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Cite as: AIP Conference Proceedings **2303**, 150016 (2020); https://doi.org/10.1063/5.0028960
Published Online: 11 December 2020

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Effect of Long Term Outdoor Exposure on Anti-Soiling Coatings for Solar Reflectors

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Abstract. Results of the outdoor exposure campaign of two newly developed anti-soiling coatings for CSP mirrors are presented in this paper. Samples of coated mirrors were exposed for two years under realistic outdoor conditions and the application of two different cleaning techniques was investigated. Mirror samples were analyzed during exposure and their reflectance and cleanliness were measured. The performance of the anti-soiling coated mirror samples was compared to conventional uncoated mirrors. Depending on the selected combination of coating and cleaning technique, an advantage or disadvantage was observed over the exposure duration. One coating presented an overall cleanliness gain of 0.008 with pressurized water cleaning, due to its superior anti-soiling behavior, while presenting a negative gain of -0.009 with contact cleaning, due to its poor durability. The other coating showed a worse anti-soiling behavior, with a negative gain of -0.005 for pressurized water cleaning, due to its poor washability, and a positive gain of 0.005 with contact cleaning.

INTRODUCTION

The worldwide deployment of Concentrated Solar Power plants (CSP) during recent years has aroused interest in the influence of site specific parameters on the efficiency of the systems. Although usually installed in regions with excellent solar resources, i.e. high irradiance, sites for CSP plants can show a wide range of environmental conditions. These range from coastal over desertic areas to high altitude locations in the mountains. Parameters such as temperature, humidity, wind and chemical compounds in the air may vary drastically among these sites. One important parameter that is very site specific, is the soiling of optical components, which is mainly dependent on particles (airborne and on the ground), wind and humidity. The soiling is a main issue for CSP due to the beam spread of the reflected rays caused by particles deposited on the mirrors in the solar field. Reflectance of the mirrors is strongly affected by soiling, which thus directly influences the optical efficiency of the solar field.

One possible approach to mitigate the issue of soiling of solar mirrors is the application of anti-soiling coatings on the surface of these mirrors. The way anti-soiling coatings are supposed to work is twofold: first the coatings reduce the amount of soiling that accumulates on the reflectors over time and secondly they improve the "washability" of the mirrors, facilitating a more effective cleaning process. There are different methods to achieve anti-soiling properties [1]. Usually the effects utilized for the manufacturing of commercial coatings are: the anti-static effect directly decreases the ability of small particles to stick to the surface, hydrophobic and hydrophilic properties change the wettability and behavior of water on the surface, as well as the photocatalytic effect helps to decompose organic matter. So far, anti-soiling coatings have not reached commercial penetration in the CSP sector.

SolarPACES 2019
AIP Conf. Proc. 2303, 150016-1–150016-10; https://doi.org/10.1063/5.0028960
Published by AIP Publishing. 978-0-7354-4037-1/$30.00

Investigations are going on in recent years, but only one commercial supplier has offered this type of coatings for solar reflectors [2].

In the EU Horizon 2020 Raiselife project, investigations are performed to raise the lifetime of different components for CSP. One work package deals with primary solar reflectors and includes a task dedicated to anti-soiling coatings. Different generations of this type of coatings are tested in accelerated aging tests as well as at different outdoor sites. This paper presents the result of an exposure campaign under realistic conditions at a typical CSP location, including the performance of regular cleaning and reflectance measurements.

METHODS

For the first generation of anti-soiling coatings within the Raiselife project, an experimental campaign was set up at the Plataforma Solar de Almería (PSA) by the team of the OPAC laboratory, a collaboration between DLR and CIEMAT. The PSA is located in Tabernas in the south of Spain. The environmental conditions can be characterized as semi-desertic, dry with little precipitation. Influence by dust and airborne particles is rather low [3], mean soiling rates of 0.5 %/d (loss cleanliness per day) have been reported [4].

Two exposure racks were installed at the PSA, called structure 1 (S1) and structure 2 (S2) (see Fig. 1 a), to be treated with two different cleaning techniques. S1 was cleaned with pressurized water with a Kärcher HDS 10/20-4M device (Fig. 1 b) at a pressure of 100 bar and a distance between nozzle and samples of ca. 50 cm. S2 was cleaned with the same device but using a contact cleaning method with a brush under a low pressure water flow. Cleaning was always performed in the same way with a defined number of five strokes per sample. The campaign was conducted from the end of January 2017 until the end of December 2018 and thus covering a period of nearly two years. In April 2018 a rigorous cleaning of all samples was performed to remove soiling that possibly accumulated over time due to incomplete cleaning.

Two anti-soiling coatings were analyzed during the exposure campaign, the first using the anti-static effect, called AS1, and the second possessing a hydrophobic surface, called AS2. Three samples of 20x20 cm² of each anti-soiling coating type were installed on the two racks together with three uncoated samples (10x10 cm²) for reference (Ref).

a) b)

FIGURE 1. a) Outdoor exposure rack 1 with exposed samples, b) Kärcher cleaning device.

Measurements and cleaning were performed every two weeks. The procedure consisted in the measurement of the monochromatic specular reflectance before cleaning to analyze the cleanliness in the soiled state. Then the two cleaning techniques were applied on the respective structures, followed by another measurement of the reflectance in the clean state to evaluate the effectiveness of the cleaning procedures. For the measurements, a mask was placed on the samples and measurements were always taken on the same spots on the samples. Five measurements were performed for the samples and the average value was calculated. For the reference samples, only one measurement per sample was done. A portable specular reflectometer model 15R-USB from Devices and Services (D&S) was used to measure the monochromatic specular reflectance $\rho_{s,\varphi}$(660 nm; 15°; 12.5 mrad) with an incidence angle of 15° and in a wavelength range between 635 and 685 nm, with a peak at 660 nm. The measurements were taken with an acceptance angle of 12.5 mrad.

From the reflectance measurements the other most important parameters for the evaluation of the coatings can be determined. The cleanliness is defined as the ratio of the actual reflectance, $\rho_{s,\varphi}$, to initial reflectance in the perfectly clean state, $\rho_{s,\varphi,clean}$:

$$\xi = {}^{\rho_{s,\varphi}}/_{\rho_{s,\varphi,clean}} \quad (1)$$

In the field, the cleanliness value potentially includes a part influenced by degradation. The cleanliness value 1 is determined at the beginning of the campaign after perfect cleaning in the laboratory. During outdoor exposure the cleaning is usually not able to completely remove all the soiling and the reflectance in the perfectly clean state is unknown. If degradation decreases the reflectance in addition to the soiling, this will directly influence the cleanliness parameter. However, experience has shown that degradation rates of commercial silvered-glass mirrors is low in Tabernas (typically ≤0.2 %-p/year [5]), thus it is reasonable to neglect the effect of silver corrosion.

The second important parameter is the difference between the cleanliness of the coated AS samples and the uncoated reference material, in the following referred to as cleanliness gain, Δ_ξ:

$$\Delta_\xi = \xi_{AS} - \xi_{uncoated} \quad (2)$$

When this parameter is positive, the cleanliness of the anti-soiling material is higher than for the uncoated reference material. In this case, there is an advantage of the coating. A negative Δ_ξ shows a disadvantage of the coating compared to the reference material.

The accumulated cleanliness gain, $\overline{\Delta_\xi}(t)$, after exposure at a certain exposure time, t, can be calculated by integrating the reflectance difference over the analyzed exposure time dividing by the exposure duration:

$$\overline{\Delta_\xi}(t) = \frac{\int_{t=0}^{t} \Delta_\xi dt}{\Delta t} \quad (3)$$

This value is extremely valuable as it determines the actual advantage of the respective coating compared to a reference material until the analyzed point in time. For the calculation of this value, a linear behavior of the cleanliness between two measurements is assumed.

RESULTS

The following structure for the presentation of the results is chosen: first the results before cleaning are presented and then the ones after cleaning. In both cases, first the results of structure 1 (pressurized water cleaning) are displayed, followed by structure 2 (brush cleaning). Always two charts are presented together: the cleanliness of all three materials (AS1, AS2, Ref) followed by the cleanliness gain for the two AS coatings.

Cleanliness before Cleaning

In Figure 2 the cleanliness and cleanliness differences are displayed for structure 1 before cleaning, meaning in the soiled state. The cleanliness mainly fluctuates throughout time between values of 0.8 and 1.0 with few cases of very strong soiling, reaching minimum cleanliness values of down to 0.45. This lowest value is reached after only a few weeks of exposure after a special event of light rain in combination with a very dusty atmosphere, leading to the strong deposition of dust on the sample surfaces. Excluding this event, cleanliness does not drop below 0.7 during the whole campaign. In general, AS1 shows the highest cleanliness values and thus also the higher cleanliness gain (see the red line in Fig. 2 b). $\Delta_\xi(t)$ is usually higher when the soiling is stronger (compare strong soiling events in Fig. 2 a). AS2 shows a lower cleanliness gain (see Fig. 2 b), staying in the negative regime for the majority of measurements.

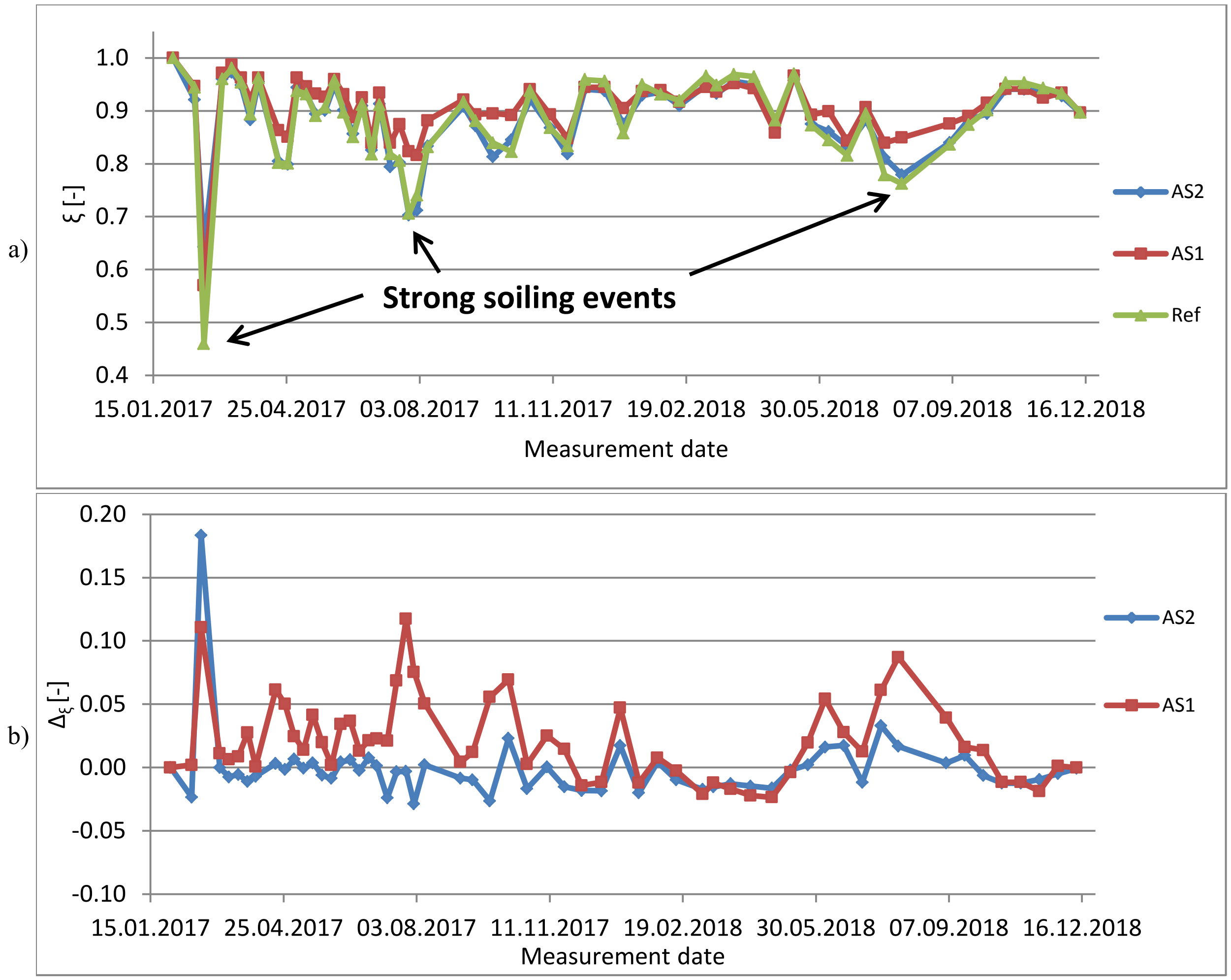

FIGURE 2. a) Cleanliness of structure 1 (pressurized water cleaning) before cleaning and b) Cleanliness gain for both AS coatings of structure 1 before cleaning.

In Figure 3, results before cleaning for structure 2, which is cleaned with the brush, are presented. Overall cleanliness values are slightly higher than for structure 1 due to the fact that the brush cleaning technique is more effective than the high-pressure water cleaning. In the beginning of the campaign, the behavior of AS1 is similar here to the one for structure 1. AS1 shows higher cleanliness values than AS2 and the reference material, thus presenting a higher gain. This behavior changes after around one year of exposure with the AS1 cleanliness dropping below the values of the other materials. The gain for AS1 then stays in the negative regime for most of the remaining time. AS2 shows less pronounced fluctuations of the cleanliness gain, but with ongoing exposure showing better behavior than AS1. The negative development of AS1 indicates a degradation of the coating by the brush cleaning. This will be further analyzed with the following presentation of the results after cleaning.

a)

b)

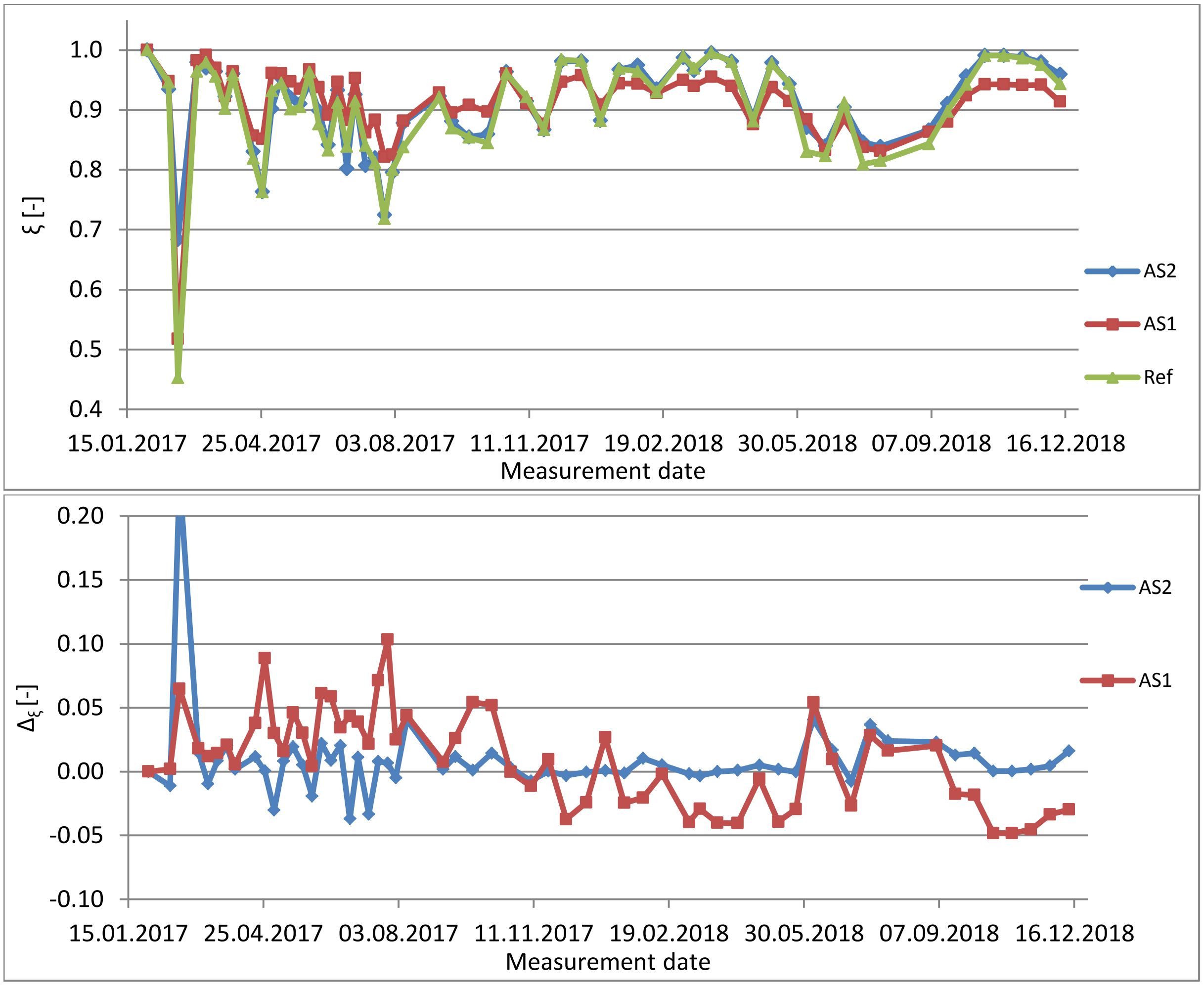

FIGURE 3. a) Cleanliness of structure 2 (contact cleaning with brush) before cleaning and b) Cleanliness gain for AS coatings of structure 2 before cleaning.

Cleanliness after Cleaning

In the following graphs, the results after the cleaning of the samples are presented. Even though measurements are performed directly after cleaning, initial reflectance and thus cleanliness is not restored for all cases. This can be explained by two facts: first, cleaning is performed with well-established parameters and not until the samples are perfectly clean. This means that, depending on the soiling state and the effectiveness of the cleaning, soiling remains on the surfaces, possibly lowering the reflectance. Secondly, the overall reflectance of the samples may be affected by permanent degradation.

In Fig. 4 the cleanliness and the cleanliness gain are displayed for structure 1 after cleaning. Two special events are marked in Fig. 4 a): the thorough cleaning in the field (Reset at 04/2018) and the measurements that were performed after finishing the exposure campaign after cleaning in the laboratory. Looking at the first graph it is clearly visible that the high-pressure water cleaning is not able to restore the initial reflectance and that soiling accumulates with time, leading to a downward trend of the cleanliness for all materials. The cleanliness stays in general at a high level compared to the before cleaning values (compare scale of Fig. 2), with values of over 0.93. The two thorough cleaning events are able to restore the cleanliness to over 0.98, showing that only little degradation takes place. Interestingly, throughout the whole campaign the cleanliness is higher for the reference material, leading to negative values for the cleanliness gain for both AS coatings. Only for few events, the gain is positive, resulting in an advantage. One event (05/2017) sticks out with a higher advantage, which was caused by a low cleanliness value of the reference material due to deficient cleaning. The negative cleanliness differences lead to the conclusion that both coatings fail in facilitating the cleaning, and because of that showing a worse washability than uncoated reflectors.

a)
b)

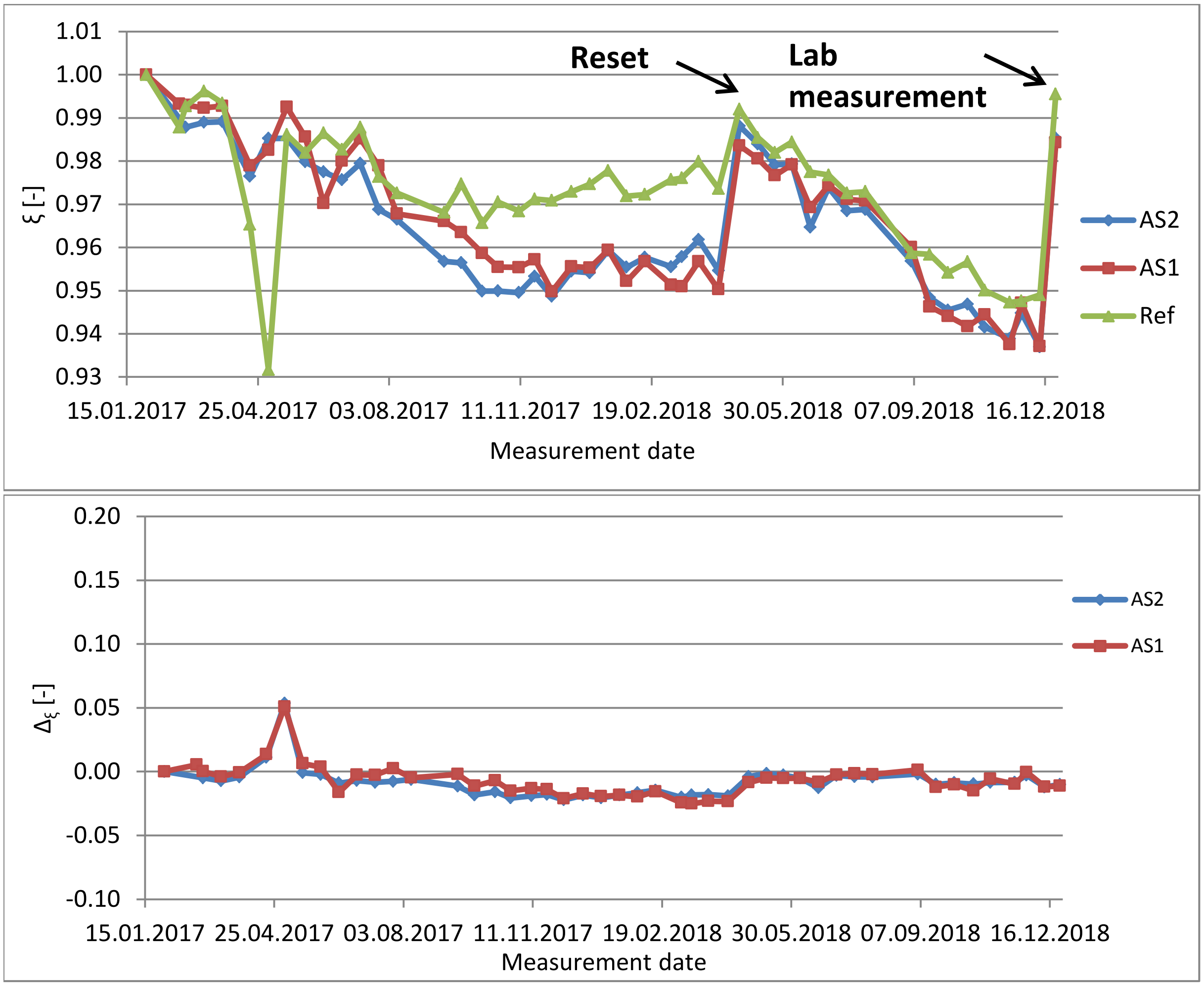

FIGURE 4. a) Cleanliness of structure 1 (pressurized water cleaning) after cleaning and b) Cleanliness gain for AS coatings of structure 1 after cleaning.

In Fig. 5 the results for structure 2 after cleaning are presented. The most striking observation is the behavior of AS1. While the cleanliness of AS2 and the reference material shows a very constant evolution, with cleanliness values remaining over 0.99, the cleanliness of AS1 shows a clear downward trend, reaching values around 0.94 at the end of the exposure campaign. Although the two thorough cleaning events were performed analogue to structure 1, they remain unperceived in the cleanliness data. Together with the high values of AS2 and Ref, this leads to the conclusion that the brush cleaning technique is able to basically remove all the soiling, restoring the full cleanliness of the reflectors. As the cleanliness of AS1 is not restored by the thorough cleaning, it must be concluded that the decrease in cleanliness is due to permanent degradation provoked by the brush cleaning. No degradation is perceived for AS2 or the uncoated reference material.

Because both AS2 and Ref material's cleanliness stays close to 1, the gain for AS2 is very close to zero. The gain decreases over time for AS1 due to the decreasing cleanliness caused by degradation.

a)
b)

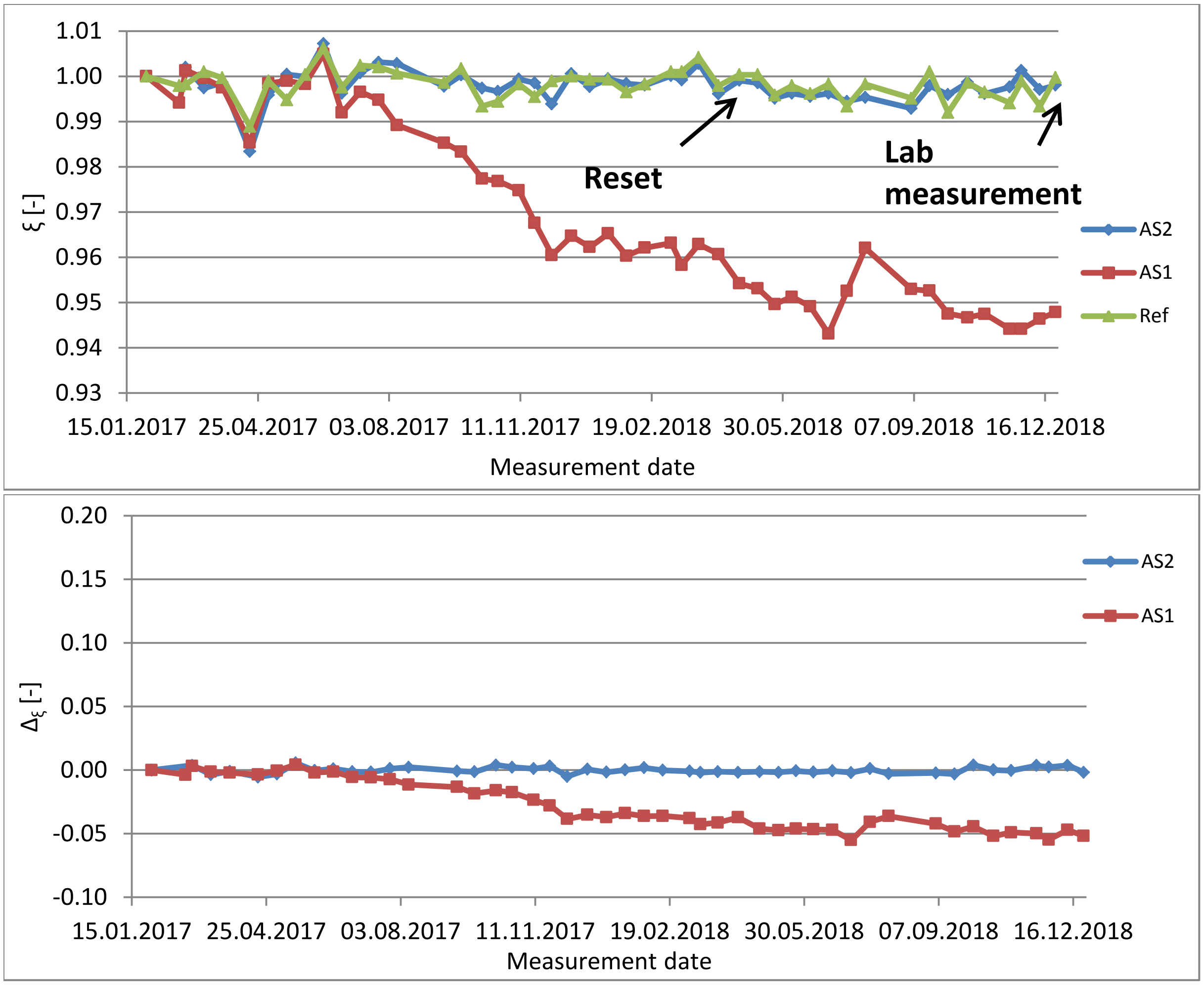

FIGURE 5. a) Cleanliness of structure 2 (contact cleaning with brush) after cleaning and b) Cleanliness gain for AS coatings of structure 2 after cleaning.

Accumulated Cleanliness Gain

The accumulated cleanliness gain is displayed in Fig. 6 for both structures and both anti-soiling coatings, with respect to the reference material. Each point in time here represents the evaluation of the accumulated gain for the exposure until that time. In the beginning of the exposure, this accumulated gain presents stronger variations with time, because the evaluation only comprises a shorter period and thus fewer values. For example, the strong dust event at the beginning of the campaign leads to high advantages of the coatings (see Fig. 2 and 3), resulting in strong positive peaks for all 4 curves in Fig. 6. The AS2 curves afterwards show a strong decrease due to lower differences for the following measurements. With longer exposure duration, variations decrease due to a longer evaluated exposure period, leading to a weaker influence of single events.

Considering the whole exposure campaign, the overall cleanliness gain of the coatings can be evaluated depending on the applied cleaning technique. This gain for the whole campaign is simply the end point of the respective curve in Fig. 6. Two of the four cases show an overall advantage of the use of the coatings: AS1 with high-pressure water cleaning ($\overline{\Delta_{\xi,S1\_AS1}} = 0.008$) and less pronounced for AS2 with brush cleaning ($\overline{\Delta_{\xi,S2\_AS2}} = 0.005$). Both remaining cases show an overall disadvantage ($\overline{\Delta_{\xi,S1\_AS2}} = -0.005$ and $\overline{\Delta_{\xi,S2\_AS1}} = -0.009$).

In the beginning, AS1 shows a very similar behavior for both structures, but with progressing time the degradation of AS1 by the brush cleaning affects the accumulated gain, reaching the negative regime after roughly 1.5 years. AS2 shows a less pronounced anti-soiling effect (see cleanliness graphs before cleaning), but also less degradation by the cleaning or other factors. The AS2 coating samples cleaned with high-pressure water show a disadvantage already after less than one year.

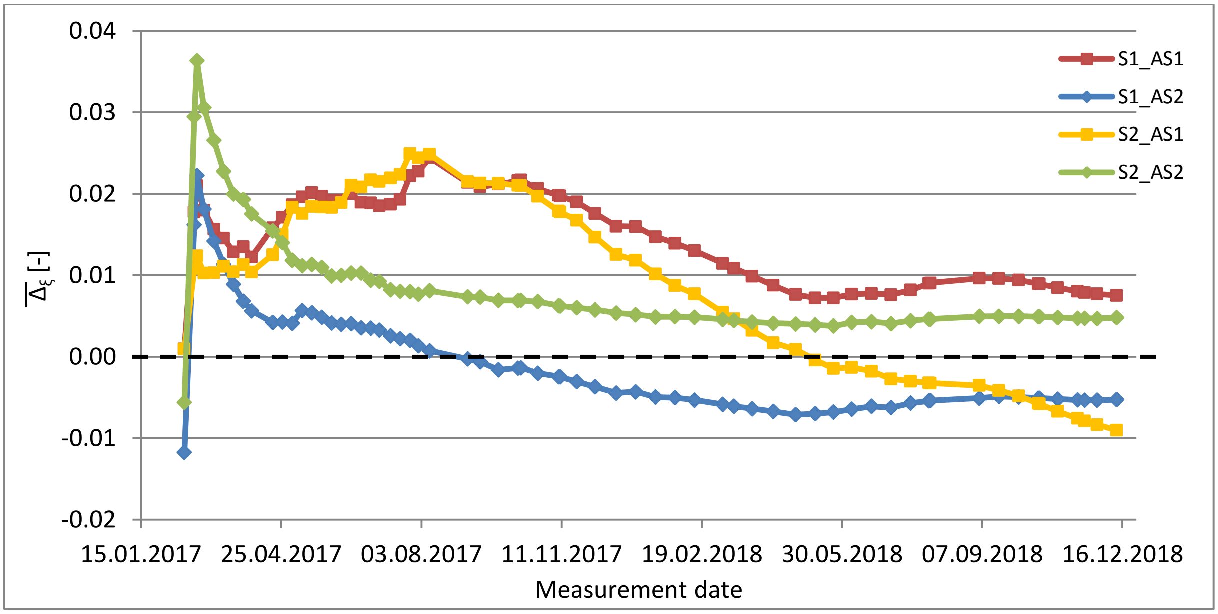

FIGURE 6: Accumulated cleanliness gain for both materials and structures over time.

When the reflectance instead of the cleanliness is taken into account for the evaluation, only one of the four cases shows an advantage (AS2 with brush cleaning). The initial reflectance of AS1 is around 1.5 percentage points lower than the uncoated reference material, while AS2 manages to achieve the same reflectance as the uncoated reference (94.5 %). This is why the accumulated reflectance gain for AS1 is lower than the cleanliness gain. The advantageous case (positive reflectance gain), AS2 with brush cleaning, presents a gain of 0.3 percentage points, raising the mean reflectance in Tabernas from 90.8 % to 91.1 %. In the other three cases the mean reflectance is lowered by the coatings.

Microscopic Analysis

Finally, microscopic analysis of the samples was performed after completion of the outdoor campaign, mainly to detect possible degradation of the coatings. In Fig. 7 example images of the coating surfaces are presented, confirming the results found and presented above. Fig. 7 a) shows the surface of AS1 cleaned with pressurized water, presenting minor defects of the coating and minimal soiling residues. Fig. 7 b) represents the surface of AS2 after pressurized water cleaning and the presence of strong soiling residues spread over the surface can be appreciated. This leads to the conclusion that this cleaning technique is indeed not effective to prevent the long term accumulation of particles on the surface of that type of coating. This fact explains the weak behavior of AS2 on structure 1 (compare blue line in Fig 6.). In Fig. 7 c) the damages caused by the brush cleaning on AS1 can be appreciated. Clearly visible vertical lines, following the movement direction of the brushes during cleaning performance, confirm the weak durability of AS1 to mechanical wear, in this case contact cleaning. These damages directly lead to a lower reflectance due to scattering and absorption at the surface and possibly facilitate the accumulation of particles. The last image (Fig. 7 d) shows the surface of AS2 after brush cleaning with no detectable defects and only minimal particle residues remaining on the surface.

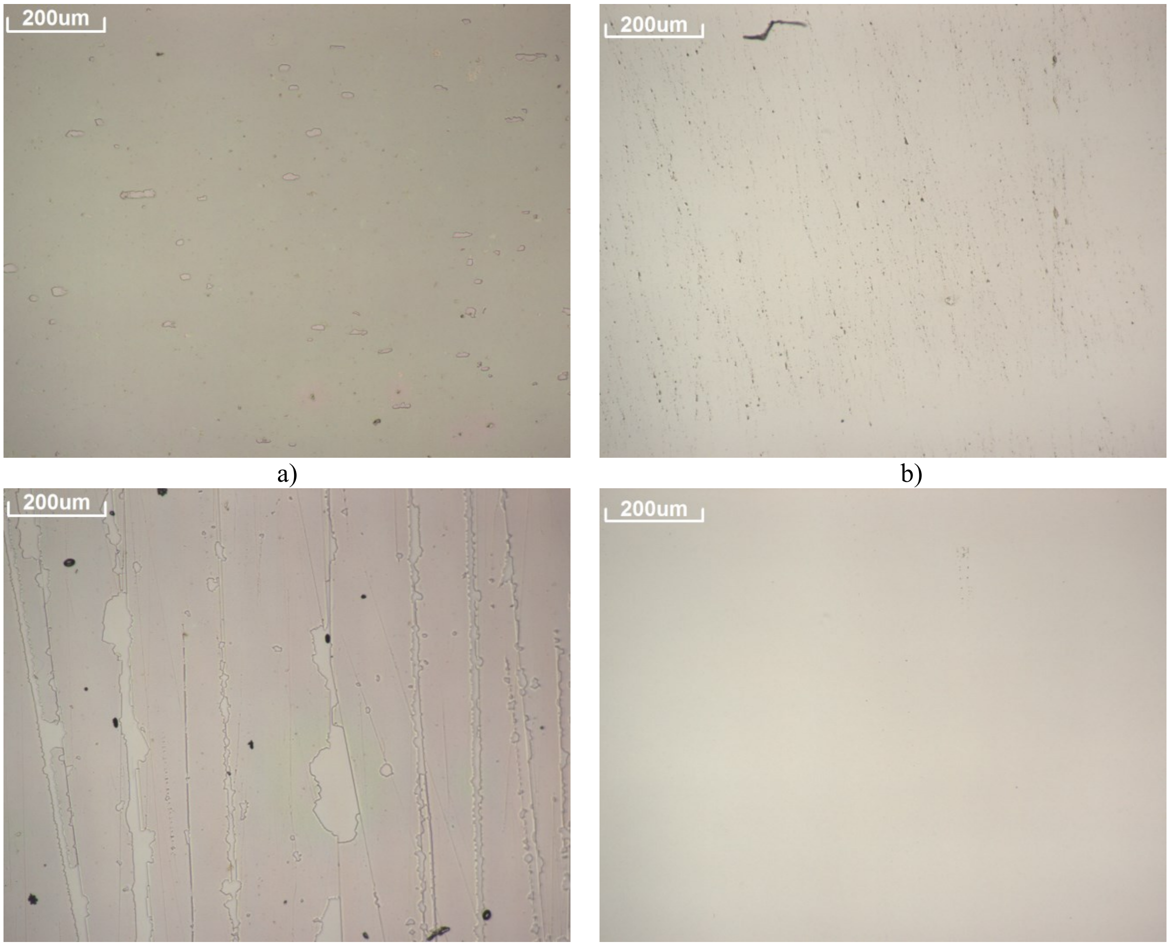

FIGURE 7: Microscope images after exposure of a) AS1 pressure water, b) AS2 pressure water, c) AS1 brush and d) AS2 brush.

CONCLUSIONS

Outdoor exposure campaigns with anti-soiling coatings require a careful selection of test parameters related to exposure environment, cleaning method and measurement technique in order to realistically represent commercial operation. Four cases were analyzed in this campaign: 2 types of coatings (AS1 and AS2) and 2 types of cleaning techniques (pressurized water and brush contact cleaning). While one coating shows an advantage for one cleaning technique, the other coating performs better for the other technique. I.e., an advantage can be detected for AS1 with pressurized water cleaning, as well as AS2 with brush cleaning. On the contrary, AS1 shows a disadvantage with brush cleaning and AS2 with pressurized water cleaning. This can be explained by various factors:

- AS1 shows the better anti-soiling properties with higher cleanliness values compared to uncoated material, especially in the presence of strong soiling. This leads to the highest accumulated cleanliness gain of the 4 cases after 2 years with pressurized water cleaning: $\overline{\Delta_{\xi,S1\_AS1}} = 0.008$.
- AS1 exhibits poor durability, mainly to mechanical stresses (contact cleaning by brush), strongly affecting the surface of the material on structure 2. This is why the gain is high in the beginning, similar to structure 1, but decreasing over time, resulting in the lowest (negative) gain at the end of the campaign after 2 years: $\overline{\Delta_{\xi,S2\_AS1}} = -0.009$. This trend is expected to continue, further decreasing the gain with longer exposure times.
- The AS2 anti-soiling properties are detectable, but lower than for AS1. The washability seems to be worse than for AS1 and the uncoated material, which is why pressurized water cleaning is not able to

restore high cleanliness values. This leads to an accumulation of soiling over time, resulting in a disadvantage (negative gain) after a relatively short period of less than one year. After 2 years of exposure the accumulated cleanliness gain is $\overline{\Delta_{\xi,S1\_AS2}} = -0.005$.

- When AS2 is cleaned with the brush cleaning technique, the accumulated cleanliness gain is positive throughout the campaign, remaining basically constant after a stabilization phase in the beginning of the campaign. After 2 years of exposure the accumulated cleanliness gain is $\overline{\Delta_{\xi,S2\_AS2}} = 0.005$. As no degradation is detected, this coating may have advantages compared to AS1 when longer exposure durations are analyzed, since the abrasion resistance of AS2 is superior to AS1.
- Taking into account the lowered initial reflectance of the anti-soiling coated samples of 1.5 percentage points (AS1), only AS2 manages to raise the average field reflectance from 90.8 % to 91.1 % in Tabernas during the exposure period of 2 years with 2-week brush-cleaning intervals.

Changing the setup of the campaign by choosing different parameters (e.g. different location with varying environmental parameters, cleaning technique or frequency) may influence the results for the coatings considerably, and thus well-known operation parameters could help selecting an adequate coating.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 686008 (Raiselife). The authors want to thank Tomás Reche Navarro and Carmen Amador Cortés from DLR and Lucía Martinez Arcos and David Argüelles Arízcun from CIEMAT for their valuable contributions to the realization of the exposure campaign and measurements.

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