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ScienceDirect

Energy Procedia 57 (2014) 3181 – 3190

Energy Procedia

2013 ISES Solar World Congress

Urban Passive Cooling. Aging Effects on Optical Properties of Roof Tiles

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Abstract

When the percentage of solar radiation absorbed by the material of the urban envelope is diminished, its surface temperature can be reduced, thus the heat level is minimized. The application of reflective materials (high albedo) over the surfaces of building envelopes results in an effective passive cooling strategy. This work evaluates the influence of wear on the thermal performance of diverse roof tiles available in the region of Mendoza, Argentina. 16 roof tiles of different characteristics (colour, shape, composition and finish). The effect of aging was quantified by means of the Solar Reflectance Index of each material throughout a period of 3 years. The results obtained have been analyzed by relating the influence of different characteristics of the roof tiles to the thermal behaviour of the material throughout time. They show that all the tested roof tiles tend to diminish their ability to reduce urban temperatures by 40%. 50% of clay compositions and 33% of concrete compositions show an SRI value of 30%, as a result of wear.

Selection and/or peer-review under responsibility of ISES.

Keywords: *Roof Tiles; Aging; Solar Reflectance Index; Material features.*

1. Introduction

The effects of global warming and climate changes are of relevant concern for environmental and human activities in the urban area [1].The building envelope is responsible for the most significant loads that affect cooling energy use [2].

During the day, the materials composing the exterior surfaces of the building enclosures are responsible for great part of the increase of temperature in the urban area. This affects both daily and night conditions of cooling, due to the combination of the thermal storing of solar radiation within the materials

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1876-6102
Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2015.06.068

and to their optical properties. By diminishing the percentage of absorbed solar radiation, the surface temperature of the exterior elements can be reduced and therefore the heat levels minimized [3].

Increasing the optical properties (albedo and thermal emissivity) of urban surfaces is expected to reduce cooling energy use both through direct savings in buildings made with high-albedo materials and through indirect savings as urban air temperatures are reduced [4]. Thus it results in an effective passive cooling strategy.

The component of the building which is most recommended as a radiating surface is the roof, since it is the most advantageous orientation for "looking at" the sky [5]. In the residential area of Metropolitan Mendoza, Argentina, the city where this research is carried out, the most common material for the resolution of roofs is the tile. It is commercialized in two compositions: clay and concrete.

In order to determine the thermal behaviour of tiles, the Solar Reflectance Index (SRI) was calculated, according to regulation ASTM E-1980 [6]. This indicator incorporates the solar reflectance (albedo) and the thermal emittance under one value from 0 to 100, which estimates the heat accumulated in the material exposed to the sun under standard environmental conditions [7].

Research studies carried out by EPA 2008 EPA 2008; Lawrence Berkeley National Laboratory and Oak Ridge Laboratory [8, 9, 10, and 11] have shown that the high initial solar reflectance of a roof can be degraded by deposition of soot, dust, and sun exposure. Therefore, the SRI is also susceptible to wear effects and it is crucial to evaluate the effects of aging over the reflective potential of the materials throughout the years.

The objective of this study is to evaluate the influence of wear in the modification of the thermal performance of diverse roof tiles. According to the method described by regulation ASTM E1980-11, the SRI variation of 16 different roof tiles was calculated over a period of three years.

The classification of materials according to their SRI allows for the comparison of results of thermal performance of materials used locally and regionally on an international level, and it also generates knowledge on the standardization of regional materials by setting the bases for the propitiation of future energy certification at urban and building levels.

2. Methodology

2.1 Samples Unit

The building characteristics of the studied area (Mendoza City, Argentina) correspond with architectonic styles resulting from the Spanish colonial tradition. Reinforced concrete structures, brick walls and slanted roofs are representative in the low density areas. The material most commonly used in the resolution of slanted roofs of the residential type is the ceramic tile, in a colonial and French shape, terracotta colour and natural or varnished finish. Simultaneously, as a result of the incorporation of new architecture tendencies, new types of tiles have been adopted, of different shape, composition and finish. Such is the case of new housing units built over the last decades, where cement tiles have been incorporated instead of ceramic tiles, in predominantly dark tonalities and with varied shapes and finishes.

2.2 Manufacturing Process of Tiles

In order to determine which are the causes of aging on a tile, it is necessary to know its manufacturing process. Due to the fact that the raw material is different, its treatment, production and use also differ.

-Manufacturing Process of Clay Tiles: Clay is the raw material for the manufacturing of ceramic tiles. The preparation of clay is made in two stages: primary crushing - humectation and refining grinding.

Primary crushing reduces material size to minimum size for the elaboration of the tile. This is generally accomplished by jaw or gyratory crushers. Secondary crushing further reduces particle size.

Then comes the extrusion stage, where a pre-shaped bar is formed which is fractioned into equally long pieces. Then the material is compressed into moulds which shape the tile.

Tiles are pressed and sent to the dry graters. Here the tiles gradually lose moisture. Enamel is applied to the top side for tiles with matte, enamel, single glazy, double glazy and aged finish. This enamel is produced with rust, clay and pigments dissolved in water. The double glazy finish repeats the process with a second dry grating. This process gives the final product a more resistant and higher quality finish.

- Manufacturing Process of Concrete Tiles: Concrete and sand are the raw materials for the manufacturing of concrete tiles. Pigments are used for colouring.

The body of the tiles is made up of a double layer of concrete: the inferior portion (which takes 60% of its density) is constituted by concrete, pigments, water and granite sand, which provides a high level of resistance to the mix. The upper portion has the same components and also river sand, which is finer and therefore provides a more delicate texture to the visible side of the tile.

Once mixed, the components are poured into metallic moulds and then extruded under a roller. This part of the process defines the shape of the tile and gives it high compactness.

Then comes the drying stage. Later polymer is applied for the finish of the product's surface. The finish varies according to the product manufactured: natural, matte or acrylic. The drying of the surface finish is carried out with a wind tunnel.

2.3. Experiment Design and Classification

In this study the thermal behaviour of tiles of different composition, colour, finish and shape is reported. The different tiles are widely used in the local building envelopes. The sample is composed by 16 types (See Table 1).

In order to estimate the SRI variation due to aging, the studied samples were monitored during a period of three years. The samples were located over a 7 cm dense base of expanded polystyrene in one of the premises of the Regional Center of Scientific and Technical Research, in the west area of the city (32º 53' latitude, 68 º 51' western longitude).

The thermal behaviour of materials was studied during three summer seasons: 2011, 2012 and 2013. From the series of measurements registered, the reported data on Table 2 corresponds to 13.00hs of the days whose meteorological variables presented representative conditions of the local climate, according to regulation ASTM 1980-11. (See Table 2).

Table 1. Material classification according to its composition, colour, finish and shape.

COMPOSITION	COLOR	FINISH	SHAPE
Clay	Terracotta	Natural Enamel Antique	 Colonial French Roman
	Black	Single glazy Double glazy Single matte Double matte	
Concrete	Terrcotta	Natural Matte	 Colonial French
	Gray	Natural	
	Black	Matte Acrylic	

Table 2. Meteorological data for days studied.

Weather Variables	10-03-2011	10-02-2012	02-01-2013
Solar Radiation (W/m^2)	915.91	929.90	979.86
Air Temperature (ºC)	29.66	28.28	25.71
Relative Humidity (%)	25.00	31.50	30.04
Wind Speed (m/s)	2.00	1.33	1.30

2.4. Calculation of Solar Reflectance Index

In this work, the reflective ability of roof tiles has been quantified by means of the Solar Reflectance Index (SRI). The SRI of each material is based on its albedo (â), its thermal emittance (ε), and its superficial temperature (Ts) exposed to the solar radiation corresponding to 13.00 hs, according to regulation ASTM E1980-11.

The SRI is defined by the calculation of a standard black surface (Tb) with a 0.05 reflectance and a 0.90 emittance, whose value of SRI is equal to 0%; and an equivalent white pattern surface of a 100% SRI, with a 0.80 reflectance and a 0.90 emittance.

Since the SRI is an index that works in the range of 0 to 100%, the materials which reach SRI values close to 100% have a higher reflective ability and therefore lower superficial temperatures, which makes them more apt for diminishing urban temperatures, whereas the materials with low SRI values register lower surface temperatures.

2.5. Thermo-physical registers and instrumentation

In order to calculate the albedo (â) of each sample a CM3 Kipp & Zonen albedometer was used along with a pair of white and black masks over the 1 m2 area surface, according to the method developed by Akbari et al., 2008. The spectral range of the CM3 Kipp & Zonen is of about 285 to 2800 m, with a maximum solar radiance of 4000 W /m2. Its nominal sensitivity is of 1.5 10-6 V/Wm -2. The indicated response time (95%) is 18 s. (Kipp & Zonen. Product catalogue, 2008).

The emittance (ε) was obtained according to regulation ASTM E1933-99a, 2006 through a temperature sensor with a type T thermocouple associated to a data logger hobbo U12. The value of the radiant flux emitted by the material was compared to the data registered in an IR Fluke 568 thermometer with emittance adjustment. This way the emittance of the material corresponds with that which makes the temperature of the thermocouple coincide with that of the IR thermometer.

The superficial temperatures (Ts) were registered on an IR Fluke Ti 55 camera, which detects infrared long wave radiation on a range of 7.5 to 14 µm within the electromagnetic spectrum. Thermal images were obtained with this instrument which registers the radiant heat of each tile. Concurrently, the surface temperatures of each material were measured and contrasted with type T thermocouples incorporated to a data logger LASCAL EL-USB-TC, which registered every minute.

2.6. Aging Measurements of SRI

In order to quantify the thermal behaviour response of the material to the passing of time, the climate and dirt, the following formula was used:

$$SRI_1 - SRI_2 = \Delta SRI_1 \quad (1)$$
$$SRI_2 - SRI_3 = \Delta SRI_2 \quad (2)$$
$$SRI_1 - SRI_3 = \Delta SRI_{Total} \quad (3)$$

Where; SRI_1= Initial Solar Reflectance Index (2011); SRI_2= Aged Initial Solar Reflectance (2012); *SRI3*= Aged Initial Solar Reflectance (2013); ΔSRI_{Total}= Difference between SRI_1 and SRI_3 values.

A value range was established by which it was determined that a material has a stable thermal behaviour when the differences of SRI observed are lower ≤20%. In contrast, the initial SRI registers higher than the aged SRI were classified as materials whose temperature diminishing capability decreases throughout time. Values between >20 and ≤30% show moderate degradation of the material and SRI difference values higher than >30% show strong degradation between the periods.

I.e.; ΔSRI ≤ 20% =Stable; ΔSRI >20 ≤ 30 % =Moderate Degrade; Δ SRI >30 % =Strong Degrade

3. Results

By means of the calculations made according to the equations and parameters of regulation ASTM E1980-11, the SRI of the tiles were obtained for three measurement periods. Under the analyzed conditions: new material (SRI_1), aged material by year 2012 (SRI_2), aged material by year 2013 (SRI_3) and their corresponding difference (ΔSRI_{Total}). (See Table 3).

3.1 Solar Reflectance Index by periods

The following extreme values were obtained for each period:

- *First period (2011):* the materials with higher initial SRI levels are: *Natural clay- colonial- terracotta* -T01- and *Enamel clay- roman- terracotta* -T08- with an albedo =0.71, and SRI= 90%. The tile with less favourable behaviour is the *Matte concrete- french*- black -T12-, with a 0.31 albedo, surface temperature of 64ºC and SRI= 47%.-

- *Second period (2012):* The extreme cases evaluated are: *Natural clay- colonial- terracotta*-T01-, *Enamel clay- french- terracotta*-T03-, and *Enamel clay- roman- terracotta*-T08-. With an SRI= 73% for the 3 tiles, (â= 0.59, 0.60, 0.59 respectively and Ts=53ºC in the three materials). The lowest SRI percentage belongs to the *Acrylic concrete- french- black* -T13-.
- Third period (2013): The materials with the highest SRI levels after 3 years of exposure are: *Natural clay- colonial- terracotta* -T01- and *Enamel clay- roman- terracotta*-T08- with an albedo =0.71, and SRI= 90%. The tile which showed the least favourable behaviour was *Matte concrete- french- black*-T12-, with an 0.31 albedo, surface temperature of 64ºC and SRI= 47%. (See T01-T03-T08-T12 and T13 in Table 3).

Table 3.Enumeration of roof tiles during the three periods of study (2011- 2012 – 2013), with their respective assigned codes; description and image; albedo (â), surface temperature (Ts_1–Ts_2–Ts_3) and Celsius degrees; Solar Reflectance Index (SRI_1, SRI_2, SRI_3) in percentages; and total SRI difference. ($SRI_1 - SRI_3 = \Delta SRI_{Total}$).

Cod.	Description		2011			2012			2013			Δ SRI Total
			â	Ts_1	SRI_1	â	Ts_2	SRI_2	â	Ts_3	SRI_3	
T01	Natural clay- colonial- terracotta		0.71	43	90	0.59	53	73	0.42	64	54	**36**
T02	Natural clay- french- terracotta		0.62	48	80	0.56	56	68	0.35	70	43	**37**
T03	Enamel clay- french- terracotta		0.64	47	81	0.60	53	73	0.40	66	49	**32**
T04	Double glazy clay- french- black		0.47	56	64	0.38	65	51	0.28	71	41	**23**
T05	Single glazy clay- french- black		0.41	58	59	0.38	66	49	0.26	74	35	**24**
T06	Double matte clay- french- black		0.41	58	58	0.37	66	48	0.21	77	29	**29**
T07	Single matte clay- french- black		0.43	57	60	0.40	65	51	0.26	74	35	**25**
T08	Enamel clay- roman- terracotta		0.71	42	90	0.59	53	73	0.42	64	54	**36**
T09	Natural clay- roman- terracotta		0.67	45	85	0.57	54	71	0.41	64	53	**32**
T10	Antique clay- roman- terracotta		0.55	51	72	0.55	55	68	0.37	67	48	**24**
T11	Natural concrete- french- terracotta		0.47	55	64	0.55	55	68	0.37	67	47	**17**
T12	Matte concrete- french- black		0.31	64	47	0.30	69	44	0.16	78	29	**19**
T13	Acrylic concrete- french- black		0.37	61	53	0.29	70	43	0.20	75	33	**20**
T14	Natural concrete- french- gray		0.65	46	82	0.57	54	71	0.38	66	49	**33**
T15	Matte concrete- colonial- black		0.46	56	63	0.30	69	44	0.20	75	33	**31**
T16	Matte concrete- colonial- terracotta		0.46	56	63	0.49	59	61	0.33	70	43	**20**

Figure 1 shows the SRI values by material during the three periods of measurement, in order to compare their reflective ability associated to wear.

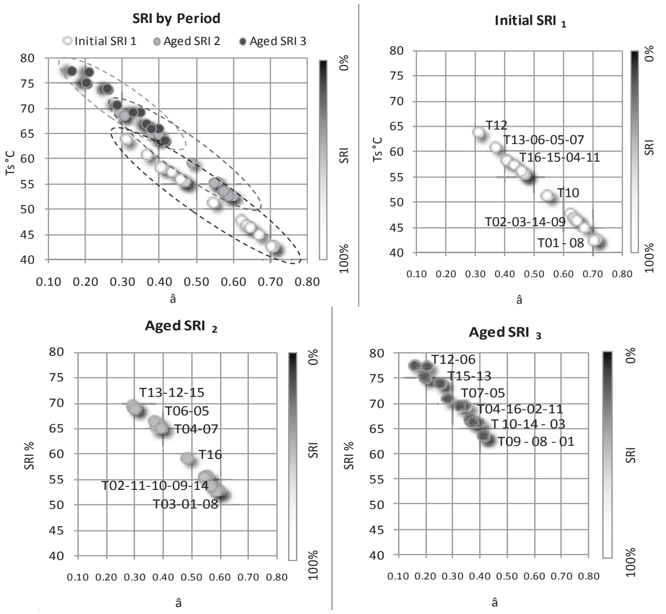

Fig.1. Solar Reflectance Index by periods.

a. Initial SRI (SRI_1). b. Aged SRI (SRI_2). c. Aged SRI (SRI_3), according to surface temperature (ºC) and albedo.

Initially the materials analyzed showed higher dispersion in their SRI values. 94% of the materials evaluated show an initial SRI in the range of 50 to 100% (Fig.1a).

In the second period the materials aged are grouped under an SRI range of 73 to 43%, where 69% of the tiles reach an SRI level higher than 50% (Fig. 1b).

In the third period of aging, the materials are grouped under an SRI range of 54 to 29%, which indicates that 80% of the materials initially considered efficient in their thermal response have worsened their functioning in 61% after two years. In addition, the graphic clearly shows that the variable most affected by aging is albedo. Likewise, the surface temperatures increased with aging between 12 and 22Cº, for the evaluated cases (Fig.1c and Table 3).

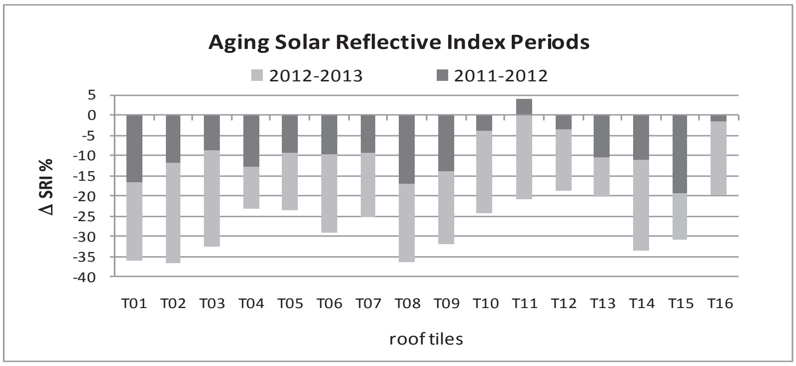

Fig.2. Aged Solar Reflective Index inter periods (2011-2012) y (2012 y 2013).

The material which shows less wear during the 2011-2012 period is the *Natural concrete- french-terracotta*-T11- with an improvement of 4%. The material that reached higher diminishing SRI levels is the *Matte concrete- colonial- black*-T15- with a value of SRI1= 19%.

During the 2012-2013 period the tiles that show lower percentages of SRI reduction are the *Double glazy clay- french-black* -T4- and *Acrylic concrete- french- black* -T13- with an identical difference of (10%). The tile which shows higher reduction is the *Natural clay- french- terracotta* -T2- (25%). (Fig. 2)

3.2. Solar Reflectivity Index Aging

By means of the calculation of the eq. 3 SRI total difference values were obtained to determine which tiles were more resistant to aging according to their characteristics (composition, colour, finish and shape).

3.2.1 Aging SRI according to its composition. (Clay- Concrete)

After submitting the tiles to the exterior climate conditions (aging), the differences in SRI levels for the *clay* and *concrete* tiles were calculated

67% of the *concrete* tiles remained stable, whereas none of the *clay* tiles were within this range. 50% of the *clay* materials registered a moderate degradation of their SRI levels. Within the materials which show strong degradation are 50% of the *clay* and 33% of the *concrete* materials evaluated. The SRI values decrease in an average 30% in the case of *clay* tiles and 23% in the case of the *concrete* tiles. (Fig. 3a)

3.2.2 Aging SRI according to its colour. (Gray-Terracotta, Black).

For the colour *gray* alternatives strong degradation registers were obtained in the SRI levels.

In the case of *terracotta* tiles, 63% reached a strong degradation, 12% showed moderate degradation and the remaining 25% were stable.

14% of *black* tiles strongly degraded their SRI, 57% presented moderate wear, while the remaining 29% were stable (Fig. 3b, and Table 3).

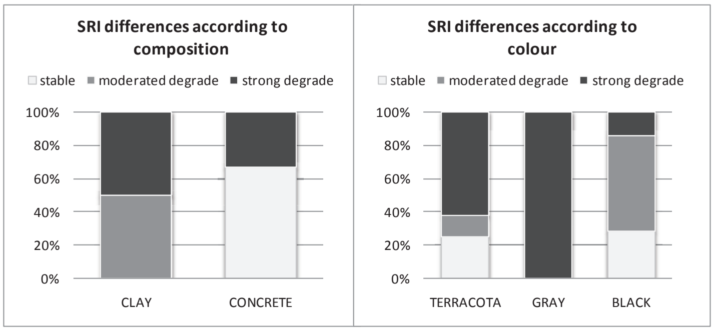

Fig.3. Relative frequencies distribution (%) of SRI differences (Δ SRI) in roof tiles.
a. According to its composition. b. According to its colour.

3.2.3 Aging SRI according to its finish. (Glazy- Matte -Aged -Acrylic).

By evaluating the finish variable in isolation, 80% of the *natural* finishes were observed to present strong degradation, decreasing their thermal condition between 33 and 36%. The remaining 20% showed a stable behaviour.

100% of the *glazy* and *aged* tiles had a moderate degradation of their SRI as a result of the passing of time, climate and dirt.

In the case of the *matte* finishes, 33% had a strong degradation and the remaining 67% showed a stable level of aging.

The *acrylic* tiles proved to be the most efficient finishes since 100% showed SRI level stability. (Fig.4a).

3.2.4 Aging SRI according to its shape

By separately analyzing the shape, it was observed that 67% of the colonial configurations had a strong degradation (between 30 and 36%) and the remaining 33% showed stability.

The French tiles registered 30% strong degradation, 40% moderate degradation and 30% stable degradation.

67% of the Roman tiles reached strong levels of degradation and the remaining 33% showed stability. (Fig.4b and Table 3).

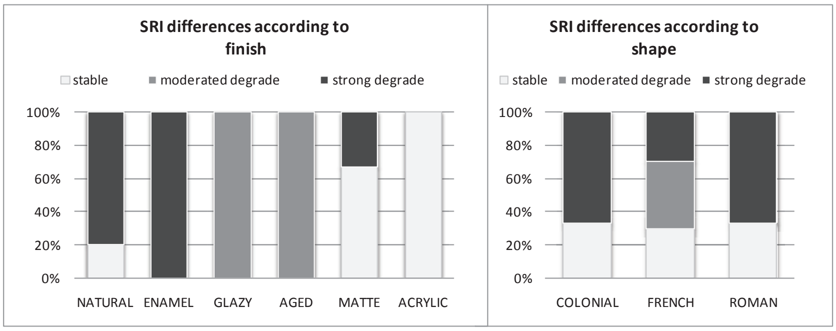

Fig.4. Relative frequencies distribution (%) of SRI differences (Δ SRI) in roof tiles.
a. According to its finish. b. According to its shape.

4 CONCLUSIONS

The roofs are a determining building component for the reduction of thermal levels and energy consumption associated with cooling. In this study it was shown that the Solar Reflectance Index of the tiles decreases rapidly with age in the total of the evaluated samples (75% of the tiles showed SRI degradation leves higher than 20%). As a consequence, the ability to diminish urban temperatures is rapidly degraded in the first years of their service life. The tendency is accentuated in the materials which were initially more efficient. Therefore, it is not enough to study the initial thermal behaviour but also track the annual evolution of SRI values throughout time. This is proved by the obtained results, for example, in the case of the most efficient tile -T08: its SRI1=90% and SRI3=54%; and the less efficient-T12- has an SRI1= 47% and SRI3=29%.

The influence of the tiles' aging in the thermal performance is closely related to the combined effect of their characteristics, such as composition, colour, finish and shape.

The mentioned variables lead to the following results:

- The *concrete* composition shows a more efficient behaviour than *clay* when submitted to weather and aging conditions
- The *black* colour is less degraded than lighter tones such as *gray* or *terracotta*.
- The *acrylic* and *matte* finishes have a less wear than the rest.
- The *french* shape is the alternative which registers a lower degree of aging in comparison to the *colonial* and the *roman*.

By comparing the initial behaviour of the evaluated samples in relation to the same alternatives submitted to wear during a 3-year period, it can be concluded that the tiles which proved most efficient at the beginning (for example: T08-T01) continue to occupy this place after aging.

The results discussed in the present study indicate that the application of tiles as roof envelope is not advisable as an urban or building cooling strategy. The total of samples tend to increase their surface temperature between 12 and 24º C as a result of the strong decrease of the SRI levels (an average 40%)

The ranges of degradation of the roof materials also depend on the pitch to which the tiles are exposed. Such variable will be considered in future studies.

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