Mathematical models to assessment the energy performance of textured cladding for facades

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The temperature increase of a city in relation to its peripheral areas leads to the formation of an Urban Heat Island. Working on the opto-thermal properties of the building envelope is a viable mitigation strategy to reduce the temperatures of a city. Having quantitative data on energy performance allows the development of precise evaluations and the selection of the most efficient data in relation to energy consumption. The degree of efficiency of a material is calculated with an indicator called Solar Reflectance Index (SRI). Since opto-thermal properties change over time, the standard recommends obtaining the SRI level of both new and three-year-aged material (SRI_3). In the present work, 80 facade claddings were evaluated to: (a) determine which qualitative variables significantly influence the SRI_3 of the claddings; (b) obtain an equation that calculates the SRI_3 without the need to monitor the large number of variables used for its calculation. For this, the following statistical methods were used: multifactorial ANOVA and linear regression model. In this correlational analysis, color, composition and texture were selected as independent variables. The research showed that color is the variable that significantly influences SRI_3 in all the evaluated claddings. By means of the equation obtained with the regression model, the SRI_3 index was predicted reaching 95% IC. These results significantly save time and simplify the process of obtaining data since it is not necessary to monitor numerous input variables to calculate the indicator.

Keywords: solar reflectance index; building materials; correlational model

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1. Introduction

The temperature increase of a city in relation to its peripheral areas leads to the formation of an Urban Heat Island (UHI). The effect of UHI is a sensitive indicator of changes in the temperature of a city. The highest intensities are caused by the replacement of permeable surfaces with artificial materials for city infrastructures and by the generation of anthropogenic heat due to population growth. In international academia, the intensity of UHI is associated with climate change and global warming [1, 2].

UHI mitigation, or urban cooling process, aims at counteracting the negative effects produced on both energy demand and on the environment. The use of solar radiation reflective materials on the surfaces of the urban building envelope -roofs, facades and pavements- is among the most widespread UHI effect mitigation technologies, and consequently of global warming [3]. The materials used in the envelope play a determining role in the thermal balance of a city. They absorb solar and infrared radiation and dissipate part of the accumulated heat towards the atmosphere through convection and radiation processes, increasing ambient temperature [4].

The thermal behavior of materials is determined mainly by their optothermal characteristics, within which albedo and thermal emissivity are the most important factors [5]. Albedo (α) refers to the percentage of solar energy reflected by a surface. This property is decisive in a material´s maximum temperatures. The thermal emissivity (ϵ) of a material determines the amount of heat, in the form of infrared radiation, per unit area at a given temperature, that is, the ease with which a surface exchanges heat. Most construction materials have infrared emissivity greater than 0.8 except for metals and some shiny materials that have low emissivity [6]. Working on the thermo-physical properties of building envelope materials is a viable mitigation strategy to reduce the temperatures of a city. Materials with high albedo level and high thermal emissivity are classified as "cool materials"[5, 7, 8]. Cool materials reduce the cooling energy demand in buildings with air conditioning and improve the comfort of buildings without conditioning [9] since they reflect most of the incident solar radiation to the sky and consequently decrease surface temperature.

The solar reflectance of a new material tends to change in the first or second year of outdoor exposure due to the deposition and retention of soot and dust; microbiological growth; exposure to sunlight, precipitation, dew; and other wear processes [10, 11].That is why the definition of parameters that characterize the thermal and optical behavior of aged envelope materials is essential.

The degree of efficiency of a material is calculated with an indicator called Solar Reflectance Index (SRI) This parameter indicates the ability of a material to reflect incident solar radiation in relation to the ability of two reference surfaces, a white pattern and a black pattern, according to the ASTM E1980 standard [12]. This is expressed in a range from 0 to 100% in which the material that achieves a higher SRI level is the most efficient. To calculate this, numerous environmental and material parameters during the occurrence of maximum solar radiation - at solar noon and in the summer period - are necessary. These parameters are: (i) meteorological conditions on the test day -sun radiation, average air temperature, relative humidity, average wind speed, and convection coefficient-; (ii) and optical and thermal properties of the material to be tested -emissivity, albedo and surface temperature-.

The SRI index allows a direct comparison between materials with different optothermal properties. Since the optical properties of materials tend to change over time, the reference standard recommends obtaining the SRI level of new (SRI_1) and three-year-aged (SRI_3) materials.

Since the 90's, the use of cool materials in roofing and pavements has been required to meet various energy efficiency standards in North America and Europe, however, the application of cool facades is an emerging measure within current standards [13]. Hence, characterizing the thermal and reflective properties of the walls to advance in their energy certification is an area that still lacks substantial progress[14].

Having quantitative data on the energy performance of materials within the urban building envelope allows accurate evaluations to be carried out and the selection of the most efficient in relation to energy consumption. In this way, the use of renewable energy and the rational use of conventional energy are encouraged.

In this framework, this research aims to give continuity to the work developed by Alchapar and Correa [13] in which possible relationships between morphological characteristics, optothermal properties and SRI wear level of a set of textured façade claddings were analyzed, in relation to their ability to mitigate urban heating. In keeping with this, the objective of the present work is to generate evaluation and forecast tools for the optothermal characterization of facade materials at the third year of aging. Through the construction of correlational models, it is expected: (i) to determine which qualitative variables significantly influence the three-year-aged Solar Reflectance Index (SRI_3) and (ii) to obtain an equation that predicts the value of the three-year-aged Solar Reflectance Index (SRI_3) of textured coatings. The purpose is to find a function that allows the SRI_3 level to be obtained without the need to monitor all the variables used for its calculation. This estimate significantly saves time and resources.

2. Method

2.1. Sample Unit

According to the demand in the local market and the frequency of use, 80 acrylic and cementitious facade claddings of varied textures and colors were tested.

The measurements were made in a property of the Mendoza Scientific Technological Center (32 ° 53'45 "S 68 ° 52'28" W) during the summer periods of 2011, 2012, 2013, 2014 under standard environmental conditions at 1:00 p.m. and on a horizontal surface, as established by the ASTM E 1980-11 standard [12]. In this monitoring, albedo value [15], thermal emissivity [16], surface temperature and solar reflectance index of new and three-year -aged materials were obtained (Table. 1). Textured coatings are classified according to compositions, finishes and colours.

- Composition: *acrylic* [C01, C40]; and *concrete* [C41, C80].
- Finish: *fine* [C01, C08] [C17, C24] [C65, C72]; *rustic*

Table 1. Morphological characteristics and optothermal properties of textured coatings. Initial albedo (α_1) and aged (α_3); initial emissivity (ϵ_1) and aged (ϵ_3); initial surface temperature (Ts_1, °C) and aged (Ts_3, °C); Solar Initial Reflective Index (SRI_1, %) and aged (SRI_3, %).

Cod	α_1	α_3	ϵ_1	ϵ_3	Ts_1 (°C)	Ts_3 (°C)	SRI_1 (°C)	SRI_3 (°C)
C01	0.86	0.50	0.85	0.95	39.00	55.00	97.00	61.00
C02	0.90	0.51	0.90	0.90	35.00	55.50	100.00	60.00
C03	0.81	0.47	0.88	0.90	41.00	58.00	92.00	55.00
C04	0.51	0.35	0.95	0.95	59.00	64.00	57.00	41.00
C05	0.45	0.31	0.95	0.97	63.00	66.00	50.00	37.00
C06	0.60	0.39	0.85	0.95	56.00	62.00	64.00	46.50
C07	0.44	0.40	0.95	0.95	63.00	61.00	49.00	47.00
C08	0.34	0.32	0.95	0.95	69.00	65.00	37.00	38.00
C09	0.79	0.45	0.85	0.90	43.00	59.00	89.00	53.00
C10	0.86	0.46	0.90	0.90	38.00	58.00	99.00	54.00
C11	0.82	0.29	0.90	0.90	40.00	69.00	94.00	31.00
C12	0.47	0.23	0.95	0.95	62.00	71.00	51.50	26.00
C13	0.35	0.26	0.94	0.97	69.00	69.00	38.00	30.50
C14	0.51	0.34	0.95	0.95	60.00	64.00	56.00	40.00
C15	0.42	0.26	0.95	0.97	65.00	68.00	46.00	31.00
C16	0.34	0.29	0.95	0.95	69.00	67.50	38.00	33.00
C17	0.82	0.35	0.80	0.90	42.00	65.00	91.00	39.00
C18	0.53	0.33	0.85	0.90	60.00	66.00	55.00	36.00
C19	0.90	0.33	0.90	0.95	35.00	65.00	100.00	39.00
C20	0.83	0.34	0.90	0.90	40.00	66.00	95.00	37.00
C21	0.43	0.28	0.95	0.97	64.00	68.00	48.00	33.00
C22	0.77	0.36	0.90	0.90	44.00	64.00	87.00	40.00
C23	0.41	0.24	0.95	0.95	65.00	70.00	45.00	28.00
C24	0.26	0.23	0.95	0.90	74.00	72.00	29.00	24.00
C25	0.83	0.45	0.85	0.85	40.00	60.00	94.00	50.50
C26	0.75	0.45	0.85	0.85	46.00	60.00	83.00	50.00
C27	0.58	0.34	0.85	0.90	57.00	65.00	61.50	38.00
C28	0.74	0.24	0.90	0.95	46.00	70.00	83.00	28.00
C29	0.50	0.35	0.95	0.97	60.00	63.00	56.00	42.00
C30	0.74	0.40	0.90	0.95	46.00	61.00	83.00	48.00
C31	0.36	0.28	0.95	0.95	68.00	68.00	39.00	33.00
C32	0.30	0.25	0.95	0.90	72.00	71.00	33.00	26.00
C33	0.86	0.46	0.85	0.90	39.00	58.00	98.00	54.00
C34	0.77	0.45	0.85	0.90	45.00	59.00	86.00	52.50
C35	0.67	0.38	0.85	0.95	51.00	62.00	73.00	46.00
C36	0.72	0.28	0.90	0.95	47.00	68.00	80.50	33.00
C37	0.44	0.32	0.95	0.95	63.00	65.00	49.00	38.00
C38	0.50	0.35	0.92	0.95	61.00	64.00	54.00	41.00
C39	0.39	0.28	0.95	0.95	66.00	68.00	43.00	32.00
C40	0.32	0.23	0.95	0.95	70.00	70.50	35.00	27.00
C41	0.85	0.53	0.90	0.90	38.00	54.00	98.00	63.00
C42	0.78	0.49	0.85	0.90	44.00	56.00	88.00	58.00
C43	0.72	0.41	0.80	0.90	49.00	61.00	77.00	47.00
C44	0.55	0.37	0.85	0.95	59.00	62.50	58.00	44.00
C45	0.53	0.33	0.93	0.95	59.00	65.00	58.00	39.00
C46	0.64	0.38	0.82	0.90	54.00	63.00	68.00	43.50
C47	0.47	0.32	0.95	0.90	62.00	67.00	51.50	35.00
C48	0.37	0.30	0.95	0.95	67.00	67.00	41.00	35.00
C49	0.94	0.54	0.85	0.85	33.00	55.00	100.00	62.00
C50	0.77	0.47	0.85	0.85	45.00	59.00	86.00	52.00
C51	0.71	0.45	0.90	0.90	48.00	59.00	79.00	52.00
C52	0.63	0.36	0.90	0.95	53.00	63.50	69.00	42.00
C53	0.48	0.36	0.95	0.95	61.00	63.50	53.00	42.00
C54	0.70	0.37	0.90	0.85	49.00	65.00	78.00	39.00
C55	0.54	0.38	0.90	0.95	59.00	62.00	58.00	45.00

Table 1 (Cont.)

Cod	α_1	α_3	ϵ_1	ϵ_3	Ts_1 (°C)	Ts_3 (°C)	SRI_1 (°C)	SRI_3 (°C)
C56	0.50	0.27	0.90	0.95	61.00	68.50	54.00	31.00
C57	0.81	0.45	0.85	0.85	42.00	60.00	91.00	49.00
C58	0.80	0.50	0.90	0.90	42.00	56.00	91.00	59.00
C59	0.68	0.44	0.90	0.90	50.00	60.00	76.00	50.00
C60	0.58	0.36	0.95	0.90	55.00	64.00	65.00	40.00
C61	0.60	0.30	0.90	0.95	55.00	67.00	66.00	35.00
C62	0.72	0.40	0.85	0.90	48.00	62.00	79.00	46.00
C63	0.52	0.28	0.90	0.90	60.00	69.00	56.00	29.00
C64	0.39	0.23	0.90	0.95	67.50	71.00	41.00	26.00
C65	0.84	0.45	0.80	0.85	40.00	60.00	94.00	50.00
C66	0.75	0.40	0.85	0.90	46.00	62.00	83.00	45.00
C67	0.63	0.35	0.85	0.90	54.00	65.00	68.00	39.00
C68	0.52	0.38	0.95	0.95	59.00	62.00	58.00	45.00
C69	0.48	0.30	0.95	0.95	61.00	67.00	54.00	35.00
C70	0.67	0.43	0.85	0.95	51.00	59.00	73.00	51.00
C71	0.50	0.32	0.90	0.95	61.00	66.00	54.00	37.00
C72	0.36	0.28	0.95	0.95	68.00	68.00	40.00	33.00
C73	0.82	0.48	0.85	0.90	41.00	57.00	92.00	57.00
C74	0.77	0.44	0.85	0.90	45.00	59.00	85.00	51.00
C75	0.73	0.39	0.90	0.90	47.00	63.00	82.00	44.00
C76	0.53	0.36	0.90	0.90	59.00	64.00	57.00	40.00
C77	0.53	0.33	0.90	0.90	59.00	66.00	57.00	36.00
C78	0.72	0.41	0.80	0.90	48.00	61.50	78.00	46.50
C79	0.49	0.27	0.90	0.90	61.00	70.00	53.00	28.00
C80	0.71	0.24	0.95	0.90	47.00	71.00	80.00	25.00

[C09, C16] [C25, C32] [C57, C64]; *medium* [C33, C56] [C74, C80].

- Colour: *white* C01, 09, 17, 25, 33, 41, 49, 57, 65, 73; *ivory* C02, 10, 18, 26, 34, 42, 50, 58, 66, 74; *stone* C03, 11, 19, 27, 35, 43, 51, 59, 67, 75; *ochre* C04, 12, 20, 28, 36, 44, 52, 60, 68, 76; *terracotta* C05, 13, 21, 29, 37, 45, 53, 61, 69, 77; *lightgrey* C06, 14, 22, 30, 38, 46, 54, 62, 70, 78; *cement* C07, 15, 23, 31, 39, 47, 55, 63, 71, 79; *darkgrey* C08, 16, 24, 32, 40, 48, 56, 64, 72, 80.

In the research by Alchapar and Correa [13], the experimental work of this test is described in detail.

2.2. Statistical methods

The research to be carried out is of a correlational type since it aims at studying how one variable influences the others. To achieve the first objective, the multifactorial ANOVA method was performed to determine which variables influence SRI3. For this, the following explanatory variables were selected: composition, color, and texture. To answer the second objective, a linear regression model was performed. The explanatory variables selected are those obtained in the first year of evaluation of the albedo (α_1), emissivity (ϵ_1), surface temperature (Ts_1), and Solar Reflective Index (SRI_1) of the material. The third-year surface temperature was also added (Ts_3). Table 2 describes the factors and levels of analysis used for the statistical models.

3. Results

3.1. Multifactorial ANOVA

The analysis is done using multifactor ANOVA without replication. The variables used to calculate the ANOVA are the following:

- Dependent variable / response: Quantitative: Solar Reflectance Index at the third year of aging (SRI_3).

- Independent / explanatory variables: Qualitative: composition, color, texture.

$Interaction between factors$

The ANOVA table decomposes the variability of SRI_3 into contributions due to various factors -color, texture, and composition-. The $p - values$ test the statistical significance of each of the factors. We used an alpha level of 0.05 for all statistical tests.

Since the color variable has $p < 0.05$, it has a statistically significant effect on SRI_3. The rest of the variables and interactions do not present a significant influence on the SRI_3 level (Table 3).

Table 2. Factors and level of analysis of samples. Sources: Author's own work.

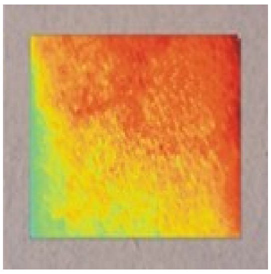
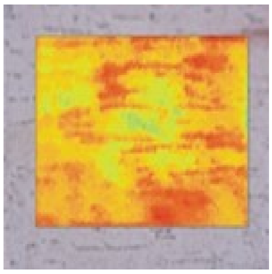
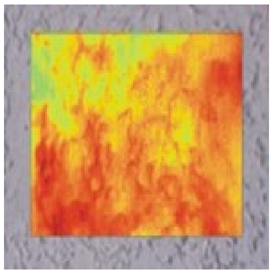
<table>
<tr><th>Factor</th><th>Level number</th><th colspan="3">level</th></tr>
<tr><td>Composition</td><td>2</td><td colspan="3">acrylic and concrete</td></tr>
<tr><td rowspan="2">Texture</td><td rowspan="2">3</td><td>fine</td><td>medium</td><td>rustic</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Color</td><td>8</td><td colspan="3">
white ivory light gray stone ocher terracotta cement dark gray</td></tr>
</table>

Table 3. Analysis of Variance for SRI_3. Sources: Author's own work.

Source	Sum of squares	Gl	Mean square	F-ratio	P-value	Significance
Main effects						
A: Color	3910.87	7	558.67	12.14	0.000	significant
B: Texture	63.03	2	31.51	0.68	0.512	not significant
C: Composition	113.04	1	113.04	2.46	0.127	not significant
						Interactions
AB	424.70	14	30.34	0.66	0.794	not significant
AC	132.94	7	18.99	0.41	0.897	not significant
BC	36.54	2	18.27	0.40	0.686	not significant
ABC	299.03	14	21.36	0.46	0.945	not significant
WASTE	1426.38	31	46.01			
Total	7379.40	78				

All F-ratios are based on the mean square of the residual error.

3.1.1. *Multiple range testing for SRI_3 by color*

After the analysis of variances, it was observed that **color** is the only variable that is statistically significant on the SRI_3 index. That is why the multiple range test was performed to detect homogeneous groups. In Table 4 and Fig. 1, evidence the existence of three groups of homogeneous colors made up of:

- Dark range: dark gray, concrete, terracotta and ocher (A, AB, B);
- Mid range: stone and light gray (C);
- Light range: ivory, white (D).

3.2. Linear Regression Model

In order to construct the linear regression model, 60 out of the 80 tested textured claddings were selected and the remaining 20 were reserved for model validation. The reserved coatings are: C21 to C30 and C71 to C80.

- Dependent variable / response: Solar Reflectance Index at the third year of aging (SRI_3) (quantitative)
- Independent / explanatory variables: composition, color and texture (qualitative); initial albedo (α_1), initial emissivity (ϵ_1), initial surface temperature (Ts_1), initial solar reflectance index (SRI_1) and surface temperature at third year (Ts_3) (quantitative).

3.2.1. *Construction of the regression model*

For the construction of the regression model, the variables with a $p > 0.05$ were eliminated from the model, until two significant variables remained (with $p < 0.05$): the initial surface temperature (Ts_1) and temperature aged at 3 years (Ts_3).

In Table 5 the highest $p - value$ of the independent variables is 0.013, which corresponds to Ts_1. Since the $p < 0.05$, that term is statistically significant with 95.0% *IC*, therefore no more variables can be removed from the model. The

Table 4. Homogeneous groups of the variable color. Method: 95.0 percent LSD. Sources: Author's own work.

Color	Cases	Mean LS	Sigma LS	Homogeneous Groups
dark gray	10	29.8	1.94	A
cement	10	34.5	1.94	AB
terracotta	10	36.75	1.94	B
ochre	10	37.6	1.94	B
stone	10	44.1	1.94	C
light grey	10	44.15	1.94	C
ivory	10	51.75	1.94	D
white	10	53.85	1.94	D

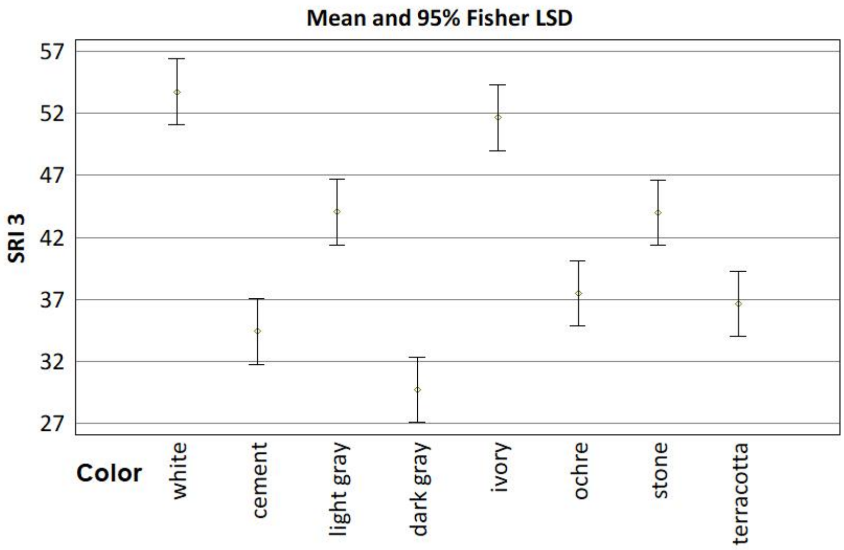


Fig. 1. SRI_3 means graph of the color variable, according to Fisher's LSD method (95% IC). Sources: Author's own work.

Table 5. Independent variables with $p < 0.05$. Sources: Author's own work.

Parameter	Estimate	Standard Error	T Statistical	P-value
Constant	180.08	1.20	149.55	0.000
Ts1	-0.026	0.01	-2.56	**0.013**
Ts3	-2.150	0.02	-88.08	0.000

equation of the model is as follows:

$$SRI_3 = 180.08\text{-}0.026^{*}Ts_1\text{-}2.15^{*}Ts_3 \tag{1}$$

R2 = 99.67%

R2 (adjusted for gl.) = 99.68%

Standard error of the est. (*SE*) = 0.56

Mean absolute error (*MAE*) = 0.44

Durbin-Watson statistic (*DW*) = 1.93 (p = 0.37)

The adjusted R_2 statistic indicates that the model adjusted explains 99.68% of the variability in the SRI_3 model. The standard error shows that the *SD* of the residuals is 0.56. *MAE* = 0.44 is the mean value of the residuals. *DW* examines the residuals to determine if there is any significant correlation. There is no indication of a serial autocorrelation in the residuals with 95.0% *IC* ($p > 0.05$).

3.2.2. Validation

This procedure is designed to compared two data samples and to determine if there are statistically significant differences between the two samples.

- Sample 1 (SRI_3 observed): 20 values in the range of 24.0 to 57.0.

- Sample 2 calculated with equation 1 (SRI_3 predicted): 20 values in the range of 23.4 to 56.5.

Table 6. Statistical summary of observed and predicted sample

	SRI3 observed	SRI3 predicted
Count	20	20
Average	38.95	39.08
Standard deviation	9.637	9.64
Coefficient of variation	24.74%	24.66%
Minimum	24.0	23.4
Maximum	57.0	56.5
Rank	33.0	33.1
Standardized Bias	0.167	0.07
Standardized kurtosis	-0.91	-0.98

Table 6 contains the statistical summary for the two data samples. The standardized bias and standardized kurtosis that can be used to compare whether the samples come from normal distributions are of particular interest. Values of these statistics outside the range of -2 to +2 indicate significant deviations from normality, which would tend to invalidate the tests that compare the *SD*. In this case, both standardized bias and standardized kurtosis values are within the expected range.

Fig. 2 demonstrates the high level of adjustment of the regression model obtained in equation 1 when comparing the predicted SRI_3 data in relation to the real ones.

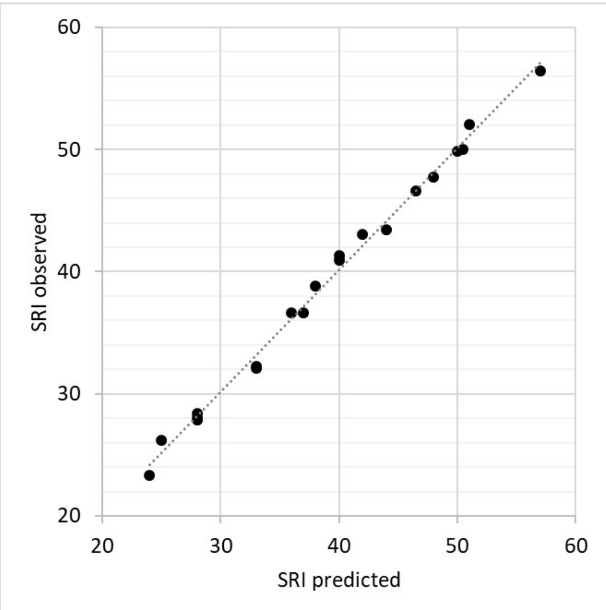


Fig. 2. Scatter plot of SRI_3 observed and predicted. Sources: Author's own work.

4. Conclusion

In this research, progress was made with the design of mathematical models based on field measurements to predict the energy behavior of textured cladding on facades. These models made it possible to systematize information acquired from the experimentation processes to generate databases of optical and thermal properties and energy indices of facade materials.

The ANOVA method determined that color is the variable that significantly influences the Solar Reflectance Index at the third year of aging, in the total of the evaluated textured coatings.

Using the linear regression model obtained in this work, the Solar Reflectance Index at the third year is predicted with 95.0% *IC*. This will allow a great saving of time and a simplification of the process of obtaining the data, since it is not necessary to monitor numerous input variables to calculate the indicator. These data show the importance of evaluating the response of coatings to aging since their impact on the surface temperatures of the facades and their ability to contribute to urban cooling varies significantly in relation to their categorization.

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