it is simple to calculate and includes both solar reflectance and thermal emissivity[4, 5]. The SRI is calculated from these values and considers environmental factors such as temperatures of the surrounding area, air and sky, wind speed, and solar irradiation[6]. The SRI is obtained from the following equation:

$$\mathrm{SRI} = 100 \cdot \frac{T_{sb} - T}{T_{sb} - T_{sw}}$$

where T (K) is the equilibrium temperature that the surface being studied would reach if the incident solar irradiation was 1000 W/m^2, air temperature T_{air} = 310 K, sky temperature T_{sky} = 300 K, for three values of the convection heat transfer coefficient: 5, 12, and 30 W/m^2·K, which correspond to three wind speeds: <2m/s, between 2 and 6 m/s, and between 6 and 10 m/s, respectively. T_{sb} and T_{sw} are the equilibrium temperatures that two reference surfaces with a thermal emissivity of 0.9 would reach: a white surface (*w*) with a solar reflectance of 0.80 and a black surface (*b*) with a solar reflectance of 0.05. The values of the equilibrium temperatures are obtained by iteratively solving the energy balances for surfaces exposed to solar radiation, in which the surface is assumed to be adiabatic and, therefore, the convection and radiation terms (solar irradiation, atmospheric irradiation, and surface emission) are considered. On evaluating the performance of a surface, the SRI values are given in the above three environmental conditions. However, for comparative purposes, the value corresponding to the intermediate value of the convective coefficient is usually used[4].

Ceramic materials have high emissivities, so that obtaining ceramic materials with high SRI values (cool materials) requires maximising solar reflectance[7].

The SRI of a black surface will be close to zero, whereas it will be close to 100 for a white surface[8]. However, although the SRI is expressed as a percentage, in view of its definition, it could also have values below 0 or above 100 on determining the SRI for surfaces whose performance under solar radiation is worse than the black surface or better than the white surface used as references[4].

Five percent of solar irradiation is in the UV spectrum (wavelength < 400 nm), 43% is in the visible spectrum (400–700 nm), and 52% is in the near infrared (NIR) region[9]. Consequently, to obtain a cool material of a certain colour, particularly if it is a dark colour, different approaches have been developed to minimise solar absorptance. One such approach consists of using pigments with high NIR reflectance[9], while another involves using a multilayer model in which a layer of material with pigments of high transparency in the NIR region is used on a layer of material with high solar reflectance[10] (for example engobe, in the case of glazed ceramic tiles[7, 11, 12]).

In any event, though the solar reflectance of dark glazes can be increased by raising reflectance in the NIR region, such glazes are always going to have low reflectance in the visible spectrum and will therefore always be less reflectant than white glazes. The latter, owing to their high reflectance in the visible spectrum, have the greatest solar reflectance, which is why dwellers in warm regions have traditionally painted outer walls white. This study was undertaken as a result of the demand for white flooring materials with high SRI values and the need to understand how glaze composition and microstructure affected the performance of these materials in regard to solar irradiation.

2. EXPERIMENTAL

Three frits were selected: a transparent frit (C), a zirconium white (B), and a matt frit (M), which were applied in different layer thicknesses (standard, half, and double) on unfired porcelain tiles coated with an engobe layer, with which in the three cases white fired glazes were obtained. The composition and thickness of the applied engobe layer was kept constant in all tiles.

In order to attempt to modify tile performance under solar radiation without visually altering tile appearance, zirconium silicate (ZS) was used as opacifier, this being added to the glazes in different ways:

1) Mass addition to the glaze suspension before application (10 or 20% by weight).
2) Spraying of two suspensions on the surface of the tiles glazed under the original conditions (standard thickness without ZS addition):
    a) MIC, consisting of a mixture of 50.6% glaze and 49.4% ZS, at a solids content of 50% (percentage by weight).
    b) PULV, made up of pure zirconium silicate at a solids content of 50%.

The glazed tiles were fired in an industrial kiln using the usual porcelain tile thermal cycle. The chromatic coordinates (L*, a*, b*) of the resulting fired glazes were determined with a Macbeth Color Eye 7000A (X-Rite, USA) diffuse reflectance spectrophotometer, in addition to glaze thermal emissivity with a Devices & Services Company model AE1 emissometer and glaze solar reflectance with a Devices & Services Company model SSR-ER V6 solar spectrum reflectometer, in accordance with standard ASTM G173-03.

The solar reflectance and thermal emissivity values were used to calculate the values of the solar reflectance index (SRI) in accordance with standard ASTM E1980-11

"Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces".

Finally, the microstructure of the surfaces and cross-sections of the fired glazes were observed with a Quanta 200 (FEI Company-USA) field-emission gun environmental scanning electron microscope (FEG-ESEM) using the backscattered electron signal.

3. RESULTS

On determining the radiative properties of the fired glazes, it was verified that, in every case, thermal emissivity exhibited the same value (0.83). Consequently, as the only differences in the SRI values were due to the variation in solar reflectance, the discussion of results is based on the values of this parameter. A list of all prepared samples, their references, and the results of some measured parameters are included in Table 1.

Fired glaze	Method	Reference	g ZS/m²	ρ_{SOLAR}	L*	SRI (12)
White	Thickness	BZ-1/2	27	0.720	89.9	87
		BZ	54	0.734	91.1	89
		BZ 2	107	0.780	93.1	96
	ZS addition and thickness	BZ+20%-1/2	74	0.767	91.7	94
		BZ+20%	148	0.814	93.9	101
		BZ+20%-2	295	0.827	94.8	103
	PULV surface deposition	BZ-PULV1	77	0.787	92.7	97
		BZ-PULV2	91	0.777	92.3	95
	MIC surface deposition	BZ-MIC1	65	0.773	92.4	95
		BZ-MIC2	73	0.787	93.1	97
		BZ-MIC3	99	0.795	93.2	98
		BZ-MIC4	165	0.820	94.1	102
Transparent	ZS addition	C	0	0.651	86.4	77
		C+10%	59	0.718	89.3	87
		C+20%	103	0.781	92.1	96
	PULV surface deposition	C-PULV1	24	0.721	89.5	87
		C-PULV2	38	0.718	89.3	87
	MIC surface deposition	C-MIC1	12	0.700	88.5	84
		C-MIC2	20	0.725	89.7	88
		C-MIC3	45	0.745	91.0	91
		C-MIC4	111	0.787	93.0	97
Matt	Thickness	M-1/2	44	0.744	91.4	91
		M	88	0.819	94.3	102
		M- 2	176	0.834	95.2	104
	ZS addition	M+10%	137	0.799	92.8	99
		M+20%	177	0.816	93.3	101
	PULV surface deposition	M-PULV1	111	0.814	93.5	101
		M-PULV2	125	0.813	93.6	101
	MIC surface deposition	M-MIC1	100	0.812	93.9	101
		M-MIC2	108	0.814	93.7	101
		M-MIC3	133	0.798	93.3	98
		M-MIC4	199	0.824	94.2	102

Table 1. *Results obtained in the experimentation. The original fired glazes (BZ, C, M) are shown in a different grey colour.*

3.1. FIRED GLAZE SOLAR REFLECTANCE

3.1.1. ZIRCONIUM WHITE

The influence of glaze thickness and zircon concentration (by adding 20% to the initial content) on solar reflectance was studied first. In this series of tests, represented by empty and solid circles, respectively, in Figure 1, the following may be observed:

- Raising total zircon content (whether by thickness or concentration) increased reflectance to a maximum of 0.827 (for sample *BZ+20%-2*, which contained 295 g/m^2 ZS), which seemed to be the limit value in this system.
- All points in these two series (empty and solid circles), which corresponded to samples with different zircon contents, incorporated in mass additions, exhibited the same trend, represented by the curve drawn in the figure. Therefore, in these two series of samples, reflectance depended solely on the amount of ZS contained in the glaze layer (g/m^2) and the concentration was not observed to have any influence.
- The trend curve shows that, for all practical purposes, the reflectance limit of 0.827 had already been reached at a ZS content of 200 g/m^2, this being much lower than that contained in sample *BZ+20%-2 (295 g/m^2)*. Therefore, one third of the fired glaze thickness of *BZ+20%-2* (the deepest area) did not contribute to reflectance.

Two series of samples were then prepared by spraying suspensions of ZS on the glazed surface, with a view to obtaining a thin outer layer with a high concentration. Figure 1 shows that, for MIC, the first additions (BZ MIC-1 and BZ MIC-2) raised reflectance above the curve (which represents what was obtained on incorporating the same amount of ZS in a mass addition). However, on increasing glaze thickness (BZ MIC-3 and BZ MIC-4) and approaching the reflectance limit value, this effect was lost and BZ MIC-4 already lay on the same trend line as the fired glazes that contained mass-added ZS.

Spraying pure ZS (suspension PULV) on the surface initially raised reflectance similarly to that of suspension MIC. On increasing the sprayed layer, this rise was no longer noted, a light reduction in reflectance even being observed, which might be due to the increased surface roughness of this fired glaze.

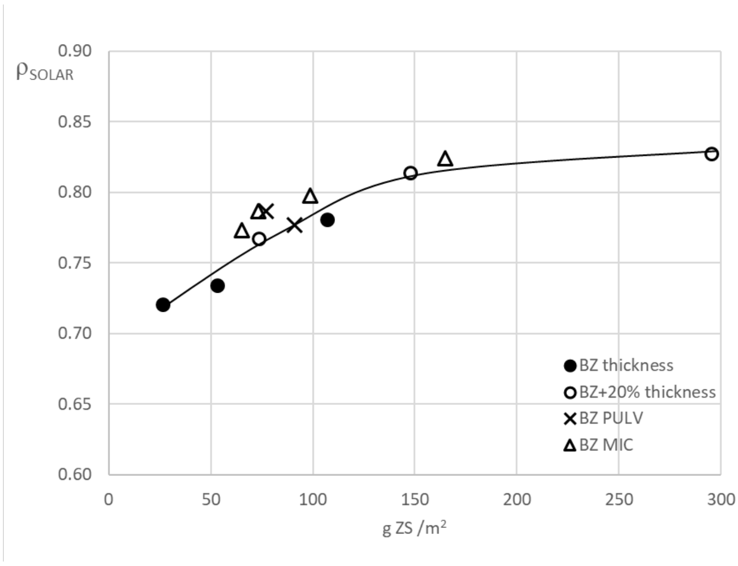

Figure 1. *Reflectance of the zirconium white glaze as a function of its zircon content (g/m^2).*

3.1.2. TRANSPARENT GLAZE

Once the influence of the ZS surface and volume concentration had been verified, a series of fired glazes were obtained using the transparent test frit and increasing the mass concentration (addition of 10 and 20% by weight to the suspension) and spraying the suspensions used in the previous section (PULV: pure ZS and MIC: mixture of glaze and ZS).

The ZS mass addition to the glaze suspension (C addition) raised fired glaze reflectance in a way that, a priori, seemed linear as may be observed in the curve that unites them. However, on plotting the reflectance of the other fired glazes, a similar curve to the one in Figure 1 can be observed, in which the asymptote was not reached, which would correspond to the maximum reflectance of this system.

The effect of spraying pure ZS (C PULV) was similar to that noted for the zirconium white glaze: namely, a first positive effect and a subsequent reduction owing to the high roughness resulting from this application.

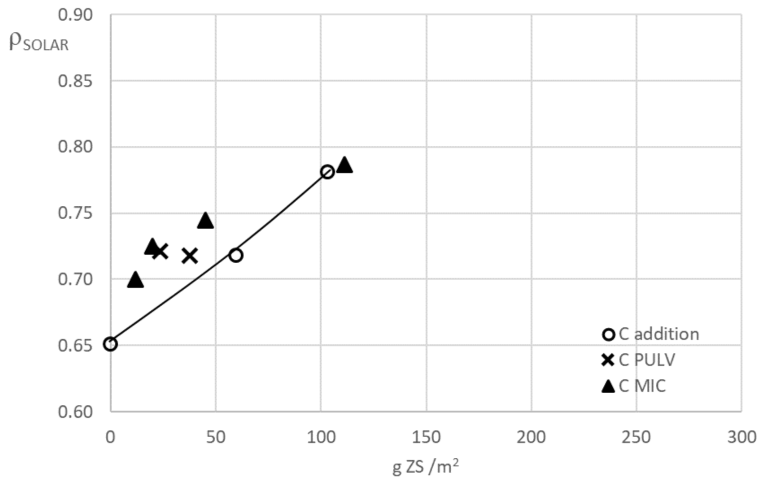

Figure 2. *Reflectance of the transparent glaze as a function of its zircon content (g/m²).*

3.1.3. MATT GLAZE

The results obtained with the matt glaze are plotted in Figure 3 and are quite different from those obtained with the other two fired glazes. The matt glaze was the most reflectant and needed the smallest amount zircon to achieve maximum reflectance (0.84 at 120 g ZS/m^2). Any attempt to improve the fired glaze with the previous strategies, whether by ZS mass addition or surface spraying the two previous suspensions (MIC and PULV), led to lower reflectance.

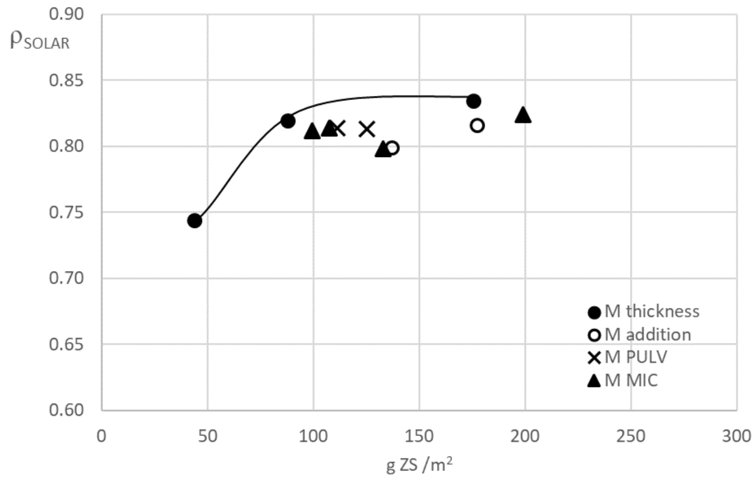

Figure 3. *Reflectance of the matt glaze as a function of its zircon content (g/m²).*

3.2. FIRED GLAZE MICROSTRUCTURE

Figure 4 shows the surface and cross-section of the transparent fired glaze, after some of the modifications performed. The original fired glaze consisted of a glass matrix in which only cristobalite crystals were discerned, which were optically transparent (they could hardly have contributed to reflectance), so that tile reflectance must have been due to the white engobe layer.

A difference was observed in zircon distribution, depending on the application involved. When the ZS was added to the glaze, zircon distribution was more cross-sectionally dispersed whereas, on spraying, surface zircon concentrations were detected. This phenomenon could explain the higher solar reflectance values in the sprayed applications. Therefore, the surface concentration of zircon particles was more effective.

On the other hand, comparison of the sprayed applications with each other in the PULV and MIC surface microstructures indicates that the surface coverage of the latter was much greater. This would explain why PULV, despite being concentrated, was less effective.

In regard to Figures 5 a) and d), which depict the surface and cross-section of the zirconium white fired glaze, a uniform distribution both at the surface and in the cross-section may be observed. However, to obtain a reflectance value of about 0.74, 54 g ZS/m2 was required compared to deposition of 20 g MIC on the transparent glaze.

The matt glaze already had a high reflectance of its own, exhibiting a microstructure with a great number of small crystals. In this case, it was observed that no type of ZS addition or deposition was effective. It was experimentally detected that, despite doubling the zircon content (from 88 to 177 g/m2), the reflectance was maintained.

3.3. FIRED GLAZE LIGHTNESS

The experimental results (Table 1) show that fired glaze lightness exhibited the same trend as glaze solar reflectance, so that these values have been plotted for all test samples in Figure 6. Regardless of the type of glaze and surface roughness (as the PULV applications were very rough), an almost perfect linear relationship between both parameters was obtained.

3.4. SOLAR REFLECTANCE INDEX (SRI)

The SRI values are set out in Table 1 and were all very high. The maximum values corresponded to the matt and to the zirconium white glazes applied as a double layer, which were higher than the value used as a reference (SRI=100). As emissivity was constant, the relationship between the SRI and solar reflectance was a straight line and the plot of the SRI versus lightness (L*) was completely analogous to that of Figure 6.

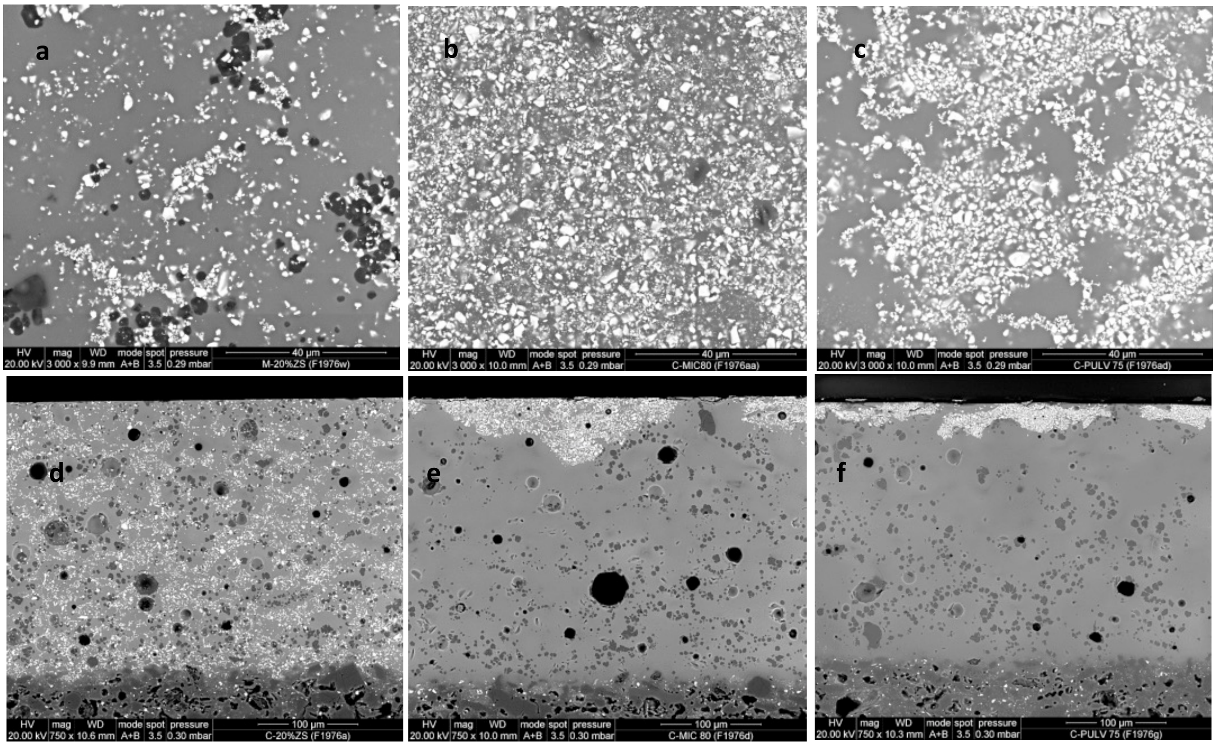

Figure 4. *Appearance of the transparent glaze after mass addition of 20% zircon (a, d) and surface deposition of MIC-2 (b, e) and PULV-2 (c, f). The top images show the surface and the bottom images the cross-section.*

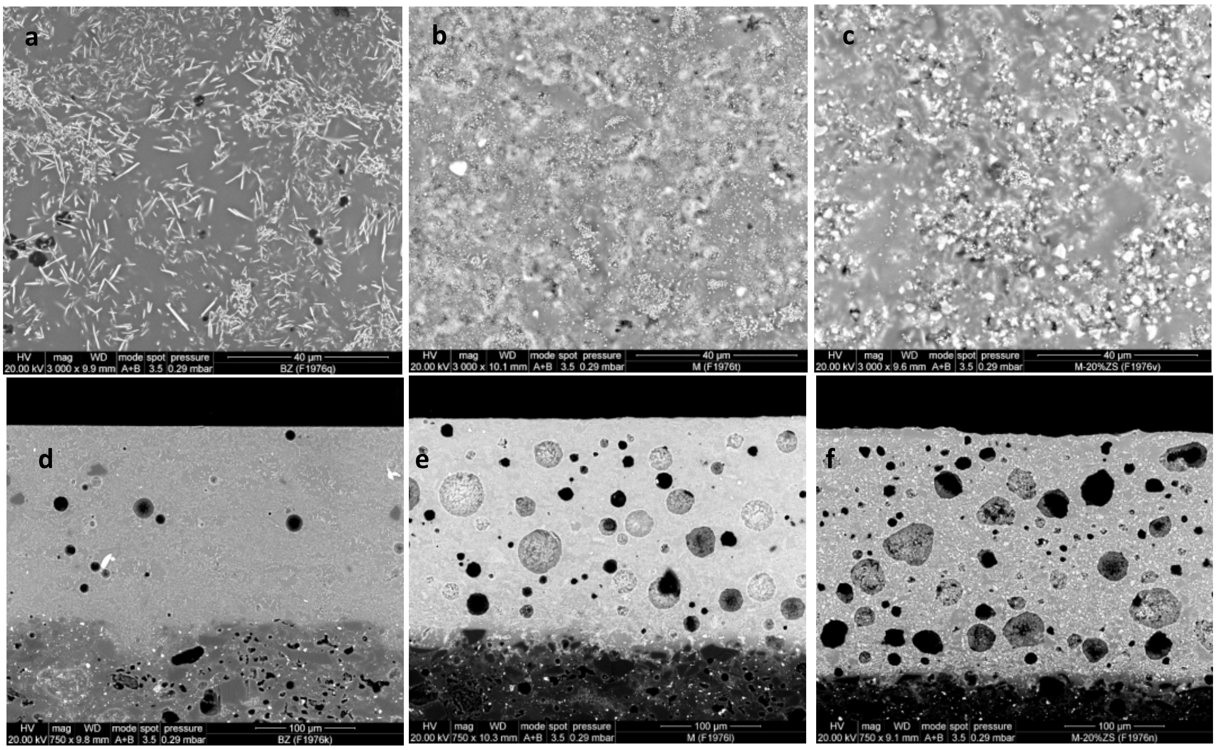

Figure 5. *Surface and cross-section of the zirconium white glaze (a, d), matt glaze (b, e), and matt glaze with 20% ZS mass addition (c, f). The top images show the surface and the bottom images the cross-section.*

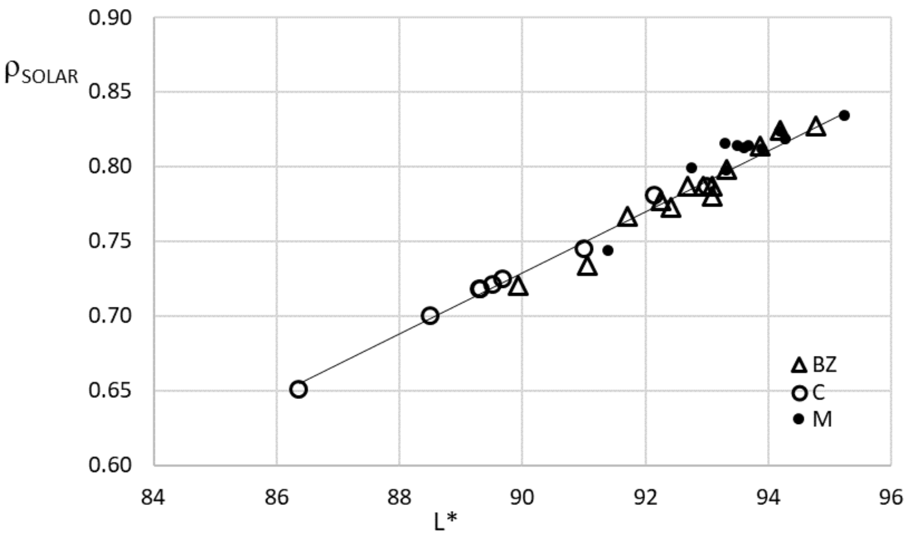

Figure 6. *Reflectance of the matt fired glaze as a function of its zircon content (g/m²).*

4. CONCLUSIONS

Analysis of the solar reflectance/SRI values of a family of white, matt, and crystalline fired glazes, with constant emissivity (0.83) enable the following conclusions to be drawn:

1) Although reflectance is a surface phenomenon in opaque media, it also occurs inside semi-transparent media. Therefore, in these glazes, layer thickness influenced the SRI. The SRI increased with thickness up to a limit value, at which all incident radiation was attenuated. Further increasing thickness did not improve reflectance.

2) In order to obtain reflectance values that were not too high (far above the limit), the most efficient approach was to deposit a uniform layer with a large amount of reflectant material on the fired glaze surface. In the case of the transparent glaze, it is possible to obtain a solar reflectance of the order of that of the standard zirconium white (BZ), with less than half the zircon content (C-MIC2).

3) However, when very high reflectance is sought, the matt glaze, developed for applications requiring a high SRI, yielded the greatest reflectance with the lowest zircon content. It was not possible to increase its reflectance with ZS additions, as its microstructure, made up of numerous very small crystals, was already very efficient.

4) The SRI indicates the temperature that a surface would reach under conditions of solar irradiation, wind temperature and speed, and temperature of the surrounding environment set out in the standard. The highest SRI value obtained in this study (104) corresponded to the matt glaze applied in double layer thickness and the lowest, 77, corresponded to the transparent glaze without any additions. Under very high wind conditions (h_c= 30 $W/m^2 \cdot K$) the matt glaze surface would reach a temperature of 41°C and the transparent glaze surface a temperature of 46°C. As wind speed decreased (h_c= 12 $W/m^2 \cdot K$), the temperature difference between the matt glaze (43°C) and the transparent glaze (53°C) would increase. At very low wind speed (h_c= 5 $W/m^2 \cdot K$), the surface temperature of the matt glaze would reach 47°C, while that of the transparent glaze would reach 63°C. The temperature difference between these two white materials, would vary from 5°C with strong wind to 16°C when the wind was calm.

5) The relationship of lightness with solar reflectance and, hence, with the SRI, was direct, so that the test pieces that exhibited the highest lightness also displayed the greatest solar reflectance. This relationship could be used to predict the SRI values from the chromatic coordinates, for a given family of glazes.

5. REFERENCES

[1] Synnefa, A., Santamouris, M., Livada, I., 2006. A study of the thermal performance of reflective coatings for the urban environment. Sol. Energy 80, 968–981.

[2] Zinzi, M.; Carnielo, E.; Agnoli, S., 2012. Characterization and assessment of cool coloured solar protection devices for Mediterranean residential building applications. Energy and Buildings 50, 111-119.

[3] Incropera, F.P.; Dewitt, D.P. et al. Fundamentals of heat and mass transfer. 6th ed. New York: John Wiley & Sons, 2007

[4] Muscio, A., 2018. The Solar Reflectance Index as a Tool to Forecast the Heat Released to the Urban Environment: Potentiality and Assessment Issues. Climate, 6,12.

[5] Schabbach, L.M.; Marinoski, D.L.; Güths, S.; Bernardin, A.M.; Fredeld, M.C., 2018. Pigmented glazed ceramic roof tiles in Brazil: Thermal and optical properties related to solar reflectance index. Solar Energy 159,113-124.

[6] ASTM E1980-11—Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low Sloped Opaque Surfaces; ASTM International: West Conshohocken, PA, USA, 2011.

[7] Revel, G.M.; Martarelli, M.; Emiliani, M.; Gozalbo, A.; Orts, M.J.; Bengochea, M.A.; Guaita, L.; Gaki, A.; Katsiapi, A.; Taxiarchou, M.; Arabatzis, I.; Fasaki, I.; Hermanns, S., 2014. Cool products for building envelope. Part I: Development and lab scale testing. Solar Energy 105, 770–779.

[8] Radhi, H.; Assem, E.; Sharples, S., 2014. On the colours and properties of building surface materials to mitigate urban heat islands in highly productive solar regions. Building and Environment 72, 162-172.

[9] Levinson, R., Berdahl, P., Akbari, H., Miller, W., Joedicke, I., Reilly, J., Suzuki, Y., Vondran, M., 2007. Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. Sol. Energy Mater. Sol. Cells 9, 304–314.

[10] Levinson, R.; Akbari, H.; Berdahl, P.; Wood, K.; Skilton, W.; Petersheim, J., 2010. A novel technique for the production of cool colored concrete tile and asphalt shingle roofing products. Sol. Energy Mater. Sol. Cells 94, 946–954.

[11] Ferrari, C.; Libbra, A.; Muscio, A.; Siligardi, C., 2013. Design of ceramic tiles with high solar reflectance through the development of a functional engobe. Ceram. Int. 39, 9583–9590.

[12] Ferrari, C.; Muscio, A.; Siligardi, C., Manfredini, T., 2015. Design of a cool color glaze for solar reflective tile application. C