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Comparative experimental study of new absorbent surface coatings for flat plate solar collectors

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Abstract

Use of solar energy has a huge an enormous importance around the world especially in processes for the generation of electric power and heating applications; these processes such as thermal heating of pools, have been a very important factor to obtain a benefits in terms of technology and economy as regards of the usage of other conventional energy sources. In this work, the pool heating process was realized using a glass covered flat plate solar collector heating system with a copper absorber tube and aluminum fins operating in forced flow; they were installed in an elementary school. The objective was to make a comparative study of the adhesion, hardness, reflectivity, absorptivity and durability of two different commercial coatings on an absorbent surface of copper and aluminum, compared to the original coating of the absorber. The adhesion force was established in accordance with ASTM D3330-09 where the original coating is classified in a scale 5B showing no damages by desquamation. While the epoxy test was classified in a scale 4B and 5B; it indicates that it has a very good adhesion force, and few damages by scaling was observed. The reflectivity was measured based on ASTM D3330-09 standards. Another result was that the absortivity of the epoxy coating had values between 0,93 and 0,95; better results than the original coating that had values between 0,88 and 0,94. The durability assessment of the epoxy coating, which is exposed since December 2011 in the pool solar heating field, confirms that at first sight appreciable alteration was not observed on its surface, neither detachment. These studies are essential to establish which of these coatings are the most adequate technically and economically for a preventive and corrective maintenance of flat plate solar collectors.

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Keywords: Solar collectors, Solar selective absorber coating, mechanical and optical characteristiques.

1. Introduction

The use of solar energy in thermal processes of heating, drying, water treatment, etc., has great importance due to the energy transition that we live. There are different technologies to collect solar energy and can be classified in low (30-60 °C), medium (60-250 °C) and high temperature (250-1500 °C) [1]. In this work only low temperature heating process were studied, where one of the most used technologies since 1960 is the flat plate solar collector heater with glass or polycarbonate cover, with copper tube and fin or copper tube and aluminum fin. It is used for heating water from 30 °C to 120 °C, depending on the design of the collector, and materials quality that will determine the thermal efficiency of this device.

There are currently millions of square meters of this type of collectors installed worldwide and particularly in Mexico (more than 1.5 million m^2 installed until 2011) [2]. The main applications of this type of solar heater in Mexico are: pool heating (50%), water heating for domestic use (45%) and other applications (5%). Use of these devices requires maintenance to continue in operation, before being replaced by other equipment or replaced by other technologies.

In the maintenance some parts can be replaced with cover glass (on breaking) and also to repair the absorbing surface by its poor condition or possible loss of thermal efficiency. In this case selective paints deposited by chemical methods or by other techniques can be used. There are various products on the market with different optical properties (absortivity and emissivity), where it is important to consider that these coatings have the best adhesion, good mechanical resistance to weathering as to prevent losses by desquamation and breaking due to temperature changes, that is not easily scratched or evaporated with temperature and can withstand when it is exposed to ambient. The absorber plate of this type of collector is generally coated with a blackened surface to absorb as much heat as possible, which is called selective surface. These coatings possess high absortivity in the wavelength range from 0,3 to 2,5 µm and low thermal emissivity in the infrared region of 2,5-20 µm [4-6].

Experimental studies are required to evaluate the properties of the coatings existing in the Mexican, Colombian and international market that can be used in solar collectors. Otherwise, these millions of square meters of existing heaters will be removed and/or replaced by technologies that do not necessarily have a better quality. In an application case, which was the origin of this work, more than 100 solar flat plate collector heaters were rehabilitated in order to heat the water in the semi-olympic pool (Figure 1) of a primary school in the Mexico City [3], instead of using a diesel boiler. During this repair the aluminum absorbent plate was rehabilitated using a commercial type epoxy coating, whose physical properties are reported in this paper.

Figure 1. Installation of 195 flat plate solar collectors in the pool of a primary school in Mexico City.

These coatings that can also be selective surfaces usually consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to long wave thermal radiation, and a thin lower layer having a high reflectance and low emissivity. Surfaces with good optical performance have high manufacturing cost, but some low cost surfaces have also been proposed [7]. Currently, the absorber coatings with acceptable thermal stability are commercially available on the market, known as the surfaces TiNOX Classic, TiNOX Energy Cu y TiNOX Energy Al [8] with absorptivity values of 0,95 and emissivity of 0,04 and hardness values H90 (semi as EN 1652) and H18 (according to EN 485) which are deposited on copper surfaces. Also the surface called Sunselect y Mirotherm [9], deposited on copper surfaces, has absortivity values of 0,95 and thermal emittance of 0,05, with a hardness of material classified as semi-hard and hard, respectively and aging tests that allow 10 year guarantee. However, there is a continued need to increase the thermal, mechanical and optical stability of these coatings in order to maintain thermal efficiency constant throughout all useful life of the collector, which should not be less than 10 years [10]. Also L. Wua et al [11], developed a selective absorbing coating of CrN_xO_y/SiO_2 film on Cu substrate (Si) deposited with a magnetron sputtering technique, which provided an absorptivity (α) of 0,947 and an emissivity (ε) of 0,05 at 80 °C. Spectral selectivity (α / ε) of the coating is stable (0,930 / 0,073), even after heat treatment at 278 °C in air for 300 hours, but decreased (0,904 / 0,135) at 278 °C for 600 h. The determining factors ruling the thermal stability were investigated using micro-Raman spectroscopy, Photoelectron Spectroscopy X-ray (XPS) and Auger electron spectroscopy (AES), These measurements revealed, that the diffusion, either through all stacked layers or near to the interface region and by adjacent chemical interactions on the interface are the Achilles heel of solar thermal coatings to maintain high thermal stability. Because of this, E. AlShamaileh [12] developed a selective coating displaying solar absorption efficiency in comparison with commercial black paint used in solar heating systems. The coating was manufactured by incorporation of metal particles composed of an alloy of nickel-aluminum (NiAl) in black paint. Its optical behavior with different percentages of NiAl alloy in the coating was studied by ultraviolet-visible spectroscopy (UV-Vis) and infrared (IR). The chemical composition of the coating was characterized by X-ray diffraction and thermogravimetric analysis. The results allowed to conclude that the optical composition of NiAl was 6% by mass and found that this new coating, applied on a thermosyphon, solar collector showed an improved thermal performance compared with untreated black paint, with an average increase in water temperature of 5 °C for one year. Therefore it was found that, despite selective coatings showed higher spectral selectivity's, their methods of application are not simple and must be under strict conditions of application, too complicated to reproduce easily. Few studies also indicate that getting good thermal, stability conditions, good adhesion, hardness and resistance to weathering are also obtained. Other conditions coatings must have as well are being easy to apply, moderate cost and with the best physical properties, mechanical and environmental. Therefore, in this work the goal was to test epoxy based commercial coatings, easy to apply, with high mechanical strength and resistant to the environment. According to these specifications; with the purpose to study their mechanical and optical properties and in the future durability test (Figure 2) and consider them as options to rehabilitate the currently installed solar collectors. For this two commercial paints were selected, one available in Mexico and the other in Colombia, with which various samples were prepared of these coatings on aluminum and copper surfaces, as well as original solar collector coating samples that had been repaired and thus perform a comparative study of their properties.

2. Experimental part

2.1 Materials

The study was performed using aluminum and copper foils with thickness of 12,38 µm and 40,00 µm, respectively, that correspond to the flap covering copper tubes through which water flows in flat plate solar water heaters. This fin, when is coated with different materials, acts as the absorber of these heaters.

A comparison of properties was made between the original coating and the coating degraded by weather, against two new coatings. One formed by epoxy (zinc phosphate) followed by a commercial matt black type polymer and the second an anti corrosive (zinc phosphate) with catalyst followed by a semi-matt black solvent acrylic finish.

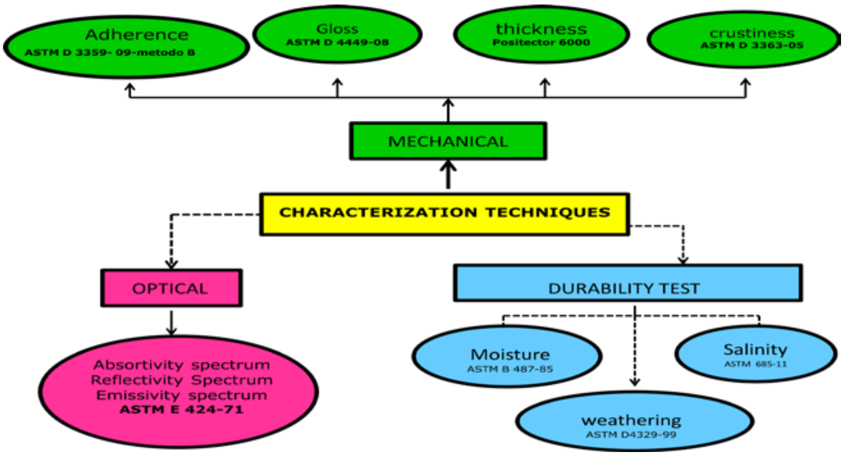

Figure 2. Set of experimental tests carried out on the coatings characterization and standards that support.

2.2 Application of coating

2.2.1 Epoxy

To the aluminum plate that maintenance could not be performed, the original coating was removed and simply cleaned with soap and water and allowed to dry. Therefore, the original coating was used as the base. Two layers of epoxy paint were applied with air gun prepared by mixing catalyst with 1:1 and allowed to dry for 2 hours at room temperature. Subsequently, the polyurethane paint mixed in a 2:1 ratio with its respective catalyst and thinner in a ½ portion for a more liquid consistency. Five layers were applied with air gun. It was then allowed to dry at room temperature for two days before being used for the evaluation tests, and to be used in the rehabilitated flat plate solar collectors.

2.2.2 Acrylic

New foils of aluminum and cooper were simply cleaned with soap and water, then dry sanded to create roughness on the surface and to obtain good adhesion and be free of grease, moisture and any other contaminants. Two layers of epoxy anticorrosive red oxide were applied with an air gun and allowed to dry for two days. Subsequently, two coats of semi-matt acrylic finish were applied and then allowed to dry for two days to achieve a solid layer. These films were used for property evaluation.

2.3 Mechanical characterization

2.3.1 Coatings thickness measuring

Measuring the thickness of coatings was conducted using a Positector 6000, equipment for metallic substrates. The adjustment or calibration of the instrument was performed with the value of a sample without coating in order to improve the performance of the instrument; four samples per coating were taken and 15 readings were realized over each one. The reported value is the average measurement.

2.3.2 Adhesion Test

Adhesion tests were performed on the coatings using ASTM D3359-09 [13]. The B method was used to measure adherence of the original coating and the epoxy, because its thickness was less than 50 μm. The spaces between cuts were 2 mm and this resulted in 6 cuts. The results are reported according to the comparison with the table. The method A (thickness greater than 125 μm) was used for the acrylic coating, for which they have a simple X-shaped cut 40 mm long, it was cut near its center with an angle of less than 30°. The result is reported based on the scale indicated in the standard. Each test was carried out in triplicate for the four types of samples.

2.3.3 Hardness Test

Hardness testing of the coatings was conducted using ASTM D 3365-05 [14] and were done in triplicate for each sample. The hardness scale was measured using pencils from 6B to 4H, in this way it can indicate hardness values from very soft, semi-soft, hard, semi-hard, hard stone, and steel hardness.

2.4 Optical characterization

I order to study the optical behavior of the samples, the absortivity and reflectivity spectra of the coatings was measured using a Cary 5000 spectrophotometer with integrating sphere, in the spectral range 300 to 2500 nm, using ASTM E424-71[15]. The test was performed on three samples of two types of coatings: the original and the epoxy. The assessment of gloss of the coatings was performed using two methods: (a) ASTM D4449-08 [16] with a lamp that consists of a white light bulb Philips 15 W to visually evaluate differences in brightness, and (b) using a light meter HD400; measuring light levels of each of the samples. This was performed by placing the sensor horizontally under a light source at 19 cm, allowing to compare relative changes in light levels of each of the coatings (original, epoxy and acrylic).

2.5 Weathering test

The evaluation of epoxy coating durability was at first in a solar field with 100 solar flat plate collectors to which we applied this new coating since December 2011.

3. Results and discussion

3.1 Mechanical Properties

Table 1 presents the results of thickness, adhesion and evaluation of the original coating hardness, for the acrylic and epoxy applied on surfaces of aluminum and copper. The coating adhesion strength of the original surface is classified on a scale indicating 5B that the edges are even and has no desquamation losses (Figure 3a), which can be attributed to the thermal diffusion of the film on the aluminum sheet [11] by its long exposure to sunlight, because these samples were taken from the solar collectors that during four years were not operational and thus heated to temperatures above 120 °C. The epoxy coating (Figure 3b) is graded on a scale of 4B-5B, indicating that it has good adhesion properties and flake loss does not exceed 5%. At the same time Figures 3c and 3d show the acrylic coating applied to aluminum and copper (adhesion test method A) 5A indicating that no desquamation was present. Therefore it can be concluded that all the coatings have excellent adhesion properties. Regarding the hardness it was found, that being independent of the type of coating, thickness and material of the surfaces absorbing the pencil produces no crack and the quality is not affected. This allows to conclude that the coating according to the way they were applied have good hardness which will imply permanence on the surface to mechanical stresses. Similar works have shown that the hardness is important in the quality of the coating, such that a good hardness results in higher durability [17]. Furthermore, the results show that the thickness of the coatings does not play a decisive role to improve or worsen the mechanical properties thereof.

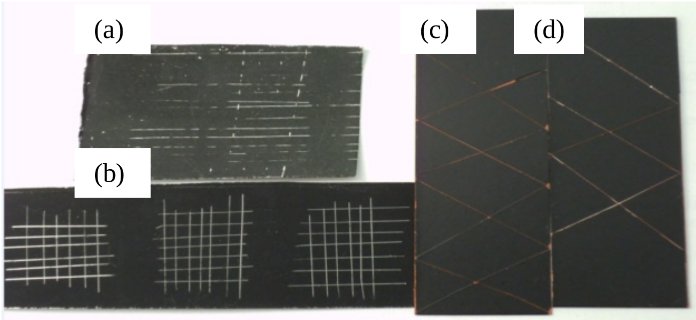

Figure 3. Photographs of the coatings tested for adhesion: method B on aluminum (a) Original, (b) Epoxy; method A (c) Acrylic on copper, (d) Acrylic on aluminum.

Table 1. Test results thickness, hardness and adhesion to various coatings applied.

COATINGS				
Type of test	**Original**	**Epoxy**	**Acrylic**	
			Aluminum	Copper
Thickness (μm)	111	373	1536	1627
Hardness	Very hard	Very hard	Very hard	Very hard
Adherence (%)	0 (5B)	5 (4B-5B)	0 (5A)	0 (5A)

3.2 Optical Properties

Figures 4a and 4b shows the reflectivity and absortivity spectrum depending on the wavelength of the original coating and the epoxy respectively applied on aluminum foil. It can be observed that the original coating has higher reflectivity than the epoxy so the absortivity of this, improved significantly compared with the original coating in almost the entire spectrum of wavelengths. The results indicated that the absortivity of the epoxy coating are satisfactory values between 93-95%, which improved those obtained with the values of the original coating that were in average between 88-94%. The surface absortivity improved in average between 4% and 6% by applying the epoxy coating.

Table 2 presents the qualitative results of the differences in brightness, they were made by observing the surfaces studied and classified according to the standard used (column two and three), and quantitative results using a light meter (column four) to measure the brightness reflected by the coatings.

It can be seen that the epoxy coating has a lower brightness compared to the other coatings. This result is in accordance with the technical specifications of epoxy where it reported it had a matt finish, while the acrylic has a semi-matte finish. It also shows that the acrylic applied to the copper surface shines a little less that applied about on the aluminum, which indicates the former is more opaque that the second.

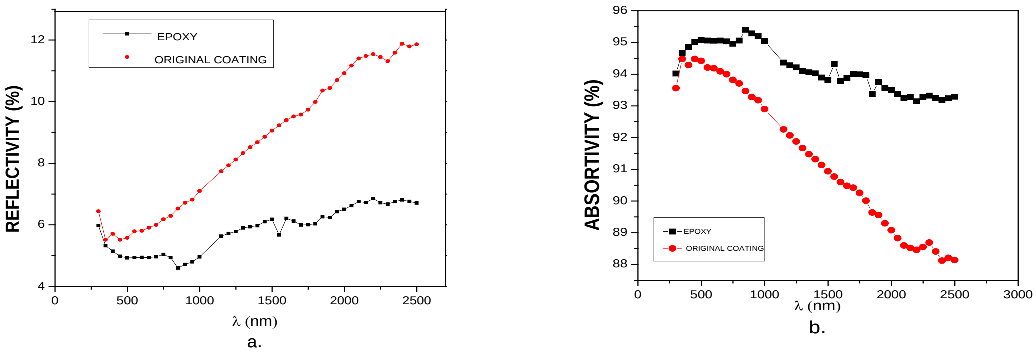

Figure 4. Reflectivity (a) and absortivity spectrum (b) of the original coating and epoxy.

Table 2. Qualitative and quantitative results of the different coatings brightness.

Coatings	Brightness difference	Valuation	Brightness (Lux)
Original	Easily visible	2	25,70,1
Epoxy	Very light	0	13,40,1
Acrylic (copper)	Distinguishable	1	15,30,1
Acrylic (aluminum)	Easily visible	2	18,80,1

3.3 Weathering

The durability evaluation the epoxy coating, which is exposed since December 2011 in a field of solar flat plate collectors, It can de concluded that at first glance there is no change in the surface or any detachment.

4. Conclusions

The tests were performed to mechanically and optically characterize the original coatings, epoxy and acrylic. The results allow confirming that the epoxy coating has better characteristics than the other, so it can be used in the preventive and corrective maintenance of solar collector heating systems. The reasons are as follows:

- Epoxy coating adhesion is slightly less than the original and the acrylic however flake loss does not exceed 5%.
- Regarding the hardness, the results showed very similar behavior among all coatings, regardless of the thickness.
- Regarding optical properties, the epoxy coating has a lower brightness than the other two coatings and better absorptivity between 4% and 6% than the original coating, showing lower values of reflectivity in the entire wavelength spectrum, which allows better thermal performance and greater useful heat gain.
- Regarding the weathering evaluated in 100 flat solar heaters rehabilitated with epoxy coating, and after 18 months of exposure to solar radiation is not observed any alteration or detachment on its surface.

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