CALCULATION OF TOTAL SOLAR REFLECTANCE (TSR) VALUES OF CERAMIC SLAB SURFACES USING QUAD(X;Y) FUNCTION

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1. ABSTRACT

Solar energy reaches the Earth's surface, ranging from 300 to 2500 nm in wavelength. The first part of this energy consists of Ultraviolet (UV) radiation (300-400 nm), which is not visible to the human eye. 5% of the total energy is UV. The second one is at visible region (400-700 nm), and around 50% of solar energy occurs in this region. Near-infrared radiation (700-2500 nm) is almost half of incident solar irradiance and responsible for surface heating. Total solar reflectance is a parameter which determines the amount of irradiated infrared energy reflected by an object.

In this study, TSR values of full-body coloured ceramic slab surfaces were calculated using QUAD function in a spreadsheet. For the calculation, reflectance measurements of the samples were performed by a UV VIS NIR spectrophotometer with 150 mm integrated sphere, according to ASTM 903_12. Spectral irradiance was evaluated according to ASTM G173 standards. All the calculated data from the spreadsheet were compared and verified with spectrophotometer report results.

2. INTRODUCTION

Porcelain tile is a ceramic material. It has enhanced technical performance and aesthetic qualities and, in recent years, the ceramic tile industry has developed products such as the porcelain slab [1]. The latest market trends go towards large dimensions, with innovative technological solutions involving a new approach to shaping and thermal treatments. The approach is able to produce large slabs of porcelain stoneware with dimensions up to 4x1.5 square meters and 3 millimetres of thickness [2].

Urban Heat Island (UHI) is an urgent problem, especially in large cities, since it worsens temperature differences with respect to rural areas [3-4]. Solar spectra ranges from 300 nm to 2500 nm, and it is divided into three bands: 300-400 nm UV radiation, 400-700 nm visible radiation and 700-2500 nm near-infrared radiation [5].

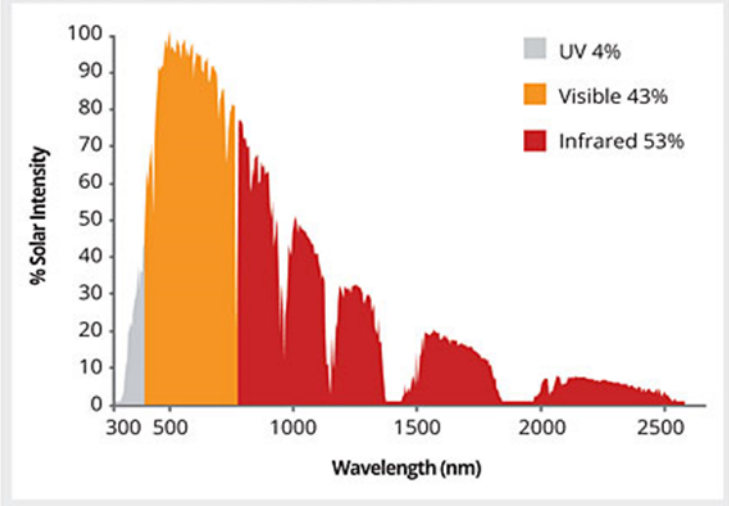

Figure 1. *Solar radiation spectral irradiance.*

Almost half of the total solar radiation is NIR (Near-Infrared Radiation) and it is responsible for heating surfaces. Cool materials are developed in order to reduce NIR effects; these materials include paints, organic membranes, shingles, concrete and other coatings. Organic or plastic-based cool materials have a lack of durability, and their application lifetime is limited. However, ceramic tiles can be used as alternatives to other materials, since they have high reflectance and durability [6].

Total solar reflectance is the fraction of incident solar radiation reflected by an irradiated surface. It ranges from 0 for a totally absorbing surface, to 1 for a reflecting surface [7]. Generally, solar reflectance of light-coloured materials is higher than that of dark-coloured ones, but this is not valid every time because nearly half of solar reflectance is of visible range.

There are several methods in order to measure reflectance performance of a given sample. The most common method is to use a spectrophotometer. A solar spectrophotometer illuminates a surface with monochromatic light at near-normal incidence and measures light reflected into an integrating sphere. A series of such measurements at wavelengths spanning the solar spectrum (300–2500 nm) yields the surface's near-normal beam, hemispherical solar spectral reflectance (r). While wavelength spacing is arbitrary, solar spectral reflectance at a 5 nm interval is sufficient to capture the spectral details of most surfaces [8].

ASTM has published a standard test method called E903-12, which covers measurement of spectral absorptance, reflectance, and transmittance of materials using spectrophotometers equipped with integrating spheres [9].

More specifically, the solar reflectance value r of every analysed surface was calculated by integrating over the range from 300 to 2500 nm the measured spectral reflectivity R_λ (defined as the ratio of reflected part and total amount of incident radiation at the considered wavelength λ), weighted by the standard spectral irradiance of the sun at the Earth's surface, I_{tot},λ [Wm^{-2} nm^{-1}] [10]:

$$\int_{300}^{2500} R(\lambda).\frac{I(\lambda)}{I_{tot}}d(\lambda)$$

In this study, TSR values of full-body coloured ceramic slab surfaces were calculated using QUAD function in a spreadsheet. For the calculation, reflectance measurements of the samples were performed by a UV VIS NIR spectrophotometer with 150 mm integrated sphere, according to ASTM 903-12. Spectral irradiance was evaluated according to ASTM G173 standards.

3. MATERIALS AND METHOD

9 different production range colours were selected (Beige Grey, White, Cement Grey, Ivory, Brown, Coral, Dark Grey, Blue and Black). All the samples to be measured for solar reflectance were prepared by cutting from production slabs. The samples were cut to 4x4 cm size and 3 mm thickness. Reflectance values of the samples were obtained using a UV VIS NIR spectrophotometer with 150 mm integrated sphere (Perkin Elmer Lambda 950 model). The measurement was performed according to ASTM 903-12 Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Sphere. Spectral irradiance was evaluated according to ASTM G173 Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface.

The data from the measurement process was evaluated using a calculation table in a spreadsheet.

QUAD (X; Y) is a special function added the to spreadsheet to integrate a spline curve fit to a set of optionally-weighted (x,y) data points. X is a vector of the point x-coordinates and Y is a vector of the point y-coordinates [11]. Total Solar Reflectance value can be calculated using the following formula:

TSR = [QUADXY (Rλ*Iλ)/ QUADXY (Iλ)] *100 (1)

4. RESULTS AND DISCUSSION

The first data set was reflectance values (%) vs. wavelength (nm). Values from the spectrophotometer can be transferred to a spreadsheet and all the calculations can be done using it. It is shown in the aforementioned data set in the following table.

The table's last column in red belongs to Standard Tables for Reference Solar Spectral Irradiances.

In Table 1, it can be seen that reflectance (%) values are in between 300 and 2500 nm wavelength scale.

	% Reflectance (R_λ)									
λ (nm)	Beige Grey	White	Cement Grey	Ivory	Brown	Coral	Dark Grey	Blue	Black	STD SPECTRA (I_λ)
300	0.05315	0.11103	0.05837	0.06094	0.04803	0.05160	0.05510	0.05767	0.04947	0.00050
400	0.16309	0.58056	0.24757	0.29727	0.06746	0.11548	0.15765	0.24328	0.06243	0.55705
500	0.22135	0.74031	0.34192	0.47044	0.07221	0.13627	0.17943	0.30216	0.06121	0.77255
600	0.29479	0.79469	0.35027	0.60470	0.09412	0.27150	0.18035	0.17499	0.06253	0.73765
700	0.34072	0.82099	0.47214	0.65321	0.12853	0.36066	0.21067	0.40689	0.07420	0.64115
800	0.42116	0.82093	0.56552	0.67993	0.20396	0.40440	0.27873	0.56283	0.11507	0.53625
900	0.45842	0.81276	0.57578	0.67325	0.22932	0.41886	0.32305	0.56701	0.15461	0.37130
1000	0.46564	0.79977	0.56645	0.65543	0.22179	0.46060	0.34594	0.54096	0.17436	0.36765
1100	0.48056	0.78268	0.55386	0.64769	0.22505	0.47233	0.37505	0.47308	0.20397	0.24290
1200	0.48401	0.79956	0.52307	0.64863	0.22317	0.46934	0.37347	0.34032	0.20942	0.22415
1300	0.48630	0.80395	0.51390	0.65614	0.22190	0.46770	0.36989	0.30321	0.20823	0.17655
1400	0.49232	0.81025	0.50976	0.66364	0.22563	0.46930	0.37084	0.29063	0.21174	0.00000
1500	0.50041	0.78729	0.50773	0.66883	0.23361	0.47250	0.37577	0.27809	0.21868	0.12530
1600	0.50923	0.81663	0.52715	0.67224	0.24305	0.47644	0.38556	0.36364	0.22774	0.11905
1700	0.52291	0.81887	0.55660	0.67757	0.25871	0.48561	0.40341	0.45374	0.24349	0.09990
1800	0.53215	0.81840	0.56139	0.67956	0.27049	0.49029	0.41318	0.46847	0.25503	0.01590
1900	0.55195	0.82715	0.57391	0.69209	0.29349	0.50673	0.43384	0.47621	0.27917	0.00000
2000	0.56961	0.83857	0.58342	0.70502	0.30986	0.51965	0.44859	0.47831	0.29604	0.01910
2100	0.60497	0.86847	0.61124	0.73646	0.34072	0.54971	0.48080	0.49745	0.32887	0.04305
2200	0.60263	0.84220	0.60319	0.71626	0.35539	0.55155	0.48582	0.49517	0.34484	0.03560
2300	0.62298	0.85960	0.61993	0.73387	0.37399	0.56686	0.50225	0.51296	0.36321	0.02940
2400	0.65625	0.88260	0.64958	0.76036	0.40451	0.59343	0.53884	0.54038	0.39034	0.02210
2500	0.67129	0.88692	0.65820	0.76227	0.43030	0.60439	0.54935	0.54549	0.41547	0.00355

Table 1. *Reflectance vs. wavelength values for selected colour samples.*

	(R_λ*I_λ)									
λ (nm)	Beige Grey	White	Cement Grey	Ivory	Brown	Coral	Dark Grey	Blue	Black	STD SPECTRA (I_λ)
300	2.657E-05	5.552E-05	2.918E-05	3.047E-05	2.401E-05	2.580E-05	2.755E-05	2.883E-05	2.473E-05	0.000500
400	9.085E-02	3.234E-01	1.379E-01	1.656E-01	3.758E-02	6.433E-02	8.782E-02	1.355E-01	3.478E-02	0.557050
500	1.710E-01	5.719E-01	2.642E-01	3.634E-01	5.579E-02	1.053E-01	1.386E-01	2.334E-01	4.729E-02	0.772550
600	2.175E-01	5.862E-01	2.584E-01	4.461E-01	6.943E-02	2.003E-01	1.330E-01	1.291E-01	4.612E-02	0.737650
700	2.185E-01	5.264E-01	3.027E-01	4.188E-01	8.241E-02	2.312E-01	1.351E-01	2.609E-01	4.758E-02	0.641150
800	2.258E-01	4.402E-01	3.033E-01	3.646E-01	1.094E-01	2.169E-01	1.495E-01	3.018E-01	6.171E-02	0.536250
900	1.702E-01	3.018E-01	2.138E-01	2.500E-01	8.515E-02	1.555E-01	1.199E-01	2.105E-01	5.741E-02	0.371300
1000	1.712E-01	2.940E-01	2.083E-01	2.410E-01	8.154E-02	1.693E-01	1.272E-01	1.989E-01	6.410E-02	0.367650
1100	1.167E-01	1.901E-01	1.345E-01	1.573E-01	5.466E-02	1.147E-01	9.110E-02	1.149E-01	4.954E-02	0.242900
1200	1.085E-01	1.792E-01	1.172E-01	1.454E-01	5.002E-02	1.052E-01	8.371E-02	7.628E-02	4.694E-02	0.224150
1300	8.586E-02	1.419E-01	9.073E-02	1.158E-01	3.918E-02	8.257E-02	6.530E-02	5.353E-02	3.676E-02	0.176550
1400	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000000
1500	6.270E-02	9.865E-02	6.362E-02	8.380E-02	2.927E-02	5.920E-02	4.708E-02	3.485E-02	2.740E-02	0.125300
1600	6.062E-02	9.722E-02	6.276E-02	8.003E-02	2.893E-02	5.672E-02	4.590E-02	4.329E-02	2.711E-02	0.119050
1700	5.224E-02	8.181E-02	5.560E-02	6.769E-02	2.585E-02	4.851E-02	4.030E-02	4.533E-02	2.432E-02	0.099900
1800	8.461E-03	1.301E-02	8.926E-03	1.081E-02	4.301E-03	7.796E-03	6.569E-03	7.449E-03	4.055E-03	0.015900
1900	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000000
2000	1.088E-02	1.602E-02	1.114E-02	1.347E-02	5.918E-03	9.925E-03	8.568E-03	9.136E-03	5.654E-03	0.019100
2100	2.604E-02	3.739E-02	2.631E-02	3.170E-02	1.467E-02	2.367E-02	2.070E-02	2.142E-02	1.416E-02	0.043050
2200	2.145E-02	2.998E-02	2.147E-02	2.550E-02	1.265E-02	1.964E-02	1.730E-02	1.763E-02	1.228E-02	0.035600
2300	1.832E-02	2.527E-02	1.823E-02	2.158E-02	1.100E-02	1.667E-02	1.477E-02	1.508E-02	1.068E-02	0.029400
2400	1.450E-02	1.951E-02	1.436E-02	1.680E-02	8.940E-03	1.311E-02	1.191E-02	1.194E-02	8.627E-03	0.022100
2500	2.383E-03	3.149E-03	2.337E-03	2.706E-03	1.528E-03	2.146E-03	1.950E-03	1.937E-03	1.475E-03	0.003550

Table 2. *Multiple reflectance by spectral irradiance values for selected colour samples.*

In Table 2, in order to integrate spectral reflectivity over the range of 300 to 2500 nm with an interval of 5 nm weighted by the spectral irradiance, the results of $R_\lambda * I_\lambda$ process were shown.

In the tables above, to summarize the wavelength range, the interval for 100 nm was selected.

For calculating the weighted reflectance by spectral irradiance and only spectral irradiance, QUAD functions were used as shown in Table.3. The function uses the data of reflectance by spectral irradiance multiplication and wavelength range.

QUADXY[(Rλ*Iλ);(λ)]	177.0993	382.1888	221.2746	290.0743	77.2930	161.1175	128.6353	182.5091	60.1742	
QUADXY[(Iλ);(λ)]	497.1757	497.1757	497.1757	497.1757	497.1757	497.1757	497.1757	497.1757	497.1757	
	$R_\lambda * I_\lambda$									
λ (nm)	Beige Grey	White	Cement Grey	Ivory	Brown	Coral	Dark Grey	Blue	Black	STD SPECTRA (I_λ)
300	0.00003	0.00006	0.00003	0.00003	0.00002	0.00003	0.00003	0.00003	0.00002	0.00050
400	0.09085	0.32340	0.13791	0.16560	0.03758	0.06433	0.08782	0.13552	0.03478	0.55705
500	0.17100	0.57192	0.26415	0.36344	0.05579	0.10527	0.13862	0.23344	0.04729	0.77255
600	0.21746	0.58620	0.25837	0.44606	0.06943	0.20028	0.13303	0.12908	0.04612	0.73765
700	0.21845	0.52638	0.30271	0.41880	0.08241	0.23124	0.13507	0.26088	0.04758	0.64115
800	0.22585	0.44022	0.30326	0.36461	0.10937	0.21686	0.14947	0.30182	0.06171	0.53625
900	0.17021	0.30178	0.21379	0.24998	0.08515	0.15552	0.11995	0.21053	0.05741	0.37130
1000	0.17119	0.29404	0.20826	0.24097	0.08154	0.16934	0.12719	0.19888	0.06410	0.36765
1100	0.11673	0.19011	0.13453	0.15732	0.05466	0.11473	0.09110	0.11491	0.04954	0.24290
1200	0.10849	0.17922	0.11725	0.14539	0.05002	0.10520	0.08371	0.07628	0.04694	0.22415
1300	0.08586	0.14194	0.09073	0.11584	0.03918	0.08257	0.06530	0.05353	0.03676	0.17655
1400	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
1500	0.06270	0.09865	0.06362	0.08380	0.02927	0.05920	0.04708	0.03485	0.02740	0.12530
1600	0.06062	0.09722	0.06276	0.08003	0.02893	0.05672	0.04590	0.04329	0.02711	0.11905
1700	0.05224	0.08181	0.05560	0.06769	0.02585	0.04851	0.04030	0.04533	0.02432	0.09990
1800	0.00846	0.01301	0.00893	0.01081	0.00430	0.00780	0.00657	0.00745	0.00405	0.01590
1900	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2000	0.01088	0.01602	0.01114	0.01347	0.00592	0.00993	0.00857	0.00914	0.00565	0.01910
2100	0.02604	0.03739	0.02631	0.03170	0.01467	0.02367	0.02070	0.02142	0.01416	0.04305
2200	0.02145	0.02998	0.02147	0.02550	0.01265	0.01964	0.01730	0.01763	0.01228	0.03560
2300	0.01832	0.02527	0.01823	0.02158	0.01100	0.01667	0.01477	0.01508	0.01068	0.02940
2400	0.01450	0.01951	0.01436	0.01680	0.00894	0.01311	0.01191	0.01194	0.00863	0.02210
2500	0.00238	0.00315	0.00234	0.00271	0.00153	0.00215	0.00195	0.00194	0.00147	0.00355

Table 3. *Calculation of Quad functions for reflectance and spectral irradiance values.*

Total solar reflectance values of samples were calculated by using Equation 1 and can be seen below in Table 4.

	TSR %		
	From Calculation Table	From Spectrophotometer	Accuracy %
Beige Grey	35.621	35.680	99.83
White	76.872	76.950	99.90
Cement Grey	44.506	44.590	99.81
Ivory	58.344	58.450	99.82
Brown	15.546	15.570	99.85
Coral	32.407	32.480	99.77
Dark Grey	25.873	25.900	99.90
Blue	36.709	36.810	99.73
Black	12.103	12.110	99.94

Table 4. *Total Solar Reflectance values of the samples.*

In order to make a comparison and verification of the calculated results, the spectrophotometer software was used, according to ASTM G 173 (Hemispherical Tilt @

37 degrees). It was found in the results from calculations that using the QUAD function was successful for obtaining TSR values comparing to software computation.

In order to evaluate TSR values of the samples, colour is one of the most important parameters. As the colour gets darker, TSR value decreases and thus, the surface temperature of the ceramic product increases due to NIR radiation, which is responsible for the Urban Heat Island effect.

For the visualisation of these values, a line chart was created to evaluate reflectance behaviours of the colours. In Figure 2, graphical fingerprints for each colourful ceramic surfaces and their response to solar radiation are shown.

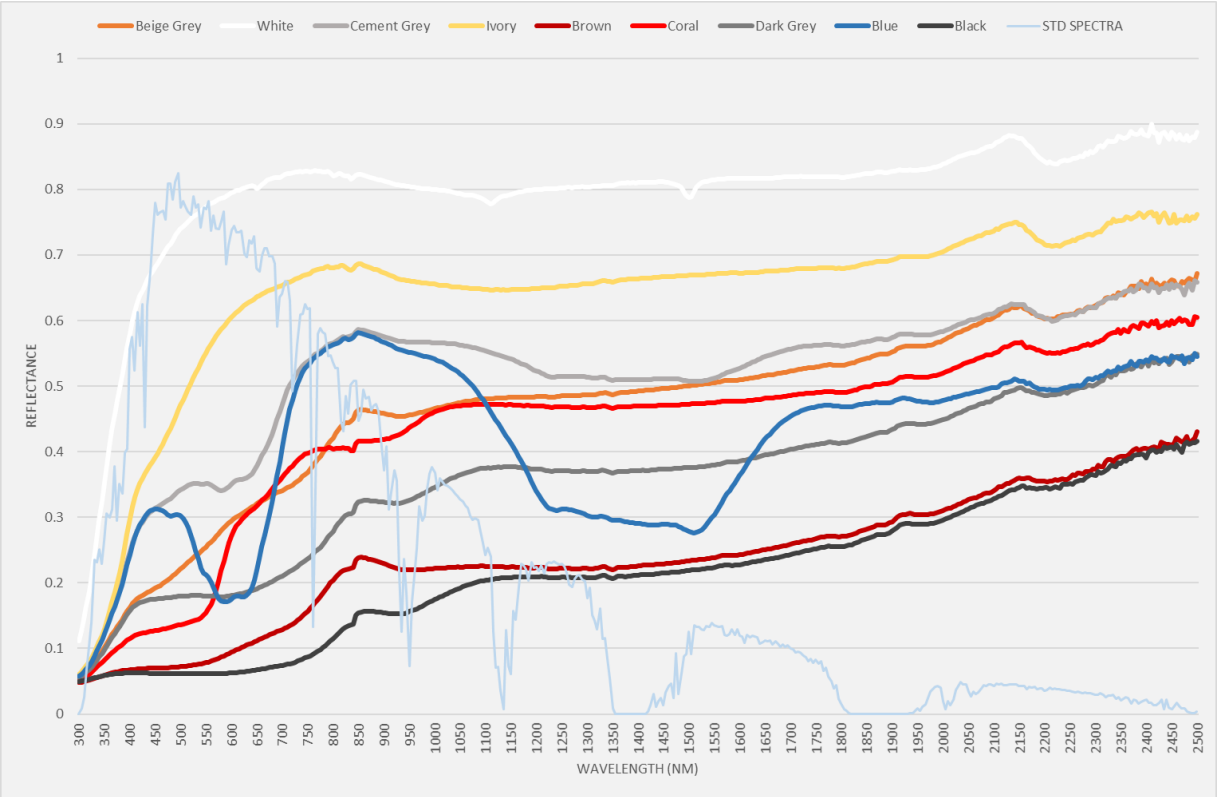

Figure 2. *Solar reflectance chart of colour samples.*

5. CONCLUSION

Solar radiation reflectance values of colourful ceramic slab samples were measured by using UV VIS NIR spectrophotometer with integrated sphere, and from the data, TSR values of each sample were calculated by QUAD function in a spreadsheet table.

It was found in the results from calculations that using the QUAD function was successful for obtaining TSR values comparing to software computation. This function can be used in order to calculate TSR for any surface when the analytic device does not have software capable of determining TSR.

6. REFERENCES

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