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Durability Assessment of Silvered Glass Mirrors Exposed in Two Different Desert Sites Suitable for CSP Installations

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Abstract. The durability of thick solar glass mirrors has been evaluated in this study by exposing samples at two potential exposure sites. Samples have been exposed for a period of 18 months at different orientations (North, South, East, and West) to evaluate the impact of orientation on the durability. The samples performance has been evaluated by measuring the specular reflectance of the glass samples before and after an appropriate cleaning process. In addition, the contact angle and the surface energy have been analysed. Obtained results show that mirror durability is very specific to the environmental conditions of the exposure site.

Keywords: Mirror Durability, Erosion, Optical Performance

1. Introduction

To be suitable to host a Concentrated Solar Power (CSP) installation, the site should fulfil a long list of criteria including a good daily normal irradiation, site flatness, proximity to water resources and to an electricity grid [1]. However, a very important criterion is generally missed from this list which is related to the aggressiveness of environmental aspects of the site against different components used in the plant. Solar mirrors are amongst the most affected components as they are directly exposed to outdoor exposure conditions [2]. Mirror lifetime is estimated at 25 years [3]. However, sometimes, it can be shorter than that due to quick degradation by the environmental conditions of the functioning site [4].

The environmental outdoor conditions that can be responsible for a mirror's degradation include the climatic conditions as well as the geological properties (sand particle characteristic properties such as hardness) present in the region [5-6]. Important climatic conditions include high relative humidity at the site, high wind speed in the direction of the exposure, as well as high gradient of temperature. High wind speed is generally associated with erosion issues [5]. This degradation phenomenon directly affects the specularity of mirror surfaces by increasing the amount of diffuse reflectivity and therefore reducing the performance of the reflector in operation [4-7]. To evaluate the aggressiveness of a CSP potential site, this paper presents the work conducted to compare the durability of solar mirrors exposed in two different potential installation sites.

2. Materials & Methods

To evaluate the effect of the environmental conditions on the lifetime of solar mirrors, mirror samples from the same manufacturer have been exposed in two different potential sites for Concentrated Solar Power installations, one in Ghardaia in Algeria (32.59 N, 3.61 E) and the other in Ghadames in Libya (30.13 N, 9.50 E). They have been exposed for a period of 18 months without any inspection.

In each site, samples of 10x10 cm^2 have been exposed in a rack elevated at 1 m from the ground as shown in Figure 1 below. Four samples are exposed vertically in four different orientations (North, South, East, and West) to evaluate the effect of the exposure orientation on the degradation rate. Tested samples are commercial silvered thick glass mirrors (4 mm). Climatic sensors have been implemented at both sites to record the variation of the environmental conditions during the exposure time to be analysed and correlated with the degradation rate.

Figure 1. Exposure test rack with mirrors facing four different orientations (N, S, E and W).

Once collected from the site and taken to the lab, samples have been visually inspected to highlight any visual degradation or main difference between samples. The optical performance as well as the surfaces' morphology have been measured for all tested samples.

The optical performance has been measured using a Condor reflectometer developed by Abengoa (Figure 2). This is an accurate optical device, designed for measurements in CSP solar field. The device allows the measurement of the specular reflectance at six different wavelengths, 435, 525, 650, 780, 940 and 1050 nm. The incidence angle of the Condor is θi = 12º and the acceptance angle is 290 nm. The device is equipped with six different LEDs, each one is specific to a given wavelength and the solar weighted reflectance is given by the device based on calculations and following the ASTM- G173 standard (Figure 3).

Figure 2. Photo of the Condor reflectometer by Abengoa [8].

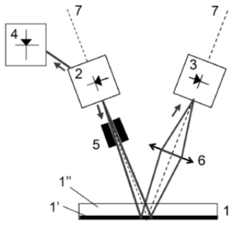

Figure 3. Optical scheme of the Condor reflectometer; (1): Mirror; (1'): Reflected surface; (1''): Glass; (2): Led, emitter; (3): reflection detector; (4): Reference detector; (5): Diaphragm; (6): Lens; (7): Optic edge [8].

Regarding the surface morphology, an optical microscope, Leica DM 2500, has been used to characterize the potential erosion degradation (cracking, pitting, material removal) that may be generated due to the outdoor exposure of the samples. In addition to the optical microscope, a 'Dynamic Contact Angle Meter and Tensiometer' of 'DATA PHYSICS' was used to measure the contact angle as well as the surface energy of the samples before and after exposure. The measurement principle is based on the standing drop method that allows the calculation of the angle θ formed by the tangent of the profile of the droplet with the line of contact between the substrate and the drop of water. The value of the contact angle is averaged over three measurements taken from the samples' surface. To avoid any chemical interaction between the droplets and the surface of the mirror, we opted for demineralized water as the fluid used for our measurements.

3. Results & Discussion

After the exposure period of 18 months in both Algerian and Libyan sites, glass mirrors samples have been taken to the lab to investigate and analyse their degradation over time. From the visual inspection before cleaning, it has been remarked that soiling particles have been homogeneously distributed upon mirrors' surfaces regardless of the samples' orientation in both sites (N, S, W and E). When comparing between Libyan and Algerian soiled samples, it has been found that the soiling layer in Libyan samples is thicker than that observed on the Algerian samples. It shows that the cementation process has been more pronounced at the Libyan site, which may be due to harsher climatic conditions or to a change in surface roughness. This will be investigated in what follows.

The drop in the optical performance of samples exposed in both sites has confirmed this difference in soiling behaviour observed between Libyan and Algerian samples (Figure 4). The results of samples' specular reflectance using the Condor reflectometer reported in Figure 4 show that the drop in specular reflectance was higher for Libyan samples. Knowing that the initial reflectance value at 650 nm is 96.2%, the drop in reflectance for Libyan samples was 25% compared to 10% for the Algerian samples.

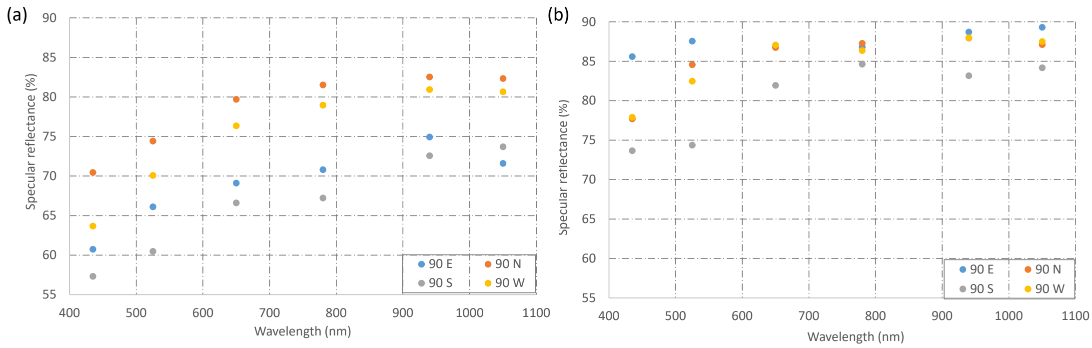

Figure 4. Specular reflectance before cleaning measured using the Condor at different wavelengths for samples exposed in (a): Algeria, (b): Libya.

It can also be seen that the drop in specular reflectance for Algerian samples (Figure 4a) has not been impacted by the orientation of the sample in the exposure rack, while it has impacted the drop in reflectance for samples exposed in Libya, where the difference in specular reflectance between samples is higher (Figure 4b). In both outdoor sites, mirrors exposed towards the South present the higher drop in specular reflectance for the different measured wavelengths. This can be explained either by the climatic conditions (rain or wind facing the exposure direction) or by an irreversible degradation that may have altered the specular reflectance of those mirror samples.

Observations under the optical microscope have shown that the Libyan samples have been become more damaged in comparison to the Algerian samples for the same exposure period (Figure 5). The dark spots in the images below are for erosion impacts generated on the Libyan samples during their exposition onsite.

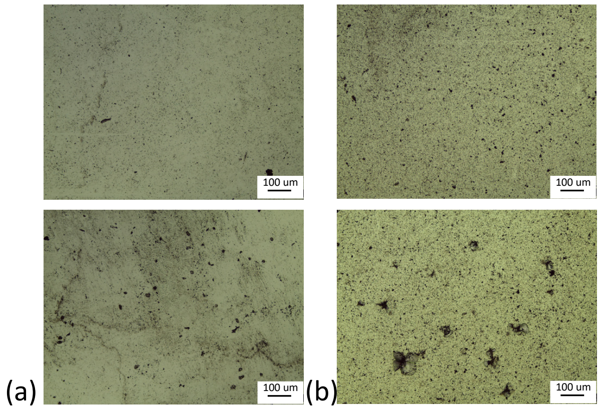

Figure 5. Optical microscope images of samples exposed at 90 degrees South oriented after 18 months before cleaning, (a): Algerian sample, (b): Libyan sample.

These erosion pits are more visible on the cleaned surface, as shown in Figure 6. The pits' characteristics (depth, length, and width) vary from one sample to another, with a maximum degradation impact on the glass sample exposed towards the south direction in the Libyan site.

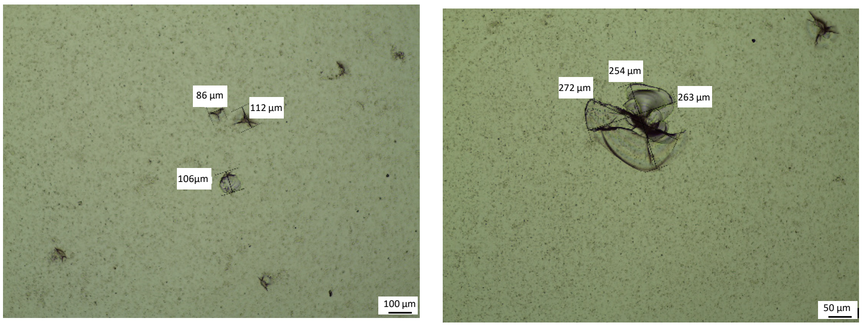

Figure 6. Optical microscope images of samples after cleaning exposed in the Libyan site for 18 months.

Specular reflectance measured after cleaning confirms the irreversible degradation of the Libyan samples where the initial reflectance value of 96.2% at 650 nm has not been recovered after the cleaning process (Figure 7a). The reduction in reflectance reached its maximum for the sample exposed towards the south with a drop of 2.2% after the exposure period of 18 months. A difference in drop of specular reflectance for samples exposed in different orientations can be seen. Regarding the Algerian samples (Figure 7b), it has been observed that samples recover their initial reflectance value after the cleaning process, which means that the samples haven't been permanently degraded as per the Libyan ones for the same exposure period.

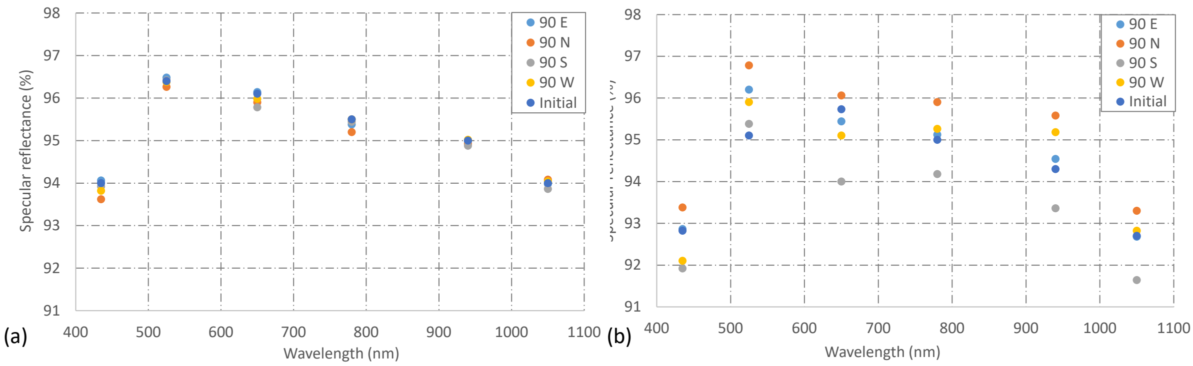

Figure 7. Specular reflectance after cleaning measured using the Condor at different wavelengths for samples exposed in (a): Algeria, (b): Libya.

To better understand the degradation of specular reflectance on the Libyan samples after cleaning, the contact angle, CA, and surface energy, SE, have been measured for all samples exposed at both sites. Results show that there is an inverted relationship between CA and SE (Figure 8). Figure 8c shows that the contact angle of Libyan samples is higher than the Algerian samples, as well as higher than the contact angle of the initial state. This can be explained by the increase of roughness in the Libyan samples, due to surface degradation, which led to the drop in specular reflectance. According to the literature, the CA decreases with the increase of roughness, but at certain amount of roughness, the CA will increase with the increase of surface roughness [9]. The surface energy parameter is a good indicator of how soiled particles will stick to the surface. It indicates the hydrophobicity of the surface and its capability of attracting or rejecting deposited soiling particles.

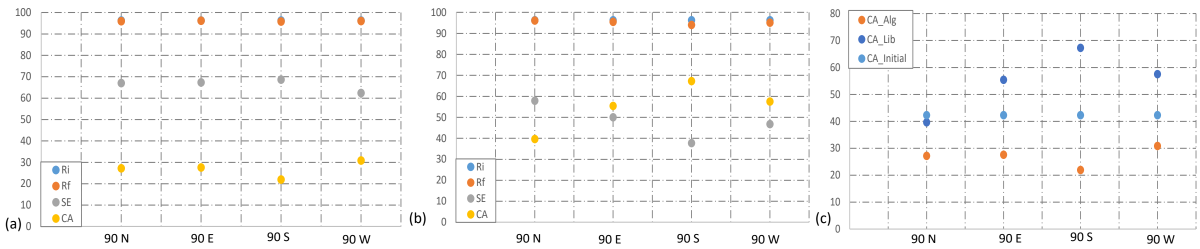

Figure 8. Comparison of Initial Reflectance Ri, Final reflectance Rf, Contact angle CA and Surface Energy SE for different samples, (a): Algerian Samples, (b): Libyan samples, (c): Comparison between Libyan and Algerian samples.

According to the literature, wind speed and direction, humidity, rain, temperature are all important climatic parameters that affect the soiling and erosion of mirrors' surfaces [1]. For the present study, as samples have been exposed for a period of 18 months without regular inspection, it has been decided to link the irreversible degradation observed on the samples' surfaces to the variation of wind speed and direction in both sites, as these appear to be the main causes responsible for the irreversible degradation generated by erosion. According to climatic data recorded on both exposure sites, results show that the wind speed in the Algerian site has been very low with 90% of readings recorded at below 6 m/s against a much higher wind speed at the Libyan site, where around 10% has been registered between 9 and 12 m/s (Figure 9). As per the wind direction, the analyses have shown that the most dominant wind direction for the Algerian site has been towards the North, while this was towards the South for the Libyan site. This explains the higher degradation rate observed on the sample exposed facing the south at the Libyan site compared to other samples.

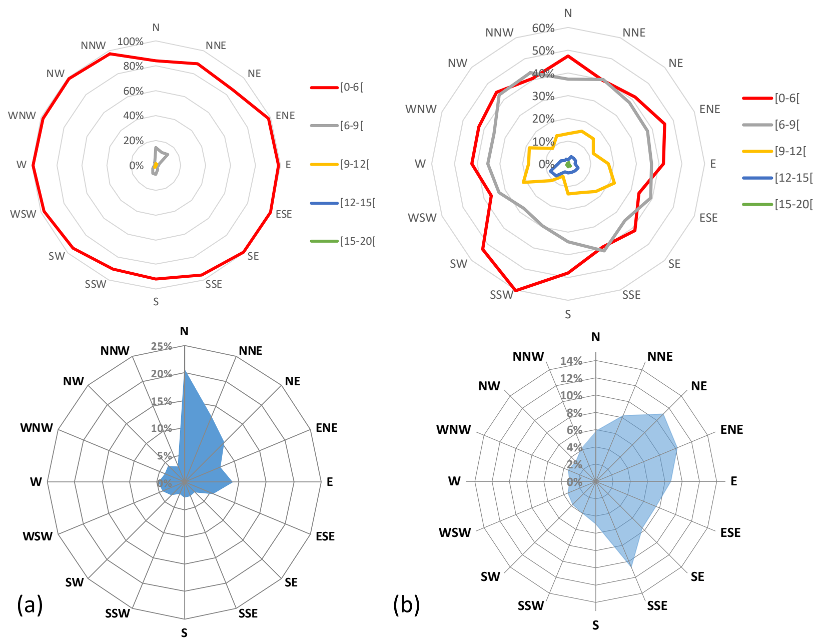

Figure 9. Wind speed and direction respectively for both Algerian (a) and Libyan (b) sites during the exposure period.

Wind speed is responsible for transporting sand particles at different heights from the ground depending on its magnitude. According to the literature, a wind speed of 5 m/s can transport particles up to 1 m from the ground level while this distance can easily reach 2 m in case of wind speeds attaining 9 m/s [10]. To confirm this trend, sand traps have been installed at different heights at the Libyan site, 0.5m, 1m, 1.5m and 2m. The objective is to evaluate the impact of exposure height on mirror degradation. Sand traps have been exposed for over a month at the Libyan site and results have shown that particles are reaching a height of 2 m above ground level (Figure 10). 4% of sand particles collected at a height of 2 m are bigger than 200 um which is due to the high wind speed recorded in the exposure site. It should be noted that this particle's size can generate a big erosion pit leading to a significant drop in specular reflectance. However, because of air turbulence at lower heights, the sand trap at 1 m shows a different particle size distribution.

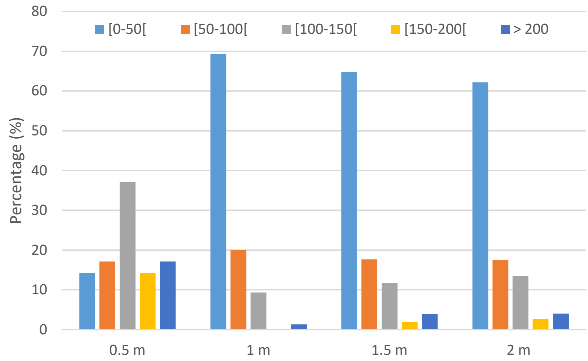

Figure 10. Particles size distribution of sand particles collected at different heights of the ground level in the Libyan site.

4. Conclusion

In this paper, we have evaluated the durability of thick silvered glass mirrors in two potential sites in Africa. Our exposure sites, in Algeria and in Libya, have been chosen for their high DNI. However, results have shown that samples exposed in the Libyan site have been much more degraded than the samples exposed in the Algerian site for the same exposure period of 18 months. Looking at the site specifications, it has been remarked that the Libyan site has been recording very high wind speeds reaching 15 m/s, while 90% of wind speed in the Algerian site has been below 5 m/s. This study confirms the importance of conducting a pre-feasibility study of climatic and geological conditions to evaluate the durability of solar mirrors at a potential site.

Data availability statement

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

Author contributions

S. Bouaichaoui and M. Abdunnabi were responsible in mounting the exposure sites and equip them with all needed tools going from the exposure rack, climatic sensors.... in both Algerian and Libyan sites respectively. M. Karim, C. Sansom, P. King and H. Almond have been responsible on analysing the degradation of all samples after the 18 months of exposure time as well as analysing the climatic conditions and the correlation study.

Competing interests

The authors declare no competing interests.

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