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Comparative Assessment of the Durability of Glass and Polymer Mirrors for Concentrated Solar Thermal Technologies

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Abstract. This paper describes experimental work that has been carried out to assess the durability of glass and polymer mirrors against erosion and soiling phenomena. Both outdoor and indoor tests have been performed and the results show that polymer mirrors are quickly degraded in comparison to glass. Soiling deposition has been simulated using a soiling test rig developed for laboratory use. Results show that polymer mirrors, due to their high roughness and their surface energy properties, can accumulate more soiling on their surface generating a higher drop in specular reflectance compared to glass mirrors. Contact cleaning processes have also been simulated on polymer mirrors and the results show that using a hard brush, even at low speed with rotational motion, causes significantly more degradation than a soft brush.

Keywords: Soiling, Durability, Erosion

1. Introduction

Solar reflectors used in Concentrated Solar Power (CSP) plants need to maintain their designed-in performance during the plant's lifetime, considered to be between 20 and 25 years, to ensure the predicted profitability of the project [1-2]. Sites for CSP installations are often arid, desert-like regions. In these dusty environments, soiling and surface erosion phenomena remain the most common problems that affect the mirrors' performance during their operational lifetime [3-5].

Surface erosion results in damage by plastic deformation in the case of ductile materials or by material removal in the case of fragile materials such as glass [6]. It is caused by the impact of the mirror surface by the sand particles transported by the wind in the exposure site [5]. This degradation phenomenon alters the upper layer of the mirror, increasing the diffuse reflectance and consequently decreasing the specular one which determines the optical performance of the mirror.

Both Erosion and Soiling phenomena are significantly affected by parameters that can be grouped into environmental conditions (Relative Humidity, temperature, rain intensity, wind speed and wind direction), surface nature (ductile or brittle material, surface roughness), sand and dust particle properties, as well as the mirror's location within the solar field (height, orientation, inclination) [4-8].

Soiling deposition phenomenon is caused by deposition of airborne particles upon mirror surfaces. These are deposited either by Brownian scattering for small particles, or gravitational settling for larger ones [9]. The particles remain upon the surface due to impaction, interception or Brownian motion forces depending on the surface intrinsic properties [8-9]. In the case of low adhesion forces, soiled particles can rebound from the surface due to the impact of the wind [7].

The drop in optical performance generated by soiling deposition can be fully recovered by adopting an appropriate cleaning process. The cleaning technique is chosen depending on different parameters related to the season, the nature of the soiling in the site, as well as the percentage of reflectance to be recovered from the cleaning process. Cleaning processes can be contactless using pressurized air nozzles or water jets or can be with contact cleaning using different types of brushes to remove the accumulated dust material from the reflective surface. However, sometimes contact cleaning can be abrasive and therefore cause an irreversible drop in the optical performance of the reflectors [9].

Glass mirrors remain the most used solar reflectors in operational CSP installations. This is because of their high initial specular reflectance that reach 97% and their excellent durability over time. However, these thick glass mirrors can easily crack or break, and their heavy weight requires strong and rigid metallic structures to hold them in place and protect them from the high wind speeds forces. For that reason, polymer mirrors remain a very good alternative. They are very light and need less substantial supporting structures in the solar field, leading to considerable cost savings as a result. However, their initial specular reflectance remains lower than the glass mirrors and their durability is unproven in CSP applications.

In the present study, three different set of experiments have been conducted to understand the following:

- *Effect of the surface nature:* A comparative study between glass and polymer mirrors to evaluate their resistance to erosion and their behavior to soiling deposition. Both outdoor and indoor tests have been performed.
- *Effect of dust particles composition on soiling deposition rate:* A simulation of soiling phenomenon using different dust particles collected from different sites. A lab test using a soiling test rig.
- *Effect of contact cleaning on Polymer mirrors:* The contact cleaning process has been simulated in the lab using a FANUC robot to evaluate the impact of a variety of parameters on the durability of polymer solar mirrors.

2. Materials and Methods

Commercially available glass and polymer mirrors have been tested in this study. Glass samples are silvered thick glass mirrors, widely used in CSP solar fields, and the polymer mirrors are Aluminum reflective surfaces with a top surface of polymer protection. Mirrors are cut to samples of (10x10) cm^2. Three different set of experiments have been carried out in order to evaluate the:

- *Effect of surface nature*: Both glass and polymer mirrors have been tested in outdoor conditions as well as using the soiling testing rig in the lab.

a) ***Outdoor testing conditions:***
Samples have been exposed in three different exposure sites in a rack at a height of 1.5m above the ground (1 site in Spain and 2 sites in Northern Africa). Sites are equipped with meteorological data to record the climatic conditions and use them to explain any potential degradation on the samples. Unfortunately, due to some technical problems encountered during the study, different mirror types were exposed in different sites: Glass mirrors were exposed

for a period of 18 months in site 1 and 2, while polymer mirrors were exposed only in site 3. This presents a limitation to our study but has been overcome by the undertaken analyses.

b) Indoor testing conditions:

To simulate the soiling deposition, a soiling test rig was designed and built in the lab (Figure 1a). It enables the operator to eject dust particles onto the mirror's surface using a glass tube to provide a near-homogenous covering on the sample surface. To enhance the particle distribution, particles are released through a rotating sieve located on the upper opening (Figure 1.b). The mass deposition density (MDD) [g/m^2] of the soiled sample is determined by weighing the sample before and after the experiment. the experiments have been carried out under "dry" conditions where no effect of humidity, rain or dew can be simulated. This presents a limitation of the current design.

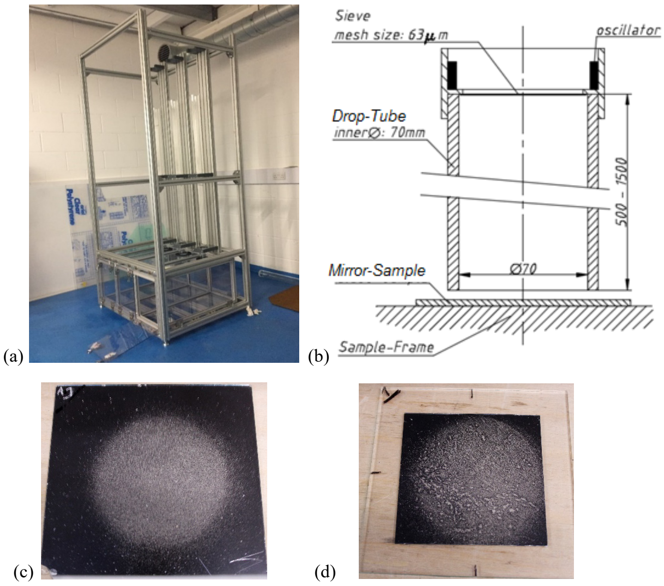

***Figure 1**. Soiling test rig (a), Schematic of the soiling rig (b), Soiled glass mirror sample (c), Soiled polymer mirror sample (d).*

- *<u>Effect of dust particles composition:</u>*

To evaluate the effect of dust particles composition, two different dust materials collected from different sites have been used.

- *<u>Effect of contact cleaning on polymer mirrors:</u>*

For this part, only polymer mirrors have been tested as they are the most affected by contact cleaning. Samples have been artificially soiled and dried before being cleaned using the FANUC Robot M-710i (Figure 2). The robot is equipped with a rotary head allowing a rotation of 300 rpm. Different parameters have been tested in this section, including:

- **Brush hardness:** three brushes with different hardness have been used, a soft (0.15), medium (0.2) and hard brush (0.25), the numbers indicating bristle thickness. These are in accordance with the ASTM 2486 standard.
- **Brush speed:** three different movement speeds have been tested, slow speed (284 mm/s), medium speed (370 mm/s) and the high speed (470 mm/s),
- **Brush motion during the contact cleaning process:** Different brush motions have been tested, linear motion, rotational one and a combination of both linear and rotational motion of the brush.

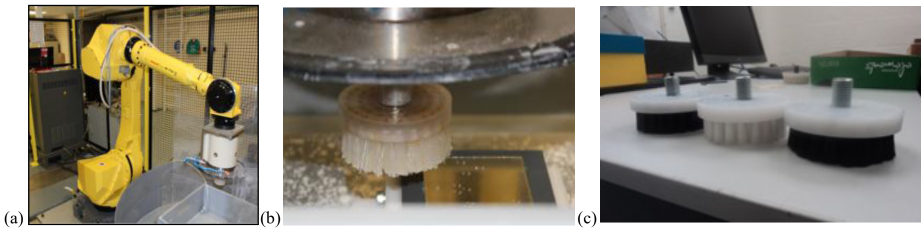

Figure 2. *Fanuc robot (a), medium brush in contact with a mirror's sample (b), different brushes used for the tests (soft, medium, and hard) (c).*

The optical performance of tested samples has been measured using a Condor reflectometer. This is an accurate, precise, robust, and easy to use portable instrument. It can make specular reflectance measurements at different wavelengths λ = [435, 525, 650, 780, 940, 1050] nm, and θi = 12º. The source of these different λ lights are six LEDs, with six corresponding detectors are included. As each LED is separated from the next by 19 mm, and the measurements for the different λ are not done at the same position on the sample. The reflectometer determines the specular reflectance for both second and first surface reflectors due to the optical arrangements. This reflectometer has a 1 mm beam diameter and φ = 290 mrad. According to the manufacturer, the repeatability is ±0.002.

3. Results and Discussion

3.1. Effect of the surface nature

3.1.1. Outdoor testing experiment

Glass and Polymer mirrors samples have been exposed for 18 and 12 months respectively in three different sites (1 site in Spain and 2 sites in Northern Africa). The results of the degradation of the specular reflectance after the exposure period are reported in Table 1 below. It should be noted that all values of reflectance are measured at 650nm wavelength using the Condor reflectometer.

Table 1. *Specular reflectance at 650nm of samples exposed in outdoor sites, Rs measured at initial state, and after the exposure period both before and after cleaning.*

	Glass mirror in Site 1	**Glass mirror in Site 2**	**Polymer mirror in Site 3**
Initial Specular Reflectance Rs (%)	96.2	96.2	95.8
Rs before cleaning (%)	81.94	66.6	53.4
Rs after cleaning (%)	95.78	94	91.6
Irreversible drop in reflectance (%)	0.42	2.2	4.2
Period of exposure	18 months	18 months	12 months

Results show that for the same type of glass mirrors exposed in two different sites with different environmental conditions, the irreversible drop in specular reflectance is different. The mirror exposed in site 1 has lost 0.42% of its specular reflectance during the 18 months of exposure period while the sample exposed in site 2 has reached a drop of 2.2% for the same exposure period. This could be explained by the impact of the climatic conditions and sand particles properties in both sites. By analyzing the wind speed and direction in both site 1 and site 2, it has been remarked that wind speed in site 1 has been very low with 90% of readings recorded at below 6 m/s against much higher wind speed recorded in site 2 (Figure 3), whereas around 10% have been registered between 9 and 12 m/s. As per the wind direction, the analyses have shown that the most dominant wind direction for the site 1 has been towards the North, while this was towards the South for site 2.

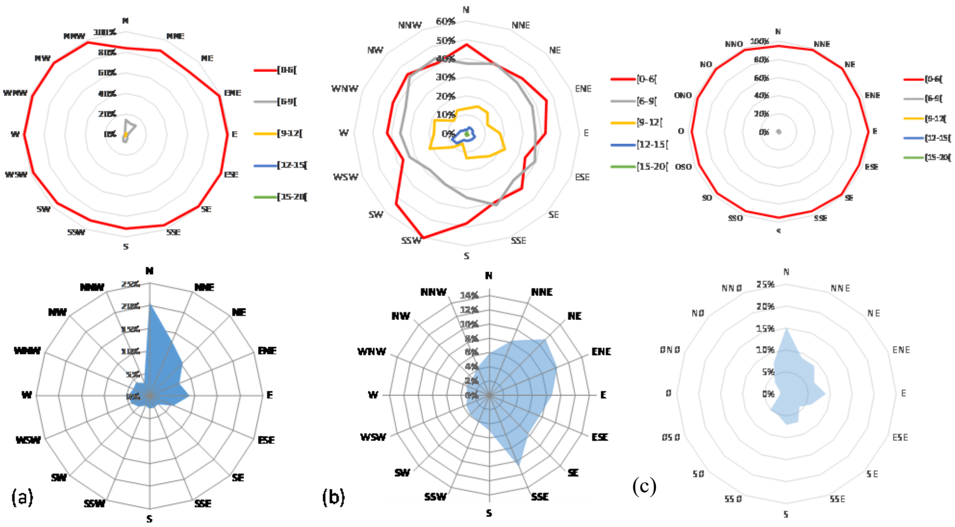

Figure 3. *Wind speed and direction respectively for site 1 (a) site 2 (b) and site 3 (c) during the exposure period of tested samples.*

Regarding the polymer mirror exposed in site 3, the results reported in Table 1 above show that this mirror has been degraded an order of magnitude more than the glass mirror exposed in site 1 for a lower exposure period. By analyzing the wind speed and wind direction presented in the Figure 3 above, we can remark that in both sites the wind speed has been very low, with lower values in site 3 in comparison with site 1. In addition, the sand particles' composition in both sites has been analyzed to understand this higher degradation of the polymer mirrors in comparison to glass. Results reported in the Table 2 below show that the sand composition is relatively comparable in both sites and cannot be used to justify the difference in drop in specular reflectance. This difference is then clearly related to the durability of polymer mirrors, being significantly lower than the durability of glass mirrors.

Table 2. *Sand particles composition sand collected from site 1 and site 3.*

	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	CaO	Fe_2O_3	TiO_2
Site 1	1.24	2.6	0.74	19.09	68.1	1.36	6.53	0.38
Site 3	1.15	3.74	0.93	17.22	66	2.04	7.38	1.12

Figure below shows the morphology of the impacts generated by sand particles upon the different types of mirrors. Material removal can be seen in the case of brittle glass mirror surfaces exposed in site 1 and 2, and plastic deformation in case of the ductile polymer mirror surface exposed in site 3.

(a) (b) (c)

Figure 4. *Erosion impacts generated on glass mirrors exposed in site 1 (a) and site 2 (b) and plastic deformation generated on polymer mirror surface exposed in site 3 (c).*

This irreversible degradation in specular reflectance observed on different tested samples has also affected the behavior of samples to soiling. By analyzing Table 1, it can be remarked that the soiling of polymer mirror has been higher than the soiling of glass mirrors exposed in both site 1 and site 2. This can be explained by the increased roughness of the polymer surface in comparison to glass surfaces. The increased roughness, added to the surface degradation, may cause particles to adhere more securely to the mirror surface, hence explaining the higher drop in specular reflectance due to soiling for polymer mirrors. This finding is also valid when comparing the glass surfaces of both site 1 and site 2. We can remark that the glass mirror that has been exposed in site 2 presents lower specular reflectance before cleaning than the mirror that has been exposed in site 1 and this could be due to the higher surface roughness in the mirror of site 2 because of the increased erosion of the sample.

3.1.2. Indoor testing experiment

To understand how glass and polymer mirrors behave under soiling deposition, a set of experiments have been carried out in the lab using our soiling test rig presented above. The initial specular reflectance of both glass and polymer samples has been measured at 650nm using the Condor reflectometer. Dust particles have been dropped onto mirrors samples twice to reach a mass deposition density of around 2g/m^2.

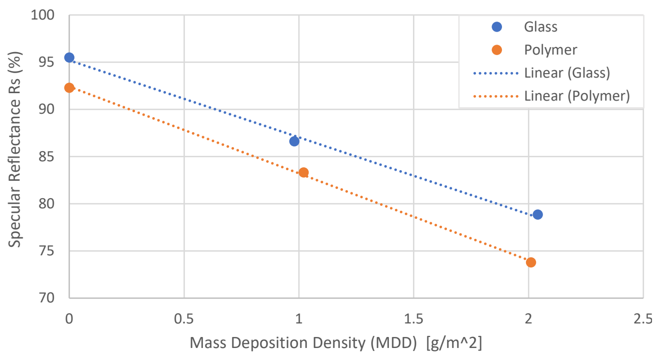

***Figure 5**. Drop in specular reflectance in correlation with the mass deposition density of the dust particles*

Knowing that their initial specular reflectance is not similar, the difference between soiling of both glass and polymer mirrors is low, with the polymer surface being soiled more than the glass one. According to the literature, it's worth mentioning that the roughness of a polymer surface is much higher than a glass one, which can explain this slight difference in soiling deposition. A higher roughness can cause higher soiling deposition and therefore higher reflectance drop. In addition, it should be noted that the amount of dust dropped onto the samples surfaces is low to avoid any multi-layering of soiled particles.

3.2. Effect of sand particles

To evaluate the impact of sand particles composition on the adhesion forces and therefore on the drop of specular reflectance, two different sand samples have been analyzed and sieved to less 63 µm to be used in this experiment.

***Table 3.** Sand particles composition of two different sand materials.*

	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	CaO	Fe_2O_3	TiO_2	$K(Si3Al)O_3$
Sand material 1, SM1	1.15	3.74	0.93	17.22	65.95	2.04	7.38	1.12	
Sand material 2, SM2				3.1	81.3		6.3		9.4

According to the graph below, It can be remarked that at 2g/m^2 of soiled particles deposited on the surface, the difference in reflectance between glass mirror soiled with SM1 and SM2 is clear. However, no major difference has been reported in case of polymer mirror samples. This could be explained by the different surface energy of both glass and polymer. Glass mirrors are more sensitive to the nature of the particles deposited upon their surface.

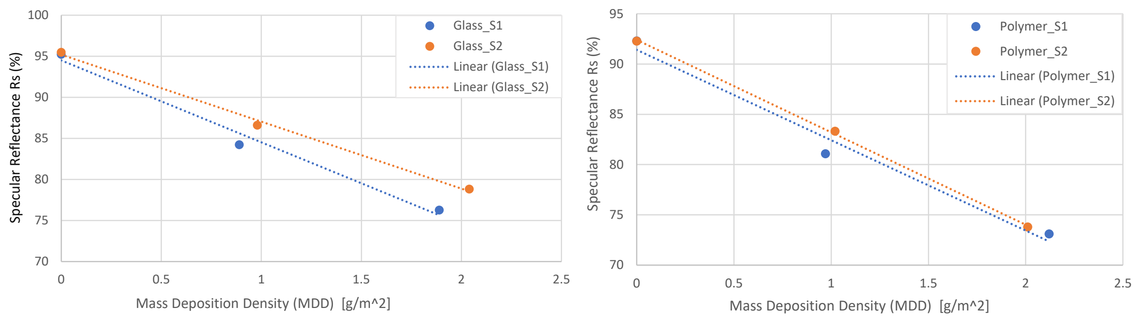

Figure 6*. Drop in specular reflectance of both glass and polymer mirrors due to soiling deposition using two different dust materials collected from different sites*

3.3. Effect of contact cleaning

In this section, it has been investigated the durability of polymer mirrors whilst undergoing contact cleaning. Samples have been soiled and dried in the ambient air before contact cleaning them using the FANUC robot in the lab as explained earlier. It has been evaluated the effect of the brush hardness, brush speed as well as the brush motion. According to the obtained results, it can be concluded that:

- As expected, the hard brush (0.25) generated more degradation of the surface than the medium and the soft brushes.
- The drop in specular reflectance of mirrors was higher when using the cleaning brush at low speed in comparison with the medium and fast speed. This can be explained by the fact that during the slow speed movement, the brush is in contact with the same surface area for a longer time, which when in the presence of a dust particle on the surface, causes more degradation.
- Rotational movement is the motion generating the highest drop in specular reflectance of the sample. This is due to the longer contact of the brush with a dust particle and the surface under the pressure of the brush.

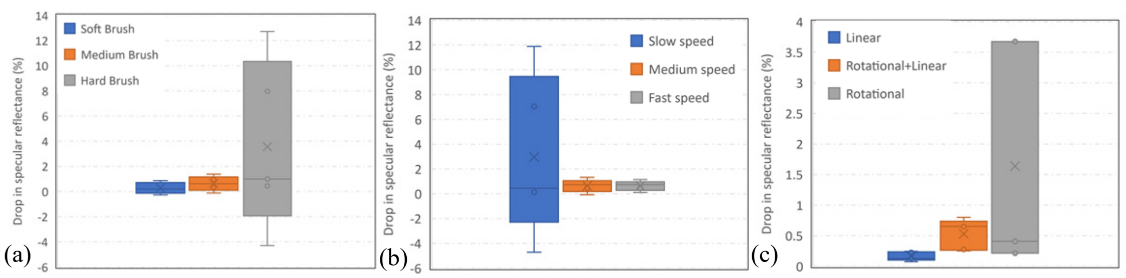

Figure 7. *Drop in specular reflectance depending on the contact cleaning parameters, different brush hardness (a), different cleaning speeds (b) and different brush motions (c).*

4. Conclusion

Three different set of experiments have been conducted in this study to compare the durability of glass and polymer mirrors and to assess the durability of polymer mirrors under contact cleaning processes.

- *Effect of the surface nature:* Results have shown that polymer mirrors are quickly degraded when exposed to outdoor conditions and that their surfaces are more soiled in comparison with glass mirrors. This has been explained by the higher roughness of the polymer mirrors which attract and hold more soiled material which leads to higher degradation after contact cleaning.
- *Effect of dust particles composition:* It has been shown that glass mirrors are more sensitive to particles composition compared to polymer mirrors.
- *Effect of contact cleaning on Polymer mirrors:* Hard brush and lower speed of contact cleaning has been found to cause the most degradation on polymer mirrors in comparison with softer brushes and higher speeds of motion. Also, it has been shown that rotational movement during cleaning can generate more degradation in comparison with linear motions.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

M. Karim: Conceptualization, Methodology, formal analysis; Investigation and Validation, Writing– original draft; C. Sansom: Methodology, Review & editing; Heather Almond: Methodology, Review & editing; Peter King: Methodology, Review & editing; Z. Hussaini: Review & editing.

Competing interests

On behalf of all authors, the corresponding author states that there are no conflicts of interest.

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