Evaluation of anti-soiling coatings for CSP reflectors under realistic outdoor conditions

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Abstract:

Soiling of solar reflectors affects their reflectance and has a direct impact on the power output of concentrated solar power (CSP) plants. One way to minimize the efficiency losses is the implementation of anti-soiling coatings on the reflector surfaces. This method is being studied for the past decade, but has not been successfully commercialized yet. The purpose of the coatings is to reduce soiling and improve the washability of the reflectors. In this work results are presented from an extensive outdoor campaign of two potential anti-soiling coatings under realistic conditions at a representative CSP site in southern Spain. Nearly six years of outdoor data are available, which makes this campaign the longest published on this type of coatings. Regular cleaning and reflectance measurements were performed during the exposure and conclusions about the performance and durability of the coatings are drawn. It is shown that in the initial state the coatings show an advantageous behavior, resulting in higher reflectance during outdoor exposure due to less soiling and better cleaning of the reflectors. The second main finding is that durability is an important issue for the implemented coatings, as their properties degrade over time resulting in lower reflectance values after several years of exposure compared to conventional glass reflectors.

Keywords: anti-soiling; solar reflector; reflectance; durability; concentrated solar power

1. Introduction:

Solar reflectors are one of the key components for the development of cost competitive concentrated solar power plants as their quality directly influences the concentration of the incoming sunlight and thus the efficiency of the plant. The main characteristic that a solar reflector has to possess, in order to be able to assure a high efficiency of the plant (that is, 20-25 % of net electricity generation to incident solar radiation in a typical parabolic-trough collector plant [Reddy et al., 2013]), is a high solar specular reflectance (around 0.945 [Sutter et al., 2019]) over the lifetime of the power plant. An initial high reflectance is as important as maintaining that high value in time. The initial reflectance can be affected mainly by two mechanisms: first, progressive degradation throughout time, which changes some of the material characteristics irreversibly (García-Segura et al., 2016), and secondly by the soiling that can get accumulated on the surface as time goes by, which can be counteracted by cleaning. This soiling has a high impact on the reflectance. Common soiling rates with daily losses of around 0.5 % are reported (Wolfertstetter et al., 2018a), which can be considerably higher depending on the site's characteristics (Wolfertstetter et al., 2018b, Bouaddi et al., 2018). Cleaning large reflective areas of the solar field in a power plant implies major operation and maintenance (O&M) costs and thus, lowers the plant's benefits (Fernández-García et al., 2014). Additionally, with the cleaning methods applied nowadays, water demand is critical since many CSP plants are situated in arid regions with scarce water resources (Sarver et al., 2013).

One way to address this issue is to apply an anti-soiling coating on the front glass of the traditional solar silvered-glass mirrors. This coating should help decreasing the amount of soiling that remains on the reflector's surface and improving its washability (Plesniak et al. (2014).

Anti-soiling coatings are nowadays used in a variety of applications and industries, on ceramic and glass surfaces (Midtdal and Jelle, 2013). Currently, investigations are being carried out in order to use these coatings in solar energy technologies, mainly for photovoltaics (Costa et al., 2016), but also for CSP applications. Anti-soiling coating developments can be derived from the following three physical mechanisms:

- Hydrophilic coatings possess a high surface energy, which results in the formation of low contact angles between the coating and water droplets. This allows very thin films of water to form in the case of washing or rain and this facilitates dirt removal. This type of coating is often silica based (Aranzabe et al., 2018).
- Hydrophobic coatings, on the other hand, have a low surface energy and contact angles are high. This provokes the formation of small water droplets which easily roll over the surface taking present dirt particles with them (Polizos et al., 2014). Formulations of silica or titania nanoparticles are usually used.
- Titania based coatings often use the photocatalytic effect (Atkinson et al., 2015, Jesus et al., 2015), enhancing the decomposition of organic matter in the presence of UV radiation.

Whereas in many applications the use of anti-soiling coatings is common, only very few commercial products are available on the market for the CSP sector (Schwarberg and Schiller, 2012). The main criteria a coating has to fulfill, in addition to the anti-soiling effect, are a high transmittance and minimal scattering, in order to maintain the specular reflectance of the base reflector. While the solar-weighted specular reflectance is the optimal way to characterize a solar reflector, for practical reasons, especially in the field, often specular reflectance is only measured at certain wavelengths (Fernández-García et al., 2017). To characterize the quality of the coating, the reflectance difference with an uncoated reference material can be determined. To directly measure the hydrophilic and hydrophobic properties of the coatings, the contact angle can be analyzed.

While the manufacturing of coatings with excellent optical and anti-soiling properties has been demonstrated, the durability of these coatings is still an important issue. It was shown that the properties of coated reflectors can deteriorate in accelerated tests when exposed to UV-radiation and abrasive forces (Plesniak et al., 2014, Giessler et al., 2006). Limited data on real outdoor exposure are available for coated CSP reflectors and it is usually restricted to a few years. A previous study (Aranzabe et al., 2018) showed good durability for two coatings after 3.5 years with a specular reflectance of 2 to

3.3 % higher than for uncoated reflectors. Another work (Sansom et al., 2016) proved that the type of cleaning has an influence on the degradation, especially for non-glass type mirrors. Apart from cleaning, abrasion by airborne particles can play an important role in the degradation of reflector surfaces (Wiesinger et al., 2018) and may possibly be more pronounced for coated reflectors, since traditional glass mirrors have shown the highest durability (Kennedy and Terwilliger, 2005).

In this work, the methodology of an outdoor testing campaign for anti-soiling coatings and their analysis is described and the results and conclusions of this campaign are presented. The main objective is to evaluate the effectiveness of the coatings to increase the reflectance in comparison with uncoated standard material with glass surface under realistic conditions. The variation throughout time of this effectiveness is used as key indicator of the coatings' durability and their performance under different soiling conditions.

2. Method and Equipment:

2.1. Outdoor campaign:

The most realistic way to assess the behavior, here mainly soiling and degradation, of materials is via an outdoor exposure campaign under conditions similar to their real use, i.e. at a representative CSP site with regular cleaning (Bouaddi et al., 2017). For this work facets of a commercial solar 4 mm thick silvered-glass mirror material with different anti-soiling coatings were exposed on the Plataforma Solar de Almería (PSA) together with uncoated facets for reference. The reflector material with the coatings was provided by a major reflector manufacturing company and the campaign was conducted in close agreement with the company. The reflector facets were cleaned and the specular reflectance, as their main performance parameter, was determined on a regular basis. The portable specular reflectometer model 15R-USB (Figure 3-b), manufactured by Devices and Services, called 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. An accuracy of 0.002 (reflectance units) is given by the manufacturer, the calibration mirror has an uncertainty of 0.0015 and the sensitivity of the equipment is 0.001. Summing up the three uncertainties and considering a coverage factor of 2 (which defines an interval having a level of confidence of approximately 95 % for normal distributions), the expanded uncertainty of the equipment is 0.006.

Table 1: Exposure site meteorological data.

Location	Mean temperature [ºC]	Yearly global horizontal irradiance [kWh/m^2]	Yearly direct normal irradiance [kWh/m^2]	Mean wind speed [m/s]	Mean relative humidity [%]	TOW (%)
PSA, 37.1°N, 2.35°W	18.3	1901	2133	3.2	59.5	16.1

The outdoor exposure campaign started in June 2011. In Table 1 the main climatic parameters at the exposure site are presented. Mean values of two years data were calculated. The time of wetness (TOW) is defined as the duration in which the relative humidity is above 80% and the temperature above 0°C

(ISO9223, 2012). Soiling rates at the PSA have been determined in the past by continuous measurements with the automatic soiling measurement system TraCS (Wolfertstetter et al., 2018a) and an average soiling rate of 0.52 %/d (drop in reflectance per day) was found. In cases of unfavorable conditions, e.g. the combination of light rain and dusty atmosphere, daily reflectance drops of up to 7 % were detected. As the degradation of the coatings is analyzed in the campaign, the effect of erosion by airborne particles can be an issue. Data gained in the past has proven that this effect is negligible at the investigated position at the PSA even for aluminum reflectors which are much more sensitive than glass reflectors (Sutter et al., 2018).

An exposure rack was set up to hold five groups of seven facets each (Figure 1). Each facet has a size of 75x106 cm^2. The frequency of measurement and cleaning was different for the different groups. Every two weeks groups 1 to 4 were measured before cleaning, followed by cleaning and the measurement of groups 2 and 4 only. Groups 1 and 3 were cleaned, followed by the measurement after cleaning with a lower frequency, every four weeks. Group 5 was not cleaned, except for natural cleaning by rain fall, and had reference purposes only. It was exposed to be measured under possible special circumstances (e.g. sand storms or similar) without the influence of regular cleaning application. As no special events were suffered during the exposure, no additional results were obtained from this group.

a) b)

Figure 1: a) Outdoor exposure site at PSA with measured facets, b) measurement mask on facet.

The cleaning was performed with pressurized water at 200 bar using a HDS 10/20-4M device from Kärcher (Figure 2-a), which is similar to known parameters used for cleaning in commercial plants (Cohen et al., 1999). The distance between the spray nozzle and the reflector surface was approximately 0.5 m. The cleaning was performed by the operator until no further cleaning effect could be appreciated. The water used is demineralized, with a maximum conductivity of 2 µS/m. The cleaning method applied was the most commonly used one in commercial CSP plants. In addition, cleaning with a brush was discarded from the beginning due to recommendation of the manufacturer and previous experience of the researchers, to avoid any damage of the coatings due to abrasion (Sansom et al., 2006).

a) b)

Figure 2: a) Kärcher cleaning device and b) D&S reflectometer placed on measurement mask.

A mask was designed and used for the reflectance measurements with the portable reflectometer (Figure 1-b Figure 2-b). The mask with 5 holes, which fit the reflectometer, was placed on the facets to always measure on the same spots on the facet. Additionally the mask served as a protection during the measurements. The average of the measurements of the five spots was calculated for each facet as the reflectance value of the corresponding facet.

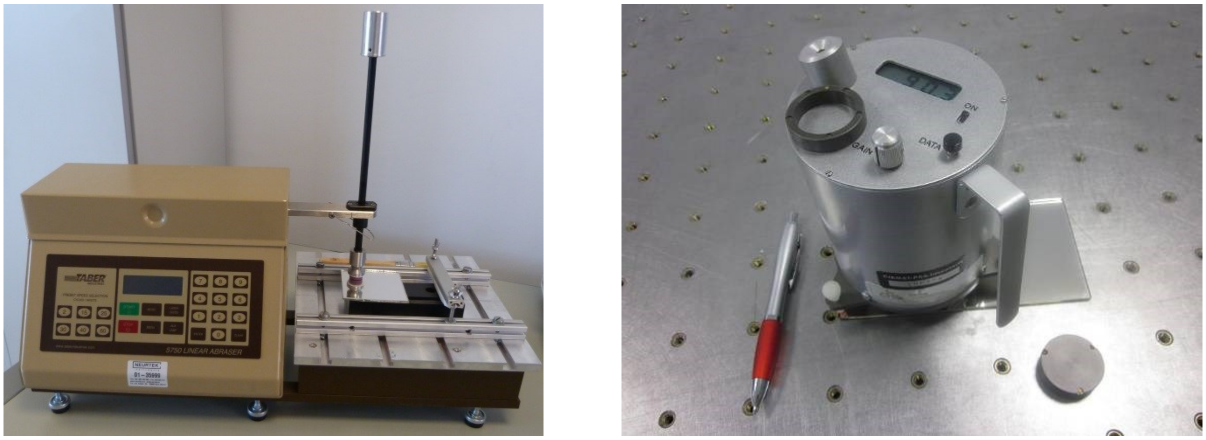
In the beginning of the campaign three different anti-soiling coatings were used together with one uncoated reference material. The measurements started in July 2011 and were continued until March 2017, thus comprising a period of nearly 6 years. In March 2013, the results of the 3 coatings were analyzed after 2 years of exposure. According to the conclusion obtained, the manufacturer decided to keep only one of the original coatings (the one with the best behavior), and remove the other two. Results of these two coatings are not shown in this paper due to confidentiality agreements with the manufacturer. In addition, another new coating was included in the analysis, which was developed by the manufacturer as an optimized product, coming from the analysis of the testing performed until that moment. Measurement results in this work focus on the three materials that were exposed and measured until the end of the study: anti-soiling coating 1 (AS1) and the reference material exposed in 2011 and anti-soiling coating 2 (AS2) exposed in 2013.

In addition to reflectance measurements, optical microscopic analysis was performed with a 3D light microscope model Axio CSM 700 manufactured by Zeiss. A scanning electron microscope (SEM) Gemini Ultra 55, manufactured by Zeiss, with an INCA FETx3 EDX system was used for more detailed surface analysis.

2.2. Laboratory test device:

As it is important to determine the mechanical stability of coated reflectors (Sansom et al., 2014), a mechanical laboratory test was conducted with the Taber linear abraser Model 5750 (Figure 3-a) to assess the resistance of the coatings to erosion wear. The tests were conducted according to standard (ISO9221-4, 2006) and (UNE206016, 2018) with an abrasion head model MIL/E/12397. The test consists in performing linear back and forth strokes of the abrasion head with a defined force (pressure of

1.24 kg/cm²) on the sample surface (size 10x10 cm²). Reflectance measurements and a microscopic analysis were performed before and after testing.



a) b)

Figure 3: a) Taber abrasion tester, b) D&S 15-R USB reflectometer.

3. Results:

The most significant value for the evaluation of the anti-soiling coatings is the reflectance difference between the coated and the uncoated reference material. As the coated and the uncoated facets are exposed under the exact same conditions, the anti-soiling facets only cause a benefit when their reflectance is higher than for the reference material. If the mean value of the coated material is higher than for the uncoated material, there is an advantage in the use of the coatings. The initial specular reflectance values of the three materials are presented in Table 2. It can be seen that the values of the uncoated and the AS2 material are very similar, with AS2 being 0.2 pp higher. The reflectance of AS1 lies below the others with a difference of 0.6 pp to the uncoated material, which is still within the uncertainty of the D&S, meaning that the coatings lower the initial reflectance of the reflectors only insignificantly and absorption and scattering of the coatings is negligible.

Table 2: Initial reflectance of the three analyzed materials.

Material	Uncoated	AS1	AS2
Initial monochromatic specular reflectance [%]	94.8±0.6	94.2±0.6	95.0±0.6

Figure 4 and Figure 5 show the development of the reflectance of the uncoated reference material over time, before and after cleaning, respectively. The focus in these graphs is to show the absence of appreciable degradation of the uncoated material for both cleaning frequencies. Figure 5 only displays the values after cleaning for the 2- and the 4-week frequency. As the cleaning by pressurized water is not able to completely remove the soiling on the reflector surfaces, the initial value of the reflectance is not restored in the field during the whole campaign. It can be seen that the reflectance is fluctuating over time, staying between 88 and 95 %, but that there is no considerable degradation. Both linear approximation lines (dotted straight lines) do not show a decrease in reflectance over time. The short term fluctuation is due to different soiling conditions and the imperfect cleaning method throughout the campaign. It can be seen that lower values after cleaning (such as the ones just after 06/06/2011 and just before 18/10/2012) match with periods of stronger soiling before cleaning (compare Figure 5 after cleaning with Figure 4 before cleaning). This is because the cleaning method is not able to restore the initial reflectance values when the soiling level of the reflectors is high. In this sense, more frequent cleaning (2 weeks instead of 4) helps restoring reflectance values. The mean reflectance value of the material cleaned every two weeks is slightly higher (around 0.5%). Although this difference is not substantial (still below the instrument uncertainty), it is assumed that more frequent cleaning cycles help to prevent the formation of strong adhesive bonds between the dust and the glass surface, and therefore the 2-weeks cleaned surface reaches a slightly higher average reflectance than the 4-weeks cleaned surface.

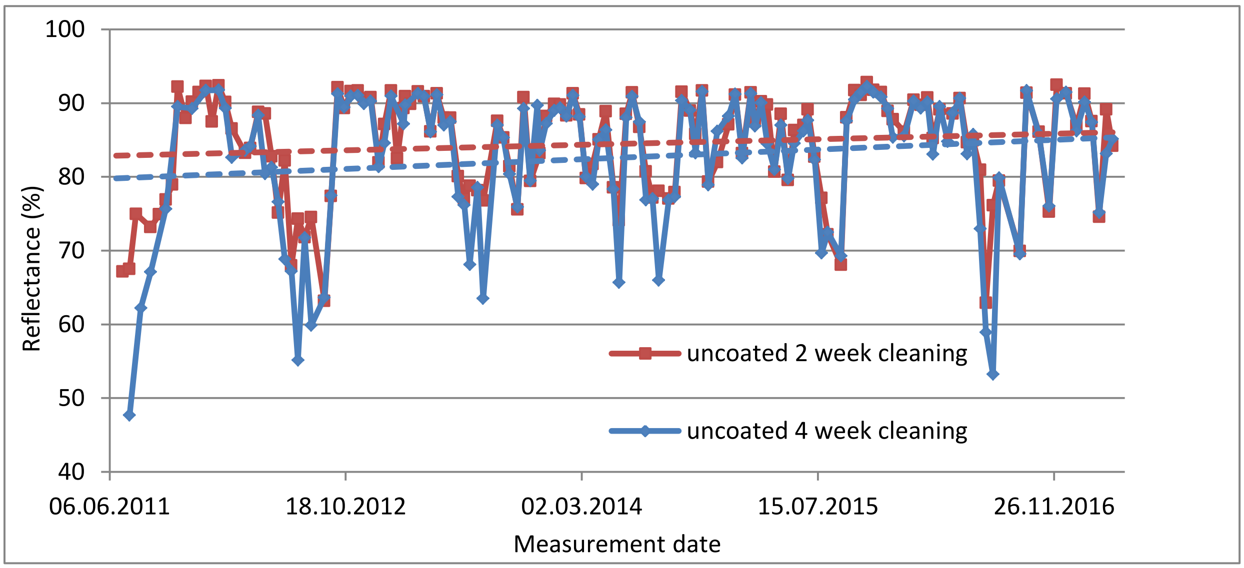


Figure 4: Reflectance values of uncoated material before cleaning for the 2 and the 4 week cleaning campaign.

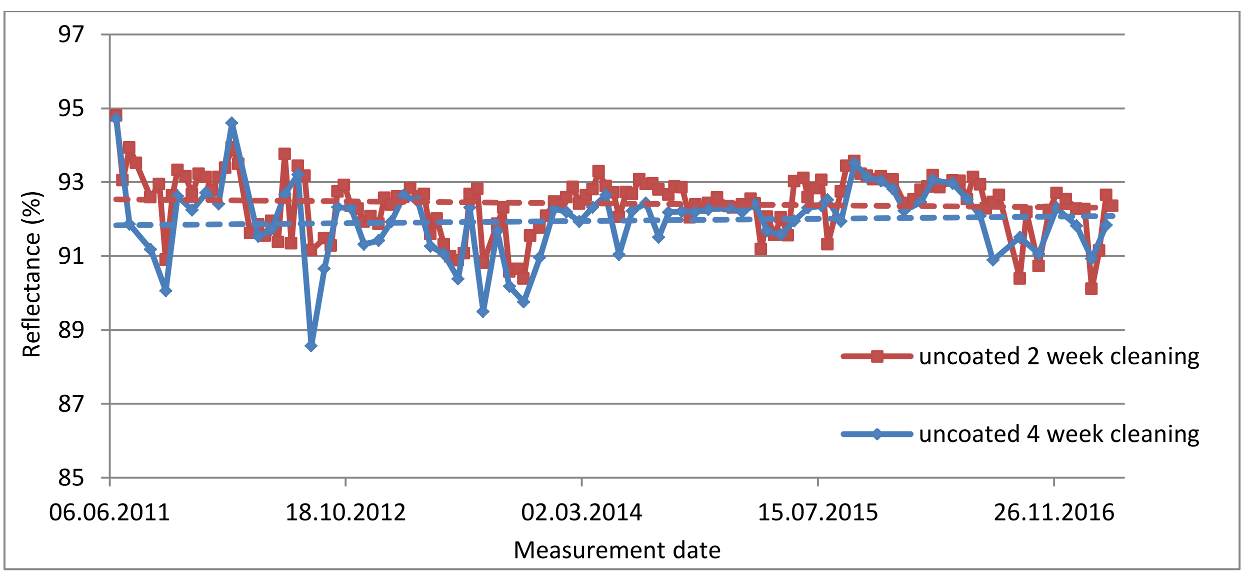


Figure 5: Reflectance values of uncoated material after cleaning for the 2 and the 4 week cleaning campaign.

Table 3: Yearly mean reflectance values and reflectance drop for all 3 materials and the two cleaning campaigns after cleaning (in %).

	2-week campaign			4-week campaign		
	Uncoated	AS1	AS2	Uncoated	AS1	AS2
1st year mean reflectance	92.7±0.9	92.6±0.9	93.5±0.8	92.2±1.1	92.3±1.2	93.3±0.9
Last year mean reflectance	92.8±0.6	89.5±1.6	90.0±0.7	92.4±0.7	90.6±0.9	90.1±0.7
Mean reflectance drop	+0.1	-3.1	-3.5	+0.2	-1.7	-3.2

Table 3 presents the mean reflectance values of the different materials after cleaning, calculated for the first and the last year of exposure, together with the resulting reflectance losses. As presented in the last paragraph, it can be seen that the mean reflectance of the uncoated material remains constant over the whole campaign, even showing slightly positive reflectance differences (0.1-0.2 percentage points). As the uncoated material does not suffer a perceivable degradation, degradation detected in the following graphs for the reflectance differences is provoked by changes of the anti-soiling coatings. Figure 6 and Figure 7 display the advantage of the coatings over time for both the 2- and the 4-week cleaning campaign before cleaning, that means in the soiled state. The advantage is defined here as the reflectance of the coated material minus the reflectance of the uncoated one. I.e. if the reflectance of the material with anti-soiling coating is higher than the uncoated material, there is an advantage and the value is positive. If the value is negative, the reflectance of the coated material is lower than of the uncoated material, which shows a disadvantageous behavior (that is, the coated material underperforms compared to the uncoated material).

The values of the new material AS2 start later because they were exposed at a later time. For both coatings the advantage is positive in the beginning and diminishing over time until there is a point when the coating becomes a disadvantage (values are negative). The slope of the linear approximation is similar for both of the materials. For the 4-week campaign the advantage shrinks slower than for the 2-week campaign.

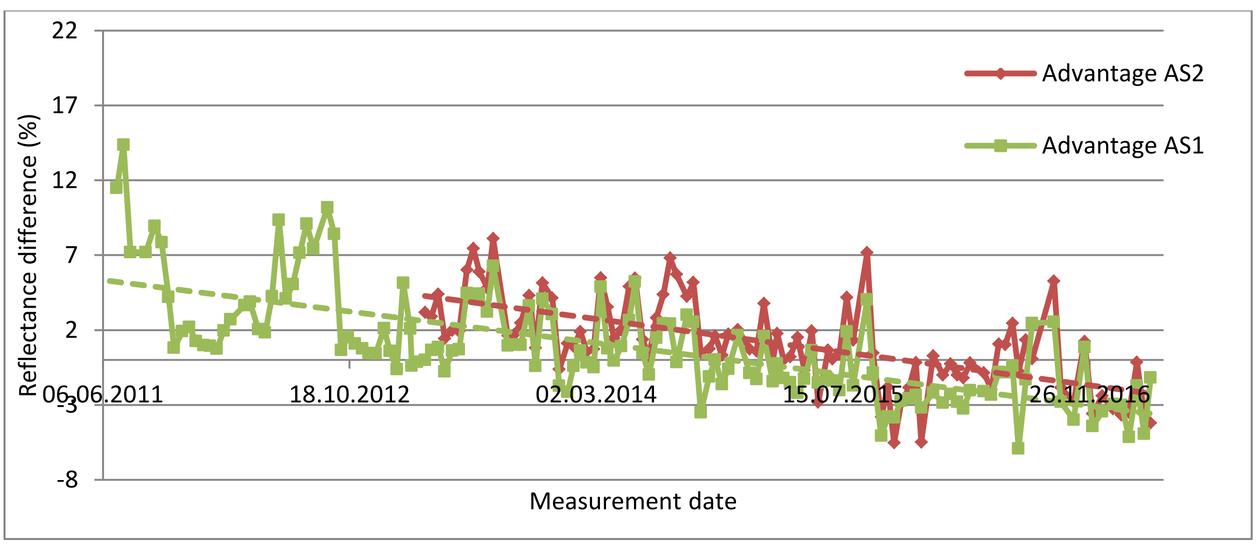


Figure 6: Advantage of anti-soiling coatings AS1 and AS2 compared to uncoated references, before cleaning every 2 weeks.

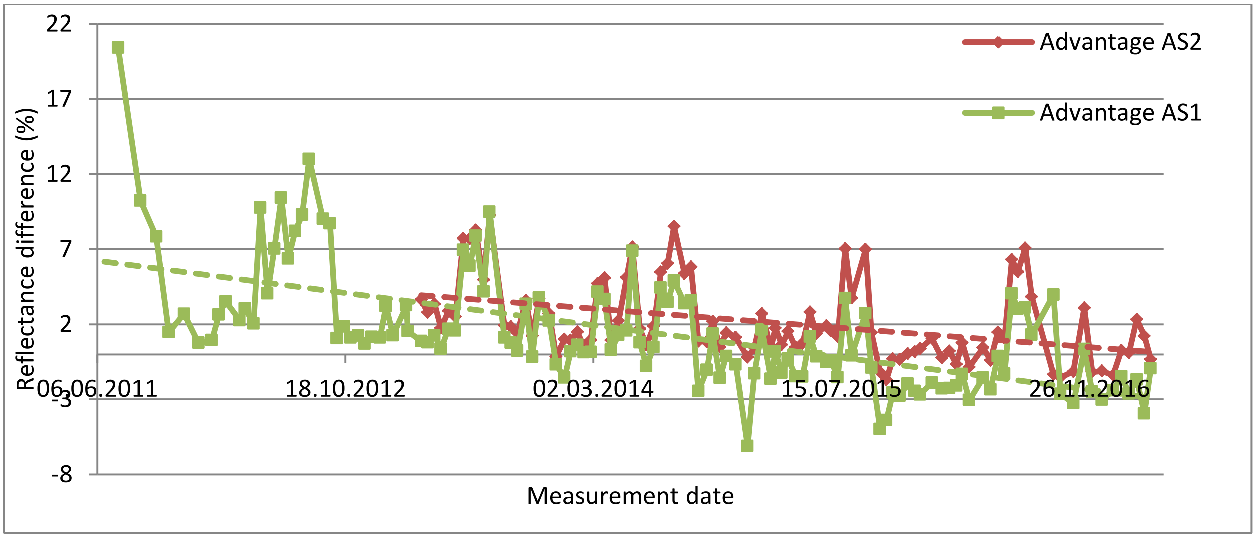


Figure 7: Advantage of anti-soiling coatings AS1 and AS2 compared to uncoated references, before cleaning every 4 weeks.

In Figure 8 and Figure 9 the advantages are displayed after cleaning. Here the advantage of the anti-soiling coatings is lower, hence the effect of the coating is more pronounced in the soiled state. Again the values start in the positive area and reach the area of disadvantage. But here the advantage is smaller from the beginning and the negative values are reached faster than for the before cleaning values. Still it can be stated that in the beginning of the campaign, even after cleaning the utilization of the coatings is beneficial. That is due to the fact that with the cleaning technique used, the facets reflectance cannot be restored to the initial value, but the cleaning is more effective for the coated samples. The negative trend of all reflectance difference curves leads to the conclusion that a degradation of the AS coatings takes place and that it is evolving with time. Looking at the reflectance losses of the coated samples in Table 3 it can be seen that these losses can reach values of more than 3 percentage points depending on the coating and parameters.

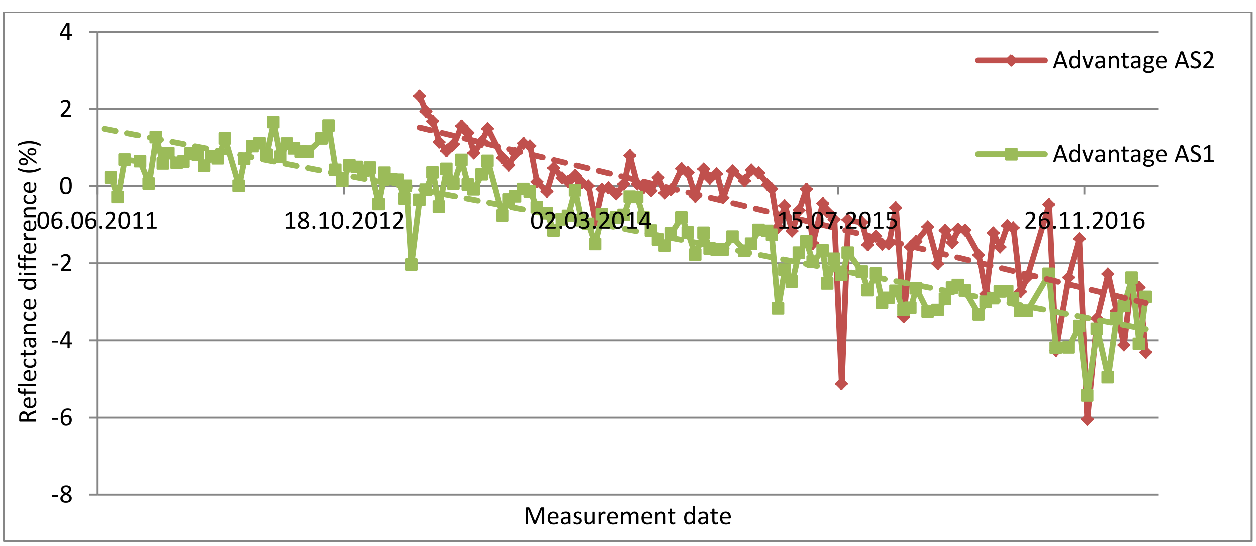


Figure 8: Advantage of anti-soiling coatings AS1 and AS2 compared to uncoated references, after cleaning 2 weeks.

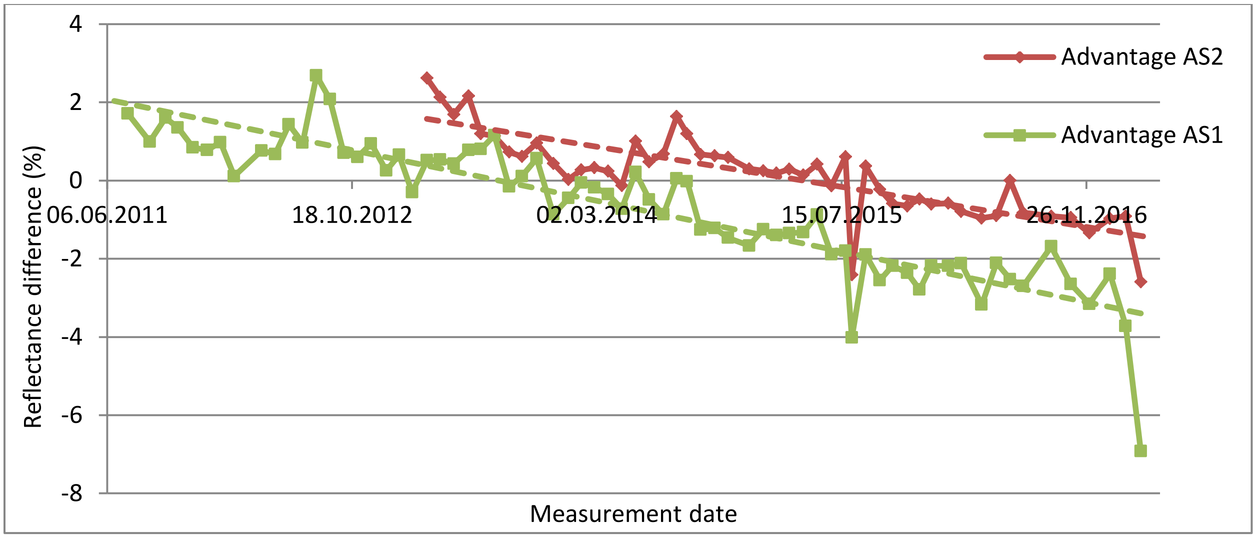


Figure 9: Advantage of anti-soiling coatings AS1 and AS2 compared to uncoated references, after cleaning 4 weeks.

In Figure 10 (2-week campaign) and Figure 11 (4-week campaign) the linear trend lines for both coatings for before and after cleaning are presented together with the corresponding averages per material. Some conclusions can be drawn here. The advantage is always higher in the soiled state, with the difference between before and after cleaning decreasing over time. Looking at the average lines per material it is possible to detect at what moment the implementation of the anti-soiling coating becomes a disadvantage. The worst case here is AS2 and the 2-week cleaning campaign. Here the point is reached already after roughly two years, whereas for AS2 with the 4-week campaign it is after nearly 4 years, or 44 months. For all cases the point is reached faster for the 2-week campaign. The comparison of the two coatings is difficult because they were exposed at different dates and thus have not seen the same outdoor conditions over their lifetime. The advantage for AS1 is higher in the beginning compared to AS2. The point where the coating becomes a disadvantage is reached earlier by AS2 in the 2-week campaign but in the 4-week campaign it is the other way around.

In general it has to be stated that the specific outdoor conditions as well as the applied cleaning strategy will have an impact on the behavior of the materials and measurements.

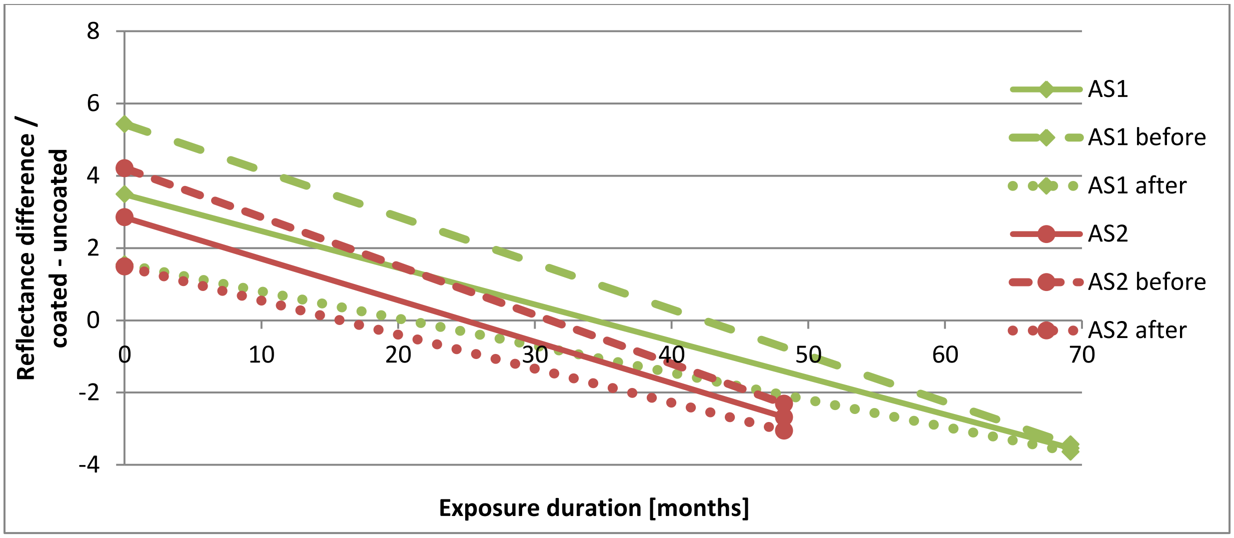


Figure 10: Linear trend of advantage of both anti-soiling coatings with exposure time during 2 week campaign, before, after and average.

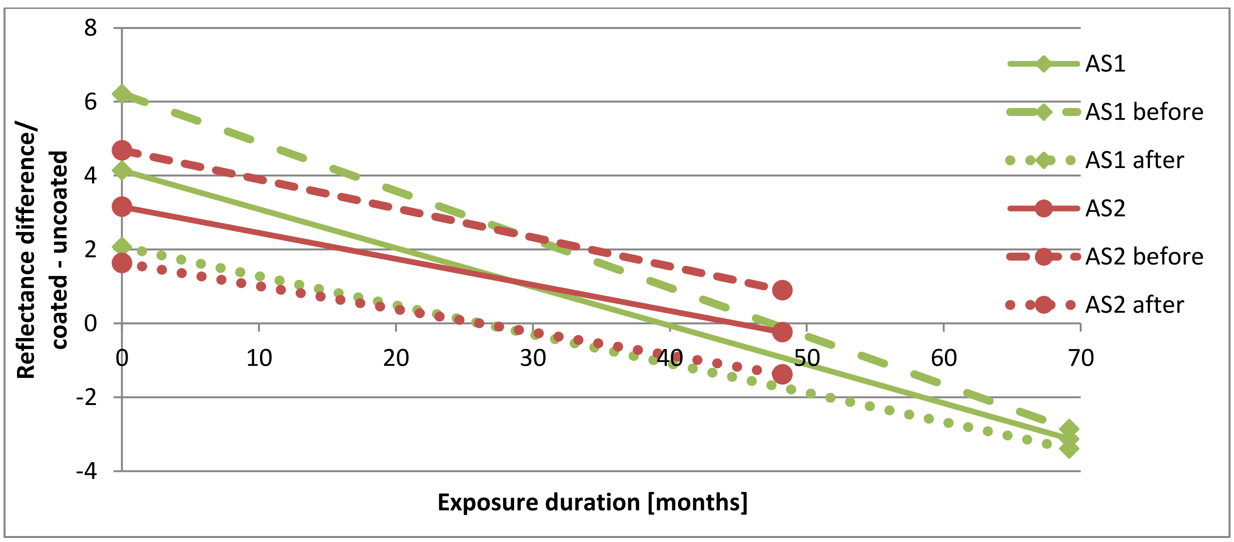
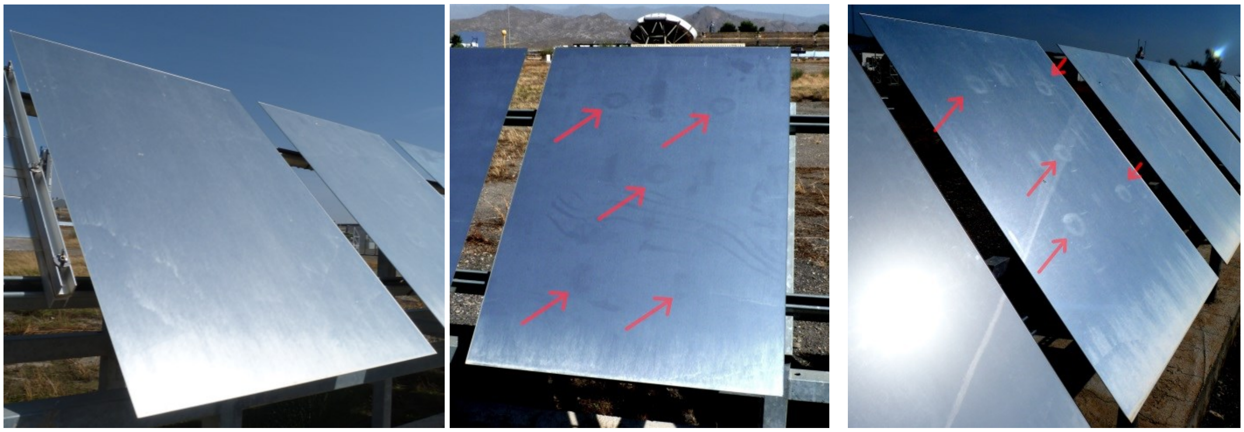


Figure 11: Linear trend of advantage of both anti-soiling coatings with exposure time during 4 week campaign, before, after and average.

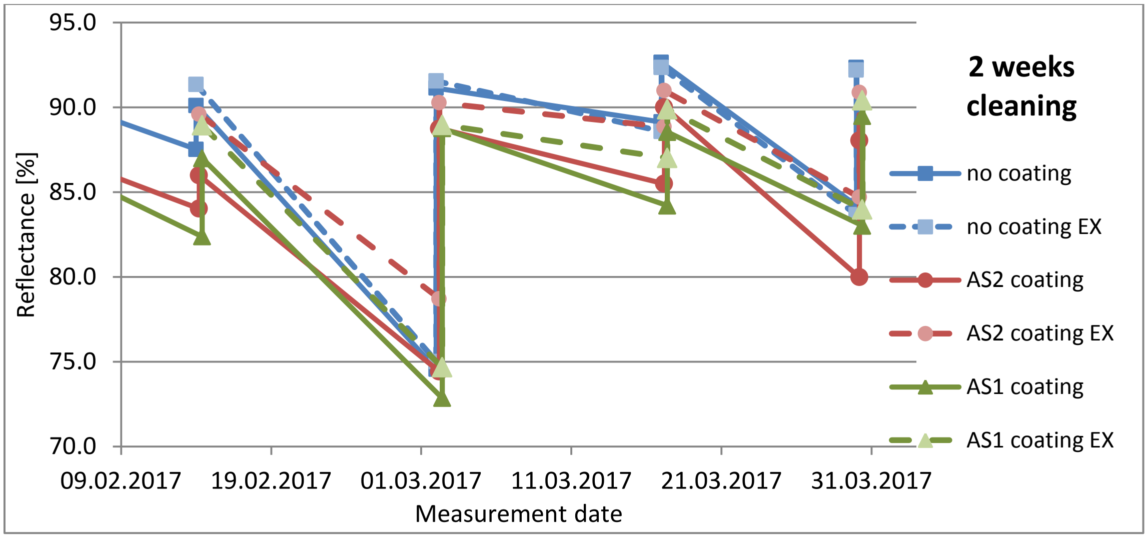
In Figure 12 images of the three investigated material types, uncoated, AS1 and AS2 facets are displayed after completion of the outdoor campaign. On the pictures of the coated facets, the areas where the measurements were taken with the D&S are clearly visible (marked in red). Apart from remaining soiling on the surface the uncoated facets don't show any signs of degradation. The marks on the anti-soiling facets are damages in the surface coatings and coincide with the measurement points. To analyze the effect of the measurement process on the coatings, an additional measurement campaign was conducted during the last seven measurements of the regular campaign and microscopic analysis was performed on these spots.



a) Uncoated facet **b) AS1 facet** **c) AS2 facet**

Figure 12: Images of facets of the three different materials with the measurement points marked in red for the AS facets.

During this campaign, five extra measurement points per sample were chosen that lie at least 10 cm away from the usual measurement points. This way an influence of potential damages, introduced by the reflectometer over the years, on the measurements could be avoided. In Figure 13 the measurements of this campaign are presented (extra measurements) and compared to the regular measurements. The continuous lines present the regular measurements and the dotted/slashed lines correspond to the extra measurements (marked “EX”). For the facets without coating the difference between the regular and extra measurement points is rather small. For the coated samples nearly all extra measurements show considerably higher values than the regular measurements. By calculating the average values for the difference between extra and regular measurements, these results can be confirmed: $\Delta_{uncoated}$ = -0.1; Δ_{AS1} = 1.81; Δ_{AS2} =2.14.



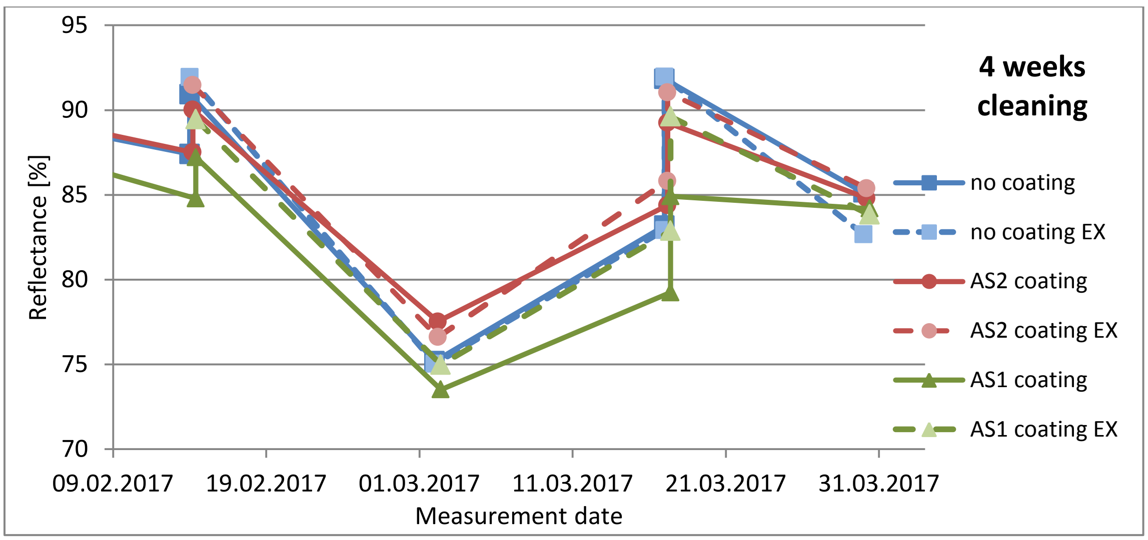
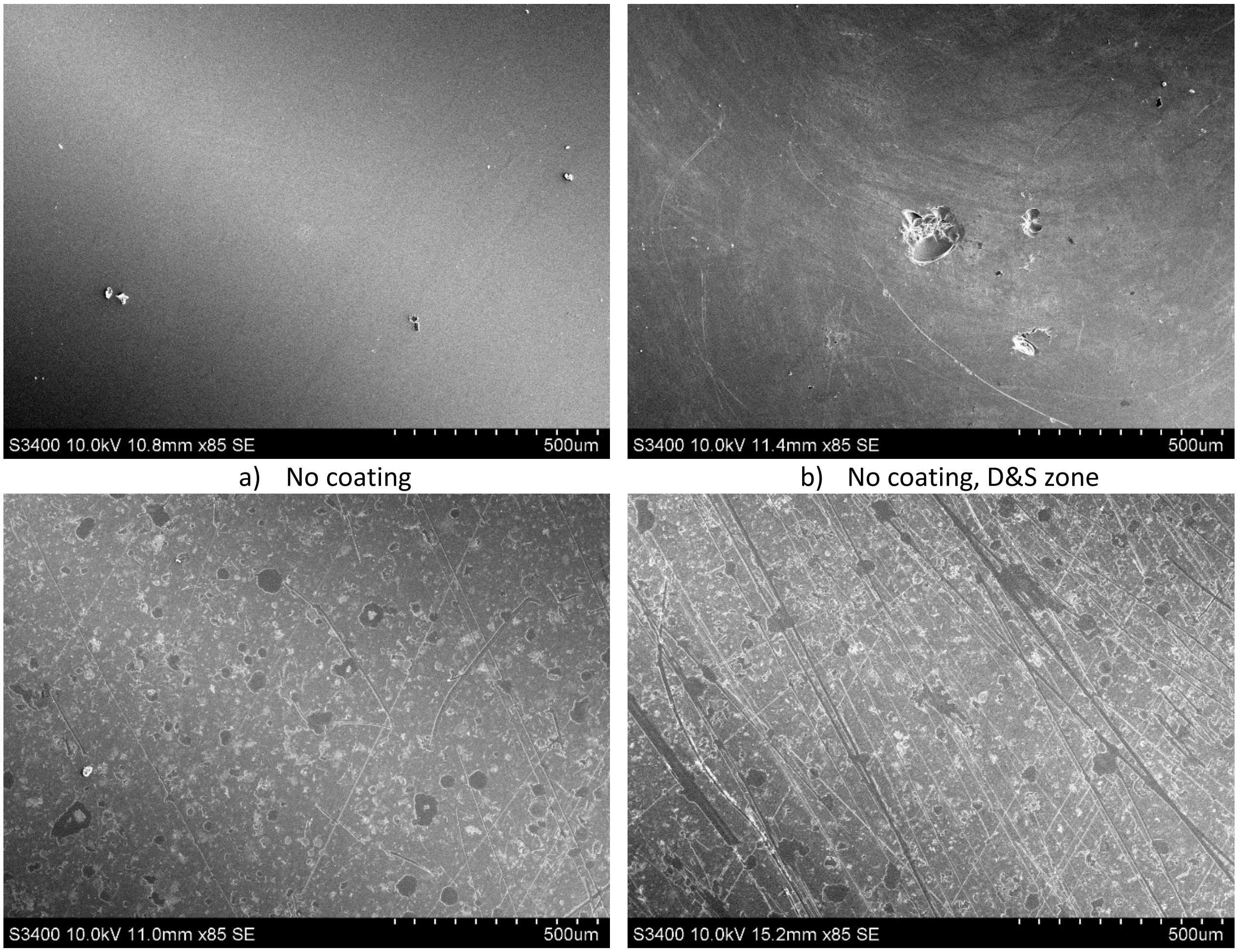


Figure 13: Difference between reflectance values for measurement spots and apart from these.

To analyze the general degradation and the difference between the regular and extra measurements, the surface of the facets was observed with light and SEM microscopy. In Figure 14 representative SEM images are displayed of areas where the D&S measurements were taken and apart from those areas. For the uncoated facets basically no degradation was detected on the zones away from the measurement points (Figure 14-a). The measurement zones show minor residues on the surface and only few punctual defects (Figure 14-b) of the surface.

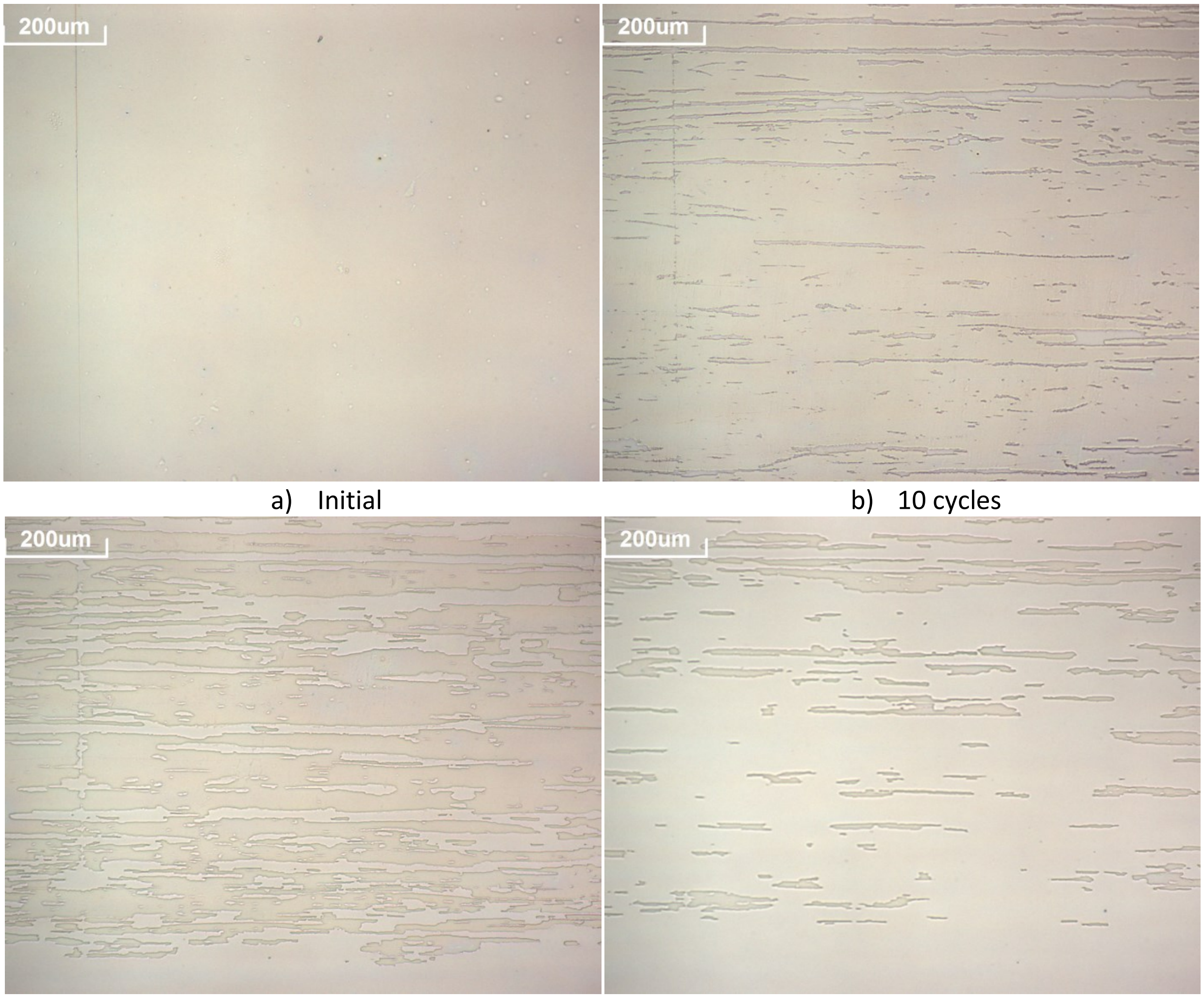
For the coated facets the anti-soiling coating is clearly visible and defects are appreciated in form of scratches and zones where the coating has been removed (Figure 14-c). These damages are considerably stronger and more densely distributed at the measurement points (Figure 14-d), which explains the reflectance differences between the different measurement points of the anti-soiling coated facets mentioned above. The higher the defect density, the higher is the scattering and absorption, lowering the specular reflectance of the material.



a) No coating
b) No coating, D&S zone
c) AS1
d) AS1 D&S zone

Figure 14: SEM images of the different zones on uncoated and AS1 facets.

To analyze the ability of the coatings to resist mechanical damages, a standardized abrasion test was done. The Taber test was conducted for 100 cycles in total. In Figure 15 microscopic images are displayed showing the initial state of the coating and the status after 10, 50 and 100 Taber cycles respectively. It can be appreciated that the surface degradation increases with the number of cycles conducted. In the initial state only minor defects can be detected (Figure 15-a), whereas with higher cycle numbers, horizontal scratches appear which follow the direction of the abraser head movement (Figure 15-b). After 50 cycles (Figure 15-c) the scratches have grown and in the lower part of the picture an area is visible in which a part of the coating has been completely removed. After finishing the 100 cycles most of the coating has been removed (Figure 15-d). The test was also done with the uncoated material. Here the abraser has no effect at all.



a) Initial b) 10 cycles

c) 50 cycles d) 100 cycles

Figure 15: microscopic images of AS1 coating before, after 10, 50 and 100 cycles of the Taber test.

These effects can be verified when the specular reflectance is taken into account. The evolution of the reflectance of the coated and uncoated material is displayed in Figure 16. For the AS1 coating the reflectance drops in the beginning due to higher scattering at the scratches and imperfections of the coating. When continuing the test, the reflectance rises again when a high percentage of the coating is removed, leaving the base glass material. No reflectance change is detected for the uncoated material.

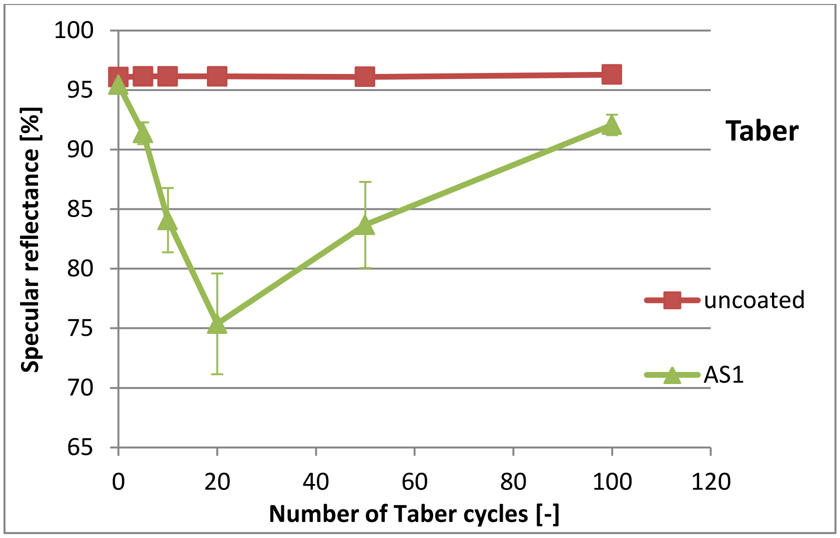


Figure 16: Development of specular reflectance of coated and uncoated sample during Taber test.

It must be concluded that the durability of the anti-soiling coatings is lower than that of the bare silvered-glass mirrors. Especially mechanical wear can harm the surface and thus lower the specular reflectance. It is important to state that the conducted outdoor campaign of this work is supposedly more aggressive than exposure under realistic conditions in a plant. Even though cleaning in the plant may be similar to the technique employed during the campaign, further mechanical stress is introduced here by the extensive measurement on designated spots. While sporadic measurements with the D&S (or other devices) are usually performed in commercial power plants, the spots for these measurements are arbitrarily chosen, avoiding the multiple repetition of measurements on the same spots. During measurements with D&S several parts of the equipment are in contact with the surface to be measured (Figure 17), mainly the three leveling screws and the rubber shielding around the measurement spot. For future measurement campaigns with similar goals as the one performed, it is important to minimize contact between instrument and sample surface to avoid unrealistic damage of the surface.

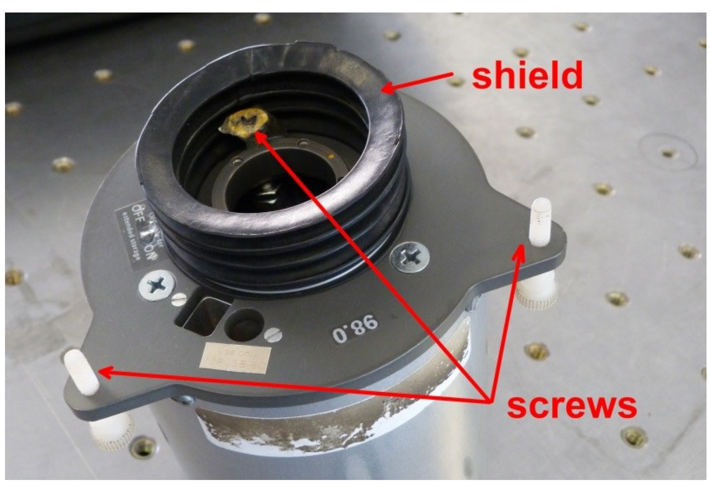


Figure 17: Lower part of D&S with parts that are in contact with surface during measurements.

4. Conclusions:

The outdoor campaign of this project produced valuable data on the behavior and performance of two anti-soiling coatings over a long period of time. A number of important conclusions can be drawn from this campaign:

- The application of the anti-soiling coatings leads to a clearly visible advantage in the beginning of exposure, shown by the higher reflectance during outdoor exposure compared to uncoated silvered-glass mirrors.
- The advantage is more pronounced in the soiled state before cleaning. But in the beginning of the campaign the advantage before and after cleaning proves that the coatings lower the effect of soiling and improve the washability of the reflectors.
- Degradation of the coated reflectors is a bigger issue than for the uncoated material. The advantage of the coatings decreases with time and becomes a disadvantage after a relatively short time. In the course of this study the time to reach that point is around two to four years.
- The advantage in reflectance and degradation of the coatings strongly depends on the environmental conditions and cleaning strategy the material is exposed to. Different climatic conditions and the performance of different cleaning techniques and frequencies may change the results considerably.
- Especially mechanical stresses have shown to alter the quality of the coatings due to the high sensitivity of the coatings compared to very hard and resistant pure glass surfaces of conventional reflectors.
- Measurement campaigns similar to the one conducted throughout this study require the utilization of measurement techniques that minimize the influence of the measurement process on the material due to the high number of measurements on the same spots. Contact between measurement equipment and material surface should be avoided by the use of soft distance pieces or adequate measurement mask design.

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Nomenclature

AS	Anti-soiling
Ciemat	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (Energy, Environment and Technology Research Centre, Spain)
CSP	Concentrating Solar Power
D&S	Devices & Services Reflectometer

DLR Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre, Germany)
DNI Direct normal irradiance
GHI Global horizontal irradiance
O&M Operation and maintenance
PSA Plataforma Solar de Almería
SEM Scanning electron microscopy
TOW Time of Wetness

Δ absolute difference between reflectance measurements
$\rho_{\lambda,\varphi}$ near-specular reflectance

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