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Date Submitted: 2019-02-27

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Citation (overall record, always the latest version): LAPSE:2019.0314
Citation (this specific file, latest version): LAPSE:2019.0314-1
Citation (this specific file, this version): LAPSE:2019.0314-1v1

DOI of Published Version: https://doi.org/10.3390/en9121006 energies

Article

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Academic Editor: Francisco Manzano Agugliaro
Received: 30 September 2016; Accepted: 24 November 2016; Published: 29 November 2016

Abstract: This paper describes the accelerated ageing of commercially available silvered polymer film by contact cleaning using brushes and water in the presence of soiling created by dust and sand particles. These conditions represent cleaning regimes in real concentrating solar power (CSP) solar fields in arid environments, where contact cleaning using brushes and water is often required to clean the reflecting surfaces. Whilst suitable for glass reflectors, this paper discusses the effects of these established cleaning processes on the optical and visual characteristics of polymer film surfaces, and then describes the development of a more benign but effective contact cleaning process for cleaning polymer reflectors. The effects of a range of cleaning brushes are discussed, with and without the presence of water, in the presence of sand and dust particles from selected representative locations. The experiments were repeated using different experimental equipment at Plataforma Solar de Almería (PSA) in Spain and Cranfield University in the UK. The results highlight differences that are attributable to the experimental methods used. Reflectance measurements and visual inspection show that a soft cleaning brush with a small amount of water, used in a cleaning head with both linear and rotational motion, can clean polymer film reflecting surfaces without inflicting surface damage or reducing specular reflectance.

Keywords: concentrating solar power (CSP); solar collector; reflectance; soiling; polymer film; mirror cleaning

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1. Introduction

Concentrated solar power (both thermal and photovoltaic) is becoming one of the most relevant technologies to cover sustainable cities demands for renewable energy [1–3]. Parabolic-trough collectors represent the most extended technology both for power generation with concentrating solar power (CSP) plants [4] and also to cover the thermal energy demand in the temperature range from 100 to 250 °C in applications such as industrial process heat, domestic hot water, space heating, solar cooling, pumping irrigation water, organic Rankine cycles, and desalination [5]. The performance of parabolic-trough plants is critically dependent on the optical efficiency of the solar field, within which the reflectance of the solar collector mirrors play a major role [6]. Generally made of silvered-glass of up to 4 mm thickness, the mirrors and their tracking and supporting structures are also a significant capital cost. Alternative reflecting materials are available [7], but their robustness and durability are yet to be proven. One of the important aspects that may degrade the mirror surface is the cleaning task, mainly when it involves a contact device, which sometimes is indispensable for removing a soiling layer that is strongly attached [8].

Energies **2016**, *9*, 1006; doi:10.3390/en9121006

This work presents the results of experiments carried out to investigate the robustness of commercially available silvered polymer film reflectors under conditions of contact cleaning [9,10]. The results clearly show that commercially available polymer film can easily be damaged under existing contact cleaning regimes. As a result, a range of cleaning brushes was tested and a new and effective contact cleaning process was developed. The experiments were performed at two locations, the PSA in Spain and Cranfield University in the United Kingdom. The polymer film used throughout was provided by SkyFuel® Inc., as the commercial product ReflecTech®PLUS, a mirror film which is a highly-reflective, silvered film designed for outdoor applications. It is used within solar concentrators and other reflectors that require outdoor durability. It is also the only mirror film with an abrasion resistant hard coat. Different methods were used in the two laboratories to simulate the accelerated aging of the polymer film. The brushes used by the two laboratories were also different in geometry, although manufactured by the same supplier and possessing the same bristle material. The results of reflectance measurements and visual inspection indicate that it is possible to remove sand and dust particles from polymer film collectors with a suitably benign contact cleaning process.

2. Methods and Materials

The experiments were carried out in both a joint laboratory between CIEMAT and DLR at the PSA in Spain, and at Cranfield University in the United Kingdom, using different abrasion test equipment and optical measurement techniques in order to maximize the validity of the results. The techniques used in this work for simulating contact cleaning are shown in Figure 1 below. The same three different cleaning brushes with a range of bristle hardnesses were used in both labs and one additional harder brush was also tested at PSA. Reflector samples were soiled with both Quartz-Silica (MIL-E-5007C) and samples of dust and sand taken from Europe, the Middle East, and the Americas. Cleaning both with and without soiling was investigated, with and without the presence of water.

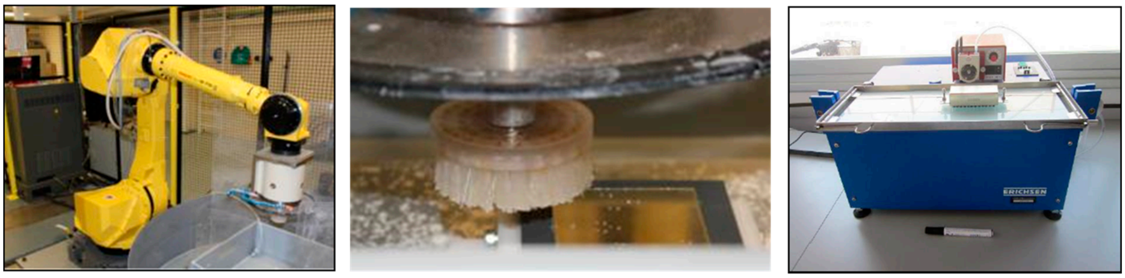

(**a**) (**b**) (**c**)

Figure 1. Cleaning simulation tools: (**a**) Fanuc robot, (**b**) With rotary brush and (**c**) The Erichsen 494.

The PSA tests were performed in accordance with ISO 11998 [11] using an Erichsen model 494 machine, which simulates CSP plant reflector cleaning with a linear motion brush head.

The Cranfield cleaning simulations used a FANUC Robot M-710i with a rotary head at 300 rpm and linear speed of 470 mm/min for 200 cycles [12]. The FANUC M-710i is a six-axis robot with a reach of 2050 mm and a load capacity of 50 kg. Optical measurements of both hemispherical reflectance and monochromatic specular reflectance were performed at both research centres, using a Perkin Elmer Lambda 1050 spectrophotometer with a 150 mm integrating sphere and a Devices and Services (D&S) 15R portable reflectometer at the PSA; and a Jasco-670 spectrophotometer with a 60 mm integrating sphere and a Condor portable reflectometer at Cranfield. The Abengoa Solar Condor has dimensions of 23,030 mm × 14,285 mm × 14,881 mm and its weight is 1500 g (see Figure 2).

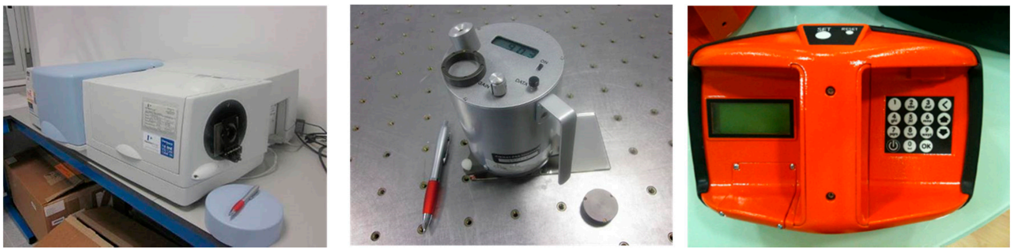


Figure 2. Perkin Elmer 1050 spectrophotometer, D&S 15R-USB and Abengoa Condor reflectometers.

2.1. The Effect of Existing Contact Cleaning Methods

Despite the addition of hard coatings, previous work has shown that the durability of polymer film reflectors under contact cleaning regimes is less than that of glass reflectors when used in CSP applications. Using hard bristle brushes with demineralized water, the film has been shown to exhibit visible scratches and a significant reduction in monochromatic specular reflectance whereas the spectral hemispherical reflectance remains unchanged. An example of this previous work is shown in Figures 3 and 4, with results from the PSA [13]. Note that the reduction in specularity is non-linear under hard abrasion conditions, with the reflectance tending to stabilize after a time represented by 40–50 cleaning cycles. 100 cycles correspond to approximately 1.9 years of operation in a CSP plant with two week cleaning intervals assuming that every spot of the surface is being cleaned with two cycles. Specular reflectance was measured on the D&S 15R-USB (660 nm, 15°, 12.5 mrad). The spectral hemispherical reflectance, ρh (250–2500 nm, 8°, h), was measured with a setup consisting of a Perkin-Elmer Lambda 1050 spectrophotometer with an integrating sphere of 150 mm diameter and an incidence angle of 8°.

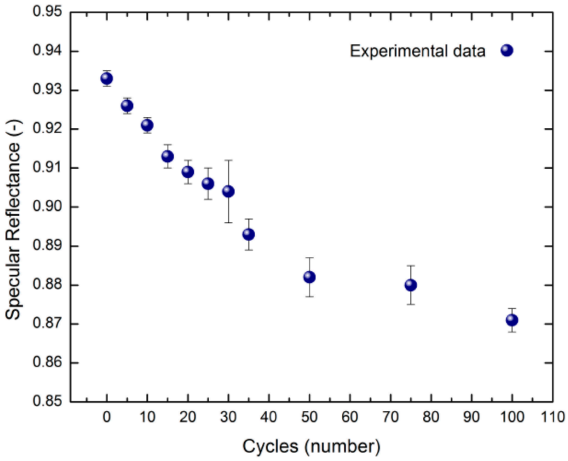


Figure 3. Monochromic specular reflectance after 100 cycles of cleaning abrasion test.

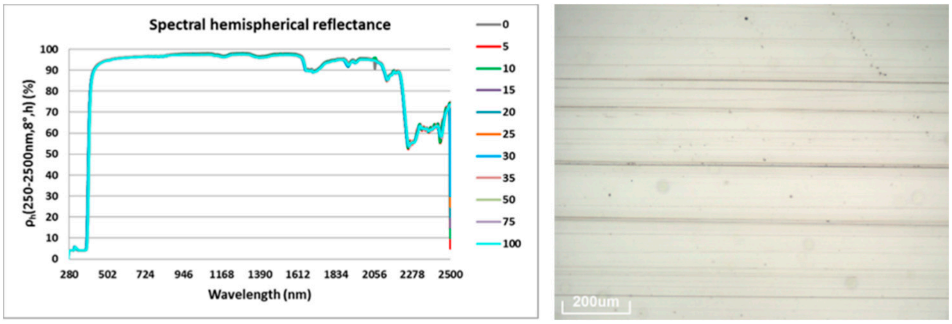


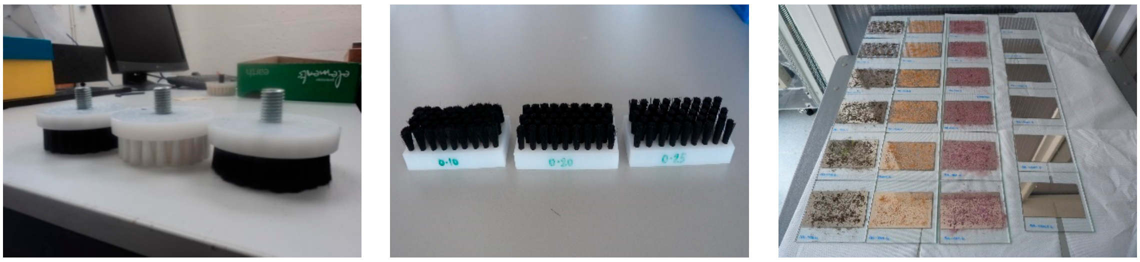
Figure 4. Hemispherical reflectance after 100 cycles and scratches after 10 cycles (cleaning abrasion test).

2.2. New Benign Contact Cleaning Regime

The next step in the present study consisted in optimizing the cleaning method to avoid, or at least minimize, the damage in the mirror surface under analysis. This section includes a description of the methodologies followed at both locations and the materials used in the experiments.

2.2.1. Sample Preparation

For the experiments at Cranfield University, samples of SkyFuel ReflecTech®PLUS polymer film were cut to a size of 3 × 3 cm^2 square. Three brushes were used (nominally labelled as "soft", "medium", and "hard" in terms of the overall hardness of the bristles). The thickness of the bristles determines the characteristic hardness of the brush. The bristle thickness is 0.1 mm for the soft brush, 0.2 mm for the medium brush, and 0.25 mm for the hard brush. Sand was used that had previously been collected from three locations (described as "Sahara", "Arizona", and "PSA"). In preparing the samples for abrasive cleaning, it was necessary to develop a technique to deposit a suspension of sand in demineralized water on each sample of polymer film, a non-trivial task owing to the highly hydrophobic surface coating on the film and achieved by physically pushing the water to the edges of the sample using a glass rod. 200 cycles, which approximately corresponds to 3.8 years of operation in a CSP plant (assuming typical washing cycles of two weeks) were applied. The testing time was approximately 4 min per sample. Where water was added, the water feed rate was 4mL per min. Figure 5 below illustrates the brushes used at both locations and the samples being prepared at the PSA.



(**a**) (**b**) (**c**)

Figure 5. (**a**) Brushes with fixings to Fanuc robot and (**b**) Erichsen kit; and (**c**) sample preparation.

For the corresponding experiments at PSA samples of SkyFuel ReflecTech®PLUS polymer film from the identical batch were cut to a size of 11 × 7 cms. Again, the same three brush types were used (nominally labelled as "soft", "medium", and "hard" in terms of the overall hardness of the bristles). The sands used were also the same (described as "Sahara", "Arizona", and "PSA"). At the PSA, the Erichsen 494 abrasion kit was used, which operates in a linear motion in contrast to the linear+rotation motion of the Cranfield University Fanuc robot head. Both types of motion have been observed during cleaning processes in a selection of solar plants during cleaning of glass solar collecting facets. The cleaning experiments are carried out both with and without the presence of water. Therefore, two sets of brushes were used, one set for dry cleaning and one set to be used in the presence of water. Using the PSA Erichsen abrasion kit, 200 cycles (each cycle involving outward and return travel) were performed for approximately 6 min per sample. Where water was added, the water feed rate was 4 mL per min.

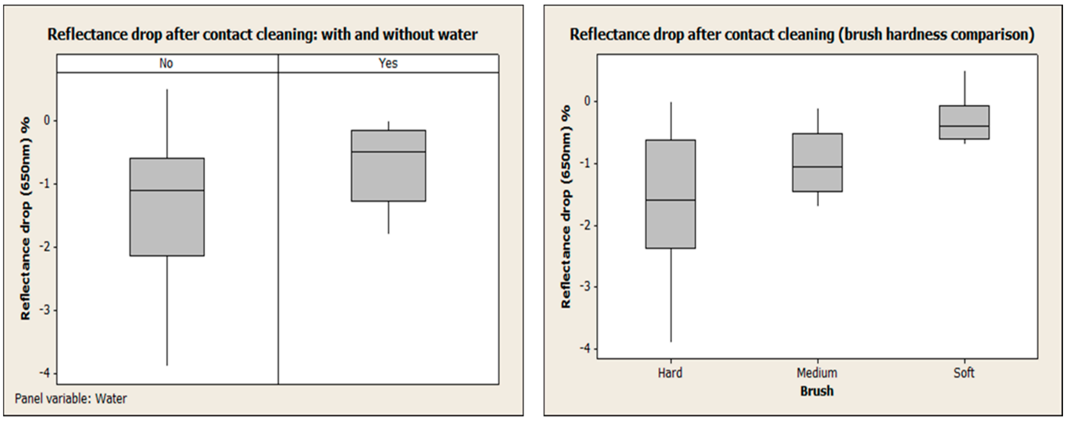
2.2.2. Contact Cleaning Experimental Set-Up

Samples were analyzed prior to any soiling and abrasive testing, measuring hemispherical reflectance using the spectrophotometer and specular reflectance using a reflectometer. At Cranfield University, the Abengoa Condor reflectometer was used throughout. At the PSA, the D&S-15R reflectometer was available to assess the reflectance of the samples before and after the cleaning runs. The comparison of the two reflectometers will be the subject of a future publication, but it is important to note for this experiment that there is a good correlation between the two instruments. Generally, the Condor will read higher than the D&S owing to its higher acceptance angle (23.0 mrad for the D&S 15R and 290.0 mrad for the Condor). Following the initial measurements of reflectance, each sample was placed on the sample table of the Fanuc robot (at Cranfield) or the Erichsen abrasion kit (at the PSA), and a series of simulated contact cleaning runs were performed. Some samples were used to set up the brush height, then the majority of the experiments were performed as we varied the brush hardness and the sand type. Runs were also performed to investigate whether the presence of water was necessary, and additional runs were also performed without sand. At the PSA, additional runs were performed on samples that had been naturally soiled outside for one week. Following each run, reflectance measurements were repeated and the samples were visually inspected for signs of surface damage. Measurements of specular reflectance were taken at six wavelengths (435, 525, 650, 780, 940, and 1050 nm) at Cranfield University using the Condor reflectometer, although only the 650 nm results are reported in this paper. This is because, at the PSA, reflectance measurements were made using the D&S 15R which operates at a wavelength of 660 nm only. The purpose of this work is to compare reflectance results at both locations, and not to compare the performance of the two reflectometers.

3. Results and Discussion

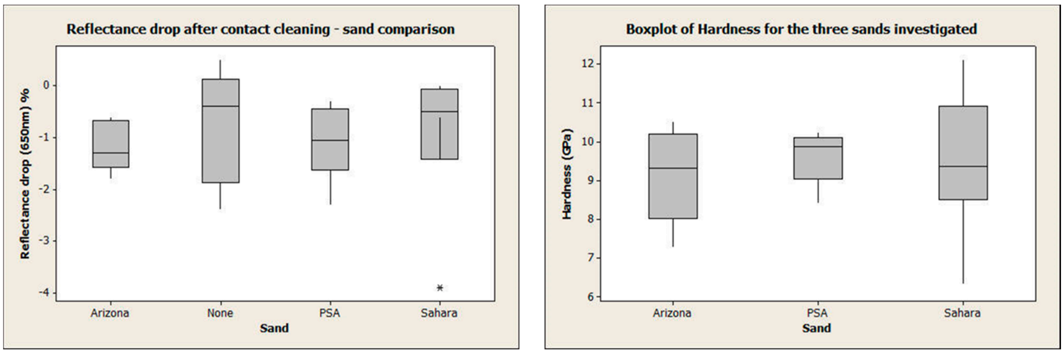
3.1. Cranfield University Experimental Results

The results obtained from the experimental runs at Cranfield University are shown in Figure 6 below, and clearly show the influence of both water and brush hardness on the specular reflectance drop of the polymer film reflector samples after the testing. As can be seen in the Figure 6a, the presence of water in the cleaning processes reduced surface damage, though not completely. The brush hardness was shown to play a significant role (see Figure 6b), with surface damage reducing as the brush hardness decreased. The role played by the soiling medium, in this case comprising three sand samples, is more complex as shown in Figure 7a below. All three sands cause a loss of reflectance in the polymer film, as indeed happens when no sand is present. However, a slightly better behavior can be noticed when the Sahara sand is tested because less reflectance decay was obtained.



(**a**) (**b**)

Figure 6. Reflectance drop for all samples, showing influence of (**a**) water and (**b**) brush hardness after 200 cycles.

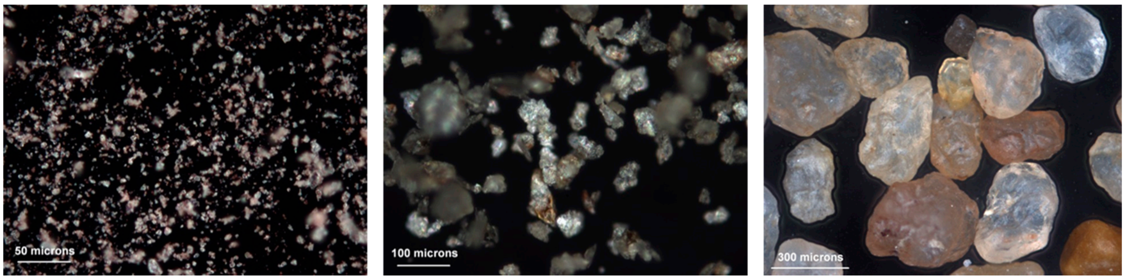


(**a**) (**b**)

Figure 7. (**a**) Plot of reflectance drop for each sand and (**b**) measurements of sand hardness after 200 cycles.

We conclude that the presence of water and the softness of the brush are the main influences on the specular reflectance, with the sand characteristics playing a secondary role. This prompted an analysis of the three sands used in the experiment. Sand hardness was determined using a nano-indentation technique with the results shown in Figure 7b. There is little to choose between the mean hardness of the three sands tested, with the most significant feature being the narrower spread in values from the samples of sand from the PSA. These small differences in hardness could explain the similar damage produced by the sands from the PSA and Arizona in the reflector samples (see Figure 7a).

Despite their similar hardness, individual sands appeared quite distinct when examined visually. Figure 8 below highlights these differences. The Arizona sand comprises small sand particles of the order of 1–10 µm, not unlike the PSA sand in terms of mean particle size although the PSA sand does contain some larger particles. The Saharan sand is very different, with particle sizes of the order of 100 µm+ and with more rounded edges on average. Yet for all three sands, Figure 6 shows that we have the capability to remove the particles from the polymer film surface using a soft brush without significantly reducing specular reflectance.



(**a**) (**b**) (**c**)

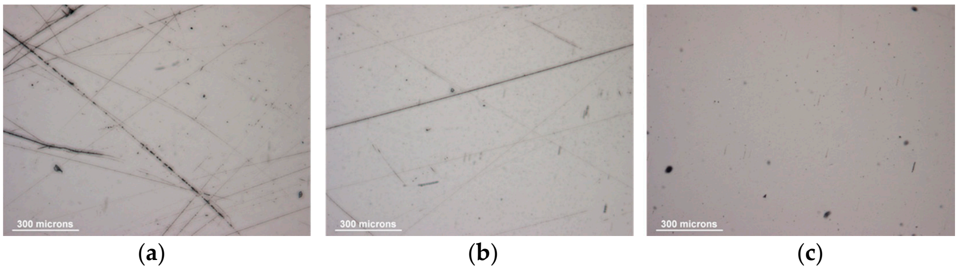
Figure 8. SEM micrographs of the three sands designated (**a**) Arizona; (**b**) PSA; and (**c**) Sahara.

The elemental compositions of the sand particles were also examined at Cranfield using energy dispersive x-ray analysis on both SFEG and ESEM scanning electron microscopes [14]. Representative compositional data in the form of atomic percentages are shown in Table 1 below, which also includes data from United States Military Standard (MIL-STD) silica for comparison. The data show that the composition of the PSA and Saharan sands are similar, despite the differences in particle sizes. Both sands contain metallic impurities in addition to pure silica. The Arizona sand is purer in composition, in addition to being a finer and smaller particulate material. The presence of calcium in all three sands is usually an indicator of calcite-rich limestone which is commonly found near roads. However, the calcium may have combined with potassium and sodium in the Saharan and PSA sands to form feldspars, the most common mineral in the earth's crust. Both the Sahara and PSA sands contain traces of aluminium, potassium, iron, and sodium. This suggests that dust particles of mica are present; which can be found in igneous, metamorphic, and sedimentary rocks. The origin of the carbon, found only in the Arizona sand, is less certain. Arizona has significant coal seams, is also a source of obsidian, and has organic impregnated clays. A more mundane explanation is that the carbon has its source in car and truck tyres, since the sands are almost always collected from road-sides. The Arizona sand is notably red in colour, the Saharan sand is notably yellow, and the PSA sand is dark brown or black.

Table 1. Elemental composition of sands used, with United States Military Standard (MIL-STD) silica for comparison.

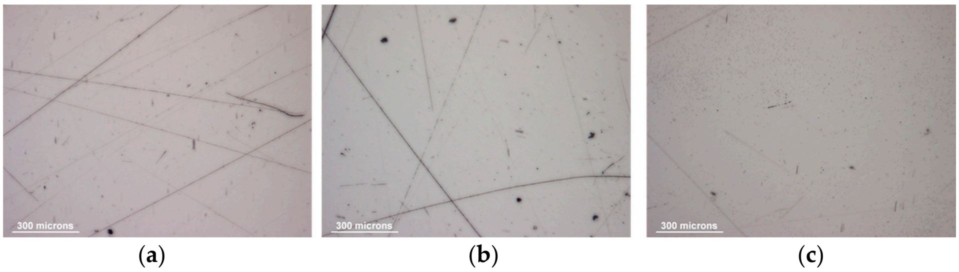
Sand Type	C	O	Na	Mg	Al	Si	Cl	K	Ca	Ti	Fe	Total
Atomic % (SFEG)												
Sahara	-	65.56	0.55	2.16	5.46	22.57	0.59	1.16	0.29	0.09	1.57	100
Sahara	-	62.86	0.41	1.49	6.81	24.36	0.53	2.01	0.38		1.15	100
Sahara	-	65.54	0.74	2.74	7.95	17.44	0.81	1.63	1.31	0.14	1.69	100
Sahara	-	76.61	0.45	1.63	3.5	6.04	0.37	0.55	9.84	-	1.02	100
Sahara	-	69.23	-	1.22	2.48	5.69	0.39	0.44	19.77	-	0.77	100
Sahara	-	65.65	-	1.07	4.08	26.82	0.39	1.06	0.26	-	0.68	100
Arizona	10.41	63.68	-	2.8	11.08	5.58	-	-	4.18	-	2.27	100
Arizona	6.92	56.66	-	0.8	16.13	14.32	-	-	1.58	-	3.59	100
Arizona	5.98	64.64	-	0.86	9.04	17.28	-	-	1.18	-	1.02	100
Arizona	6.39	62.28	-	0.84	13.72	13.5	-	-	1	-	2.28	100
Arizona	4.4	64.33	-	0.3	12.28	16.08	-	-	0.44	-	2.18	100
Arizona	5.45	66.9	-	0.23	5.6	21.17	-	-	0.21	-	0.45	100
PSA	0	58.34	0.54	0.53	8.79	26.01	0.36	2.01	1.43	-	1.98	100
PSA	-	63.93	3.75	0.55	14.35	14.9	0.17	0.6	0.25	-	1.5	100
PSA	-	49.32	-	-	14.93	21.9	0.67	10.64		-	2.54	100
PSA	-	46.54	0.91	0.76	18.32	21.82	-	5.67	1.24	-	4.74	100
PSA	-	59.18	-	0.97	12.47	19.83	0.47	3.24	0.59	-	3.26	100
MIL-STD silica	-	64.41	-	-	0.93	34.18	-	-	-	-	0.48	100
MIL-STD silica	-	67.81	-	-	1.35	30.84	-	-	-	-	-	100
MIL-STD silica	7.09	59.5	-	-	0.33	32.92	0.16	-	-	-	-	100
MIL-STD silica	-	70.71	-	-	5.62	19.23	0.11	4.14	-	-	0.2	100
MIL-STD silica	-	66.92	-	-	0.19	32.62	0.16	-	-	-	-	100
MIL-STD silica	-	63.34	-	-	0.31	36.2	0.14	-	-	-	-	100

In addition to assessing the optical properties of the polymer film before and after the cleaning experiments, the reflecting surfaces were examined by visual microscopy. A selection of these images is presented in Figures 9–11 which show the polymer film sample surfaces after having been soiled with the three sand samples and after cleaning with the range of brushes in the presence of water. For example, in Figure 9 we can see the scratches caused when the polymer reflector is cleaned with the hard brush, as demonstrated optically in Figure 6 earlier. Note that severe surface damage is not seen in Figure 9c with the Saharan sand, which was also noticed in the reflectance decrease (see Figure 7a), and which we attribute to the size of the particles. In this case, we speculate that the large Saharan sand particles have been swept from the surface during the first cleaning cycle of the hard brush. Figure 10 shows the corresponding result for the medium hardness brush. The surfaces exhibit surface scratches once again, as we might expect from the specular reflectance results. The final set of images, shown in Figure 11, represents the soft brush cleaning. For the soft brush cleaning, it is clear that no scratching of the surface occurred during particle removal. The only features visible on the surface of the film are a small number of dust particles and the occasional water stain. Again, the result confirms the specular reflectance measurements of Figure 6.



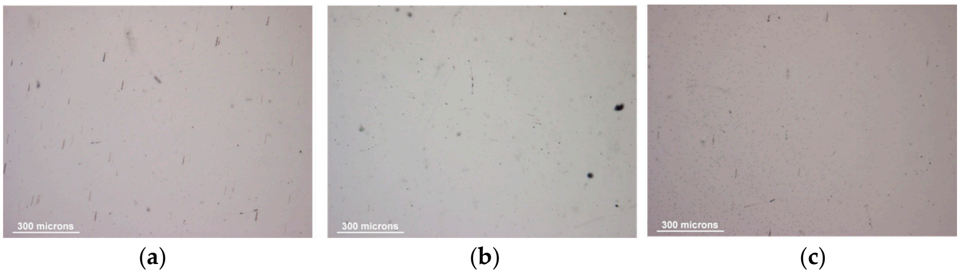
(**a**) (**b**) (**c**)

Figure 9. Polymer film surface cleaned with the hard brush, water assisted, soiled with the following sands: (**a**) Arizona; (**b**) PSA; and (**c**) Sahara after 200 cycles (Cranfield).



(**a**) (**b**) (**c**)

Figure 10. Polymer surface cleaned with the medium brush, water assisted, soiled with the following sands: (**a**) Arizona; (**b**) PSA; and (**c**) Sahara after 200 cycles (Cranfield).

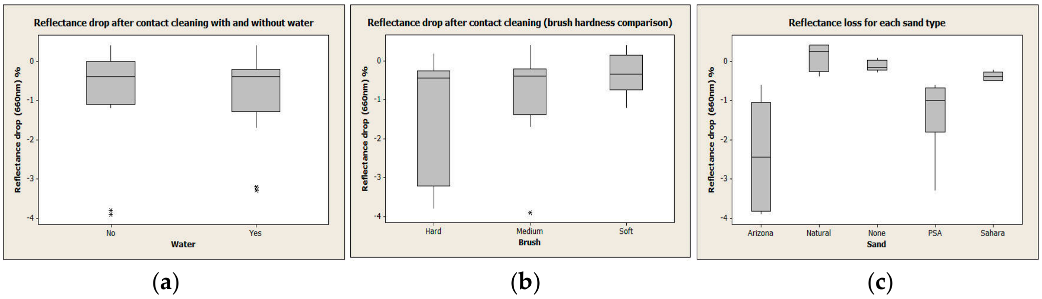


(**a**) (**b**) (**c**)

Figure 11. Polymer film surface cleaned with the soft brush, water assisted, soiled with the following sands: (**a**) Arizona; (**b**) PSA; and (**c**) Sahara after 200 cycles (Cranfield).

3.2. PSA Experimental Results

The results obtained from the experiments carried out at the PSA are shown in Figure 12. It should be noted that the sand types used at the PSA are the same as in the case of the Cranfield University experiments. Therefore, the earlier analysis of sand particle hardness, size, shape, colour, and composition are valid for the PSA experiments as well.



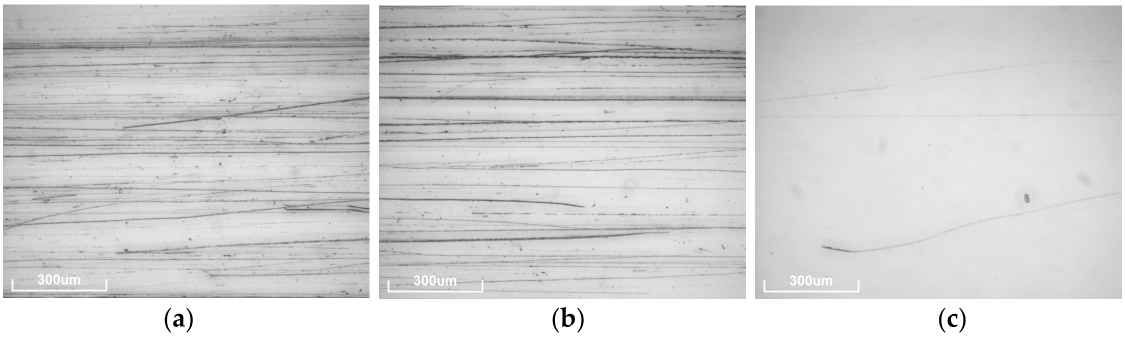
(**a**) (**b**) (**c**)

Figure 12. Reflectance drop as measured on the D&S, shown in comparison to the presence of (**a**) water; (**b**) brush hardness and (**c**) sand type.

For these PSA results the measurements of reflectance were taken using the D&S reflectometer, rather than the Condor instrument that was used at Cranfield. Although there is a strong correlation between the two instruments, measurements of identical samples will not yield identical values. There are two main reasons for this. Firstly, the reflectometers have significantly different acceptance apertures, 23.0 mrad for the D&S 15R-USB and 290.0 mrad for the Condor. Different acceptance angles will cause differences in reflectance values of soiled surfaces since the larger acceptance cone will gather more scattered radiation. Secondly, the damage we are seeking to quantify is localized on each sample, often in the form of scratches (see Figures 9 and 10, for example). Both instruments have beam spot sizes in the order of millimeters, and the specular reflectance can vary considerably over short distances. It should also be mentioned that the reflectance was measured at a wavelength of 650 nm using the Condor and 660 nm using the D&S instrument. However, if we assume that the Pettit approximation is true [15] then the ratio of specular reflectance to hemispherical reflectance is wavelength independent. From Figure 4, we can see that there is little difference between the hemispherical reflectance of polymer film in the range 650–660 nm, and therefore there is no significant impact on specular reflectance. As mentioned previously, a comparison of these two reflectometers is to be the subject of a future publication.

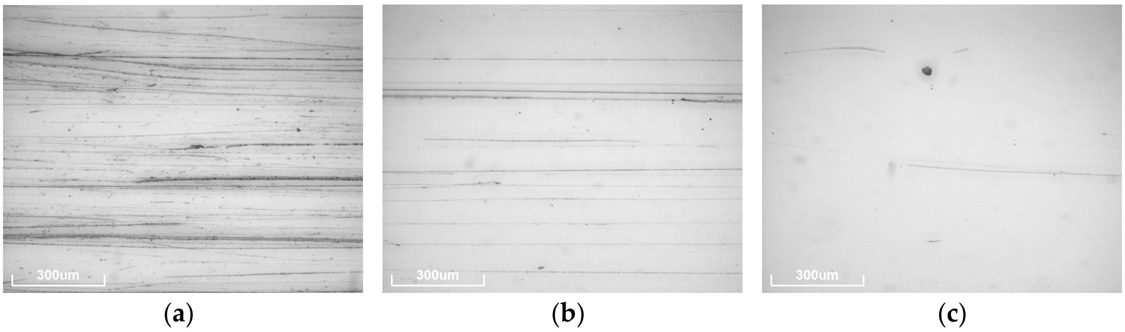
The plots in Figure 12 need to be compared with the corresponding plots from the earlier work done at Cranfield University (Figures 6 and 7) in order to gauge the effects of brush type, sand, and water on the polymer film during simulated contact cleaning. To recap, the experiments at Cranfield University strongly suggested that the specular reflectance (and surface damage) was mostly attributable to the hardness of the brush used and the presence of water during cleaning (water being preferable for minimizing damage). The sand used was not a significant factor, to the extent that Figure 7a showed that a reflectance drop occurred whether sand was present or not. Firstly, for the PSA experiments, Figure 12a shows the influence of water during the cleaning process. This is not so marked as in the case of the Cranfield experiments. Since the brush bristles, water quality, sand particles, and the polymer film itself are all constants across both experiments at both locations, we postulate that the results must be a manifestation of the different simulated cleaning processes that were run on the Fanuc robot and the Erichsen abrasion kit. In Figure 12b, the role played by the brush is similar to that played in the Cranfield samples, and the lowest values of reflectance drop are to be found again using the soft brush. In Figure 12c, the reflectance drop is now strongly influenced by which sand is used, and there is a much bigger difference between whether sand is present or not. As expected, with no sand present on the surface there is only a small impact on reflectance. A similar result is noticeable for natural soiling, which is predictable given the short period of exposure and the fine dust particles that were collected. Of the three sand types that produced a loss of reflectance, the greatest loss was found to be from using Arizona sand/dust, which contained the smallest particles.

The results can be explained by examining the different cleaning processes carried out at the two locations. The Fanuc robot simultaneously produces both rotational and linear motions whereas the Erichsen machine provides linear motion only. Therefore, it is likely that the sand is staying on the reflector surface longer on the Erichsen than on the Fanuc. Under those conditions, we would expect the sand to be a major factor in the PSA results and a lesser factor in the Cranfield results, which is indeed the case. The presence of water on the Erichsen machine may also help the smaller particle Arizona sand to stick to the brushes and cause the more significant damage seen with the PSA sand. At Cranfield, the sand is probably removed very quickly, whether there is water present or not, due to the fast multi-axis motion of the cleaning head. Then the influence of the water is simply to soften the bristles of the brush, which would be beneficial. The larger Saharan sand particles are likely to be removed very quickly on both the Erichsen and the Fanuc kits. There is additional evidence for these conclusions from the PSA visual inspection images shown in Figures 13–15, where the visual damage on the Saharan samples is noticeably less than other samples. The same trends are apparent from both sets of visual data (comparing Figures 9–11 with Figures 13–15). However, it is noticeable from Figure 15 that the soft brush still causes some small surface scratches on the Erichsen kit, unlike the minimal damage seen using the soft brush on the Fanuc kit. This strongly suggests that the most effective cleaning process requires a rotational movement of the brush cleaning head.



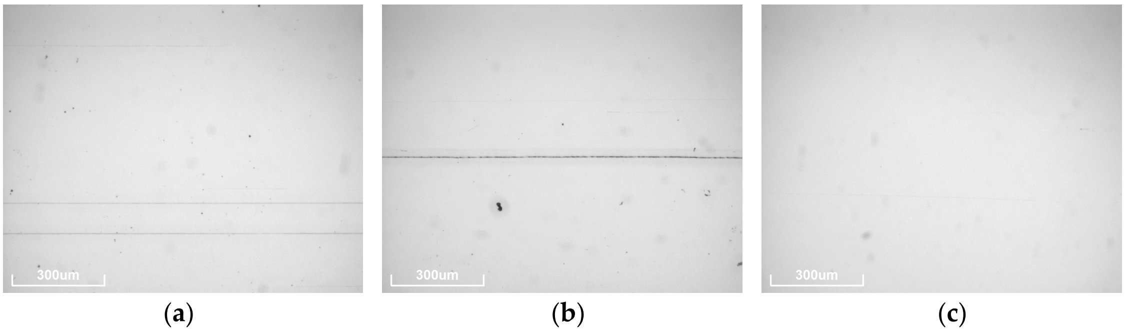
(**a**) (**b**) (**c**)

Figure 13. Polymer film surface cleaned with the hard brush, water assisted, soiled with the following sands: (**a**) Arizona; (**b**) PSA; and (**c**) Sahara after 200 cycles (PSA).



(**a**) (**b**) (**c**)

Figure 14. Polymer surface cleaned with the medium brush, water assisted, soiled with the following sands: (**a**) Arizona; (**b**) PSA; and (**c**) Sahara after 200 cycles (PSA).



(**a**) (**b**) (**c**)

Figure 15. Polymer film surface cleaned with the soft brush, water assisted, soiled with the following sands: (**a**) Arizona; (**b**) PSA; and (**c**) Sahara after 200 cycles (PSA).

The key results and their significance are summarized below:

- As with all solar collectors, soiling must be periodically removed from collector surfaces.
- For silvered polymer film collectors, brush-and-water contact cleaning is highly effective in removing soiling, but has been shown to damage the film.
- This work shows that a soft brush with water is an effective method to remove soiling without damaging the surface of the film.
- Cleaning is most effective with both a lateral and rotational movement of the brush.
- The soft brush with water regime was effective in removing all three sand types considered.

- The results were validated by carrying out the soiling trials in two locations with different experimental apparatuses and different analytical tools.
- Silvered polymer film solar reflectors can reduce the cost of solar heating and cooling in sustainable communities of the future.

4. Conclusions

This work demonstrates that it is possible to contact clean polymer film solar reflectors effectively by using a soft brush in the presence of water. Under such a regime the specular reflectance of the film is maintained and there is no visible damage to the surface layer of the film. The polymer film was tested under accelerated aging conditions when soiled with sand particles from three locations, using sand and dust samples that cover a range of particle sizes, shapes, hardnesses, and elemental compositions. The soft brush cleaning process, with water, produced good results in all cases. However, the experiments also brought to light differences that depend on the movement of the brush cleaning head. The most effective cleaning method employed a brush with simultaneous linear and rotational movement, resulting in more rapid removal of particles. Effective cleaning can also result from brushing with a linear motion only, but there is evidence that smaller sand and dust particles may adhere strongly to the soft bristles in the presence of water, therefore producing some surface damage and a corresponding loss in reflectance. The polymer film cleaning experiments and optical measurements were carried out at both Cranfield University in the UK and at the PSA in Spain, using different cleaning rigs and different reflectometers in order to further validate the results of the cleaning experiments. Having the capability to effectively contact clean polymer film reflectors using existing techniques involving brushes and water increases the viability of using such reflecting materials in solar radiation collecting applications. The flexibility and potentially lower cost advantages of polymer-based reflectors are likely to play an increasingly important role in the expansion of renewable energy technologies.

Acknowledgments: The research work leading to this article received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 609837 (Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy, STAGE-STE). Also, financial support by the Access to Research Infrastructures activity in the Seventh Framework Program of the EU (SFERA 2 Grant Agreement n. 312643) is gratefully acknowledged.

Author Contributions: Christopher Sansom, Aránzazu Fernández-García, and Florian Sutter were responsible for the design of the experiments and the methodology adopted. They were also responsible for sample selection and procurement, scheduling, and arrangement of locations and facilities plus the interpretation of results. Heather Almond and Lucía Martínez-Arcos were responsible for the execution of the experiments, data gathering by optical testing, and visual inspection at the PSA. Similarly, Heather Almond and Peter King were responsible for the execution of the experiments, data gathering by optical testing, and visual inspection at Cranfield University. Christopher Sansom wrote the article with Aránzazu Fernández-García plus the support of the rest of the team.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CSP	Concentrated solar power
PSA	Plataforma Solar de Almería
D&S	Devices and Services
SFEG	Schottky Field Emission Gun
ESEM	Environmental Scanning Electron Microscope
MIL-STD	United States Military Standard

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