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Study of the surface damage of glass reflectors used in Concentrated Solar Power Plants

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Abstract

Solar mirrors are exposed, during their operation in Concentrated Solar Power plants –CSP-, to climatic stress factors that cause their degradation and therefore a decrease in the global efficiency of the plant. Sandstorms are among parameters that cause a decrease of mirrors optical performances by generating surface erosion. The intensity and the gravity of this erosion phenomenon is function of climatic, geological parameters and mirrors surface nature.

To evaluate the effect of these parameters on the optical performance degradation, two approaches were adopted, namely the natural aging tests in two different sites in Morocco, and the aging tests in controlled environment in a sandblasting chamber. The objectives are, by monitoring the stress factors in natural aging sites, to define aging tests under controlled environment that reproduce similar degradation phenomenon that those observed on mirrors exposed in natural aging sites. Degradations observed in both natural and controlled aging tests are compared and correlated to validate the methodologies and the hypotheses on the analysis of the degradation phenomenon. The aging tests in controlled environment permits the evaluation of the effect of each influencing parameter separately from the others on the mirrors surface erosion, and eventually accelerate the apparition of surface erosion on mirrors.

Under controlled environment, tests show that glass mirrors present maximum surface erosion at normal impact angle and that the loss in specular reflectivity is directly related to the wind speed. Exposed mirrors in natural aging sites present low loss in reflectivity which doesn't exceed 0.4% after 240 days of outdoor exposure. Concerning the effect of sand properties on erosion phenomenon, it was found that the sand hardness affect the roughness parameters, while the sharp forms influence on the impacts

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properties (roughness parameters, impacts number, impacted area, impacts size diameter). By increasing the sand particle's size, the impacted area increase and the losses in relative specular reflectivity increase.

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Keywords: Solar mirrors; Surface erosion; Natural aging; Outdoor aging

1. Introduction

In a Concentrated Solar Power plant -CSP-, more than 30% of the global investment is reserved for solar field that includes mirrors costs (installation, operation and maintenance, replacement of mirrors breakage…) **[1-2]**. To ensure high global yield of CSP plant, solar specular reflectance of mirrors are among the key-parameters that should be kept at its highest level during the entire service lifetime of mirrors **[3-4]**. This latter is directly related to the location of the power plant since several climatic stress factors like temperature, humidity, dew, irradiation and windstorms can cause various mirrors degradations such as surface erosion, corrosion of reflective layer, delamination, photo-degradation of polymeric protective layer, etc **[5]**.

To evaluate the effect of degradation phenomena on the mirrors optical performance, many studies are conducted on natural aging sites **[6-10]** where glass sheet or mirrors samples are tested during an exposure time. Natural aging tests are useful and necessary to observe and analyze degradation mechanisms under natural climatic conditions. However, it requires a long time before obtaining remarkable degradations and it is complex, in this case, to evaluate and understand the degradation linked to only one stress factor since samples are exposed to a mix of climatic parameters leading to several simultaneous degradation mechanisms. In fact, to accelerate the apparition of degradation phenomena and to dissociate the effect of each influencing climatic parameter, aging tests in controlled environment are often adopted **[2, 11-16]**. They permit to test, on specific chambers, the effect of some climatic parameters such as UV radiation, humidity, temperature, windstorms.

In this work, we are interested on windstorms effect on the surface erosion of mirrors. This phenomenon is directly influenced by the climatic and the geological parameters of the mirrors exposure site and their surface's nature parameters **[5, 11-12]**. The aim of the present study is to evaluate the effect of these influencing parameters on surface erosion phenomenon during natural aging and by conducting representative and accelerated tests in controlled environment. For this purpose, natural aging tests are made in two representative sites in Morocco. Conditions of representative tests in sandblasting chamber are defined based on the monitoring of influencing climatic parameters and on the geological analysis of both natural aging sites. These tests used both sand particles representatively extracted from the natural aging sites to approach the real aging conditions. To confirm our results, normalized sand particles are used in order to compare the obtained tendencies with literature.

2. Experimental procedure

Silvered mirrors of 0.95 mm thickness are used to evaluate the effect of surface erosion on the mirrors performances. In this conception, the glass substrate is coated with a silver reflective layer on the backside to create a second-surface mirror. To protect this reflective layer from any eventual degradation, mirror backing system is covered by several protective paints. For the present study, mirrors of 7 x 7 cm² are used for both natural and controlled environment tests. These mirrors are cut and supplied by the manufacturer without edge protection. In order to avoid the edge effects, samples of 20 x 20 cm² are added for the natural aging tests.

2.1. Natural aging tests

Two different sites in Morocco, distant with more than 500 km, are chosen to conduct the natural aging tests. The first site is a Oceanside site located in Temara near to the Moroccan capital Rabat. The site is aboard the Atlantic Ocean, see.Fig.1, and it is characterized by its high degree of humidity and wind speed. The second site is a desert site located in Skoura near to Ouarzazate city in the south of Morocco; see.Fig.1 which presents a high ambient temperature. In both natural aging sites, mirrors are exposed in racks with an inclination equal to the sites latitude, and oriented towards south.

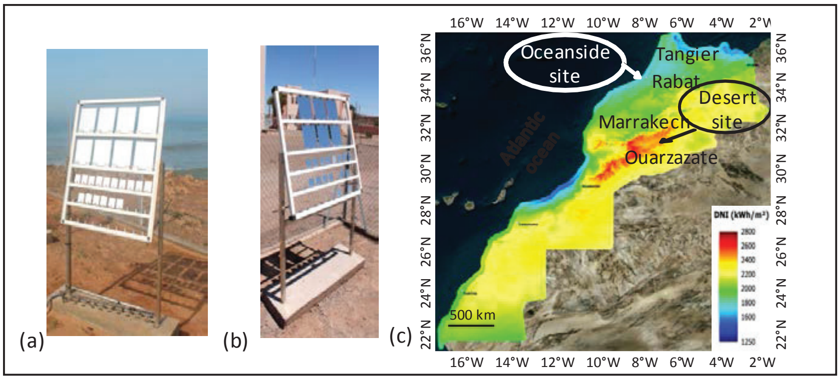

Fig.1. (a): Temara Oceanside site; (b): Skoura desert site; (c): Map of direct solar bearing in Morocco DNI (Source: solar-med-atlas.org).

Climatic parameters of both sites are monitored with meteorological stations. The main measured parameters are wind speed and direction, ambient temperature, relative humidity, global irradiation and rainfall.

Among climatic parameters, wind speed and direction are known as the most influencing parameters on surface erosion phenomenon **[16]**.

The recorded data from September 2012 to June 2014 show that for the maximum wind speed values, the Oceanside site present more than 25% of wind values higher than 5 m/s, see.Table.1. This later value is considered as threshold value of wind speed able to transport sand particles with diameter lower than 0.2 mm **[17-18]**. In desert site, wind values above 5 m/s represent only 18% of the global recorded data. The high wind speed values in the Oceanside site which reach a value of 22 m/s against 17 m/s for the desert site can be explained by the proximity of the site of the Ocean, see. Fig.1above. This wind speed analysis is used to determine the wind velocities used for aging tests in controlled environment.

Table.1. Occurrence frequency of maximum wind speeds recorded by a mesh of 10 minutes in both exposure sites between September 2012 and June 2014.

Wind speed (m/s)	Oceanside site (%)	Desert site (%)
V < 5	74.74	81
5 < V < 10	22.82	17.83
10 < V < 15	2.17	1.15
V > 15	0.28	0.01

The wind direction is interesting to estimate the main impact angle of sand particles on mirrors surface. The obtained results from the wind direction analysis in both sites will be used to choose the impact angles used for aging tests in controlled environment. From the wind rose recorded from September 2012 to May 2014, see. Fig.2, it was shown that the wind direction in the Oceanside site is characterized by a dominance of the south and south-west orientations, while in the desert site the wind direction is dominated by the east-north-east and west-south-west directions. Assuming that mirrors are exposed in both sites according to the south and with inclination equal to the site latitude, the potential incidence angle in Oceanside site will be more close to the normal impact angle that in the desert site.

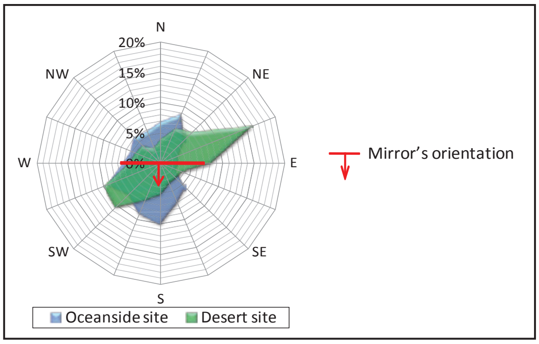

Fig.2: Wind rose from the recorded data between September 2012 and June 2014.

Concerning the geological influencing parameters, size distribution, hardness and shape of sand particles are the most influencing parameters on surface erosion phenomenon. A complete geological study was made on representative sand extracted from both exposure sites to determine the main sand properties. Results in details were reported in a previous work **[19]**. The main sand properties of both sands are presented in the followed section. This geological analysis permits the identification of the sand particles properties which are helpful to highlight the effect of each sand particles property.

In addition to the geological analysis and in order to determine the sand particles properties that reach different heights from the ground, sand trap systems have been installed in desert site, see.Fig.3.a. The trapped sand particles are regularly analyzed. To evaluate the combined effect of height and impact angle on surface erosion, an erosion rack has been installed in the desert site, see. Fig.3.b. The exposed mirrors are oriented trough four different orientations according to the predominant wind orientations, e.g. east-north-east, and four different inclination.

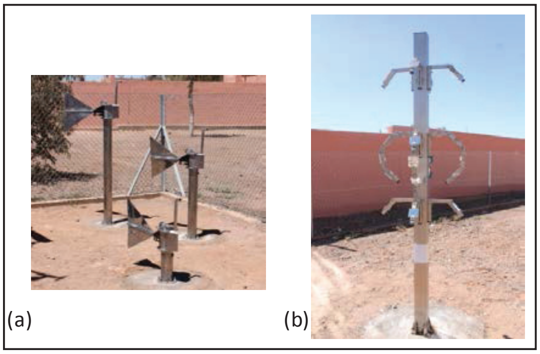

Fig.3: (a): Sand trap systems and (b): Erosion rack to evaluate the effect of impact angle on surface erosion, equipements exposed in Skoura desert site.

To focus on the effect of surface erosion on mirrors optical performance and in order to simulate and accelerate the effect of each influencing parameter, several tests were made in controlled environment. The used chamber is presented in what follow.

2.2. Erosion tests in sandblasting chamber

Horizontal sandblasting chamber is used for tests in controlled environment, see.Fig.4. The nozzle diameter is about 1.5 cm and the homogeneity of the flow is ensured by using an air homogenization tube. The sample holder can rotate from 0° to 90° to vary the impact angle. The wind velocity varies with the distance L, between the air homogenization tube and the sample holder.

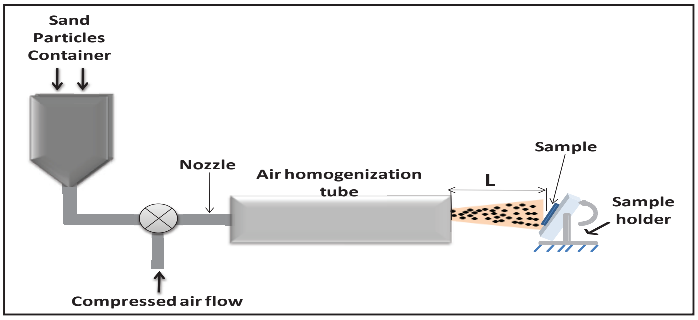

Fig. 4: Sandblasting chamber used for simulating the surface erosion phenomenon.

To approach the real conditions of natural aging in controlled environment, four wind velocities are chosen according to the recorded data from both natural aging sites, namely 3.8 m/s; 6.3 m/s; 9.2 m/s and 15.1 m/s.

In order to evaluate the effect of the impact angle as parameter on surface erosion rate, mirrors are tested under four different impact angles, namely 20°, 40°, 70° and 90°. These chosen impact angles cover all the potential angles identified from the wind direction analysis in the natural aging sites. The normal impact angle was added in order to evaluate the effect of this impact angle on surface erosion and to confirm our obtained trend with literature.

To evaluate the effect of sand properties on the surface erosion, sand particles are extracted from both natural aging sites. In addition to these natural sand particles, normalized sand MIL-STD 810-F is used in order to compare the obtained results with the literature. The main sand properties of the three used sand particles are regrouped in the table below.

Table 2: Sand properties of both extracted sand samples from the exposure sites.

Sand properties	Oceanside sand	Desert sand	Normalized sand
Dominant size fraction	70% between 0.1 and 0.4 mm	50% bigger than 1 mm	100% bigger than 0.15 mm
Hardness	3-4	5-6	7
Shape	Sharp	Sharp to round	Sharp

The sand hardness is defined according to the mineralogical composition of the sand aggregate. Mohs scale permits the classification of the mineral hardness from 1 for talc mineral to 10 for diamond. Concerning the sand particle shape, a visual chart is used to determine the sand particle's shape from binocular loupe observations, see. Fig.5 **[20]**. This parameter is considered as quite affecting the surface erosion rate since round particle present less damage than a sharp one **[21]**.

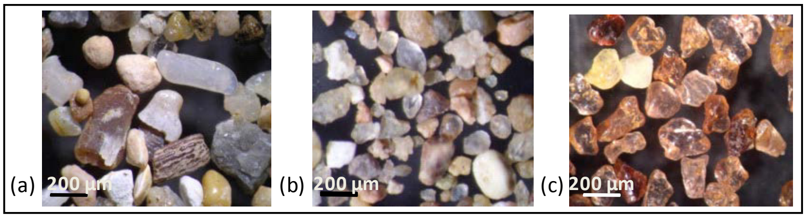

Fig.5: (a): Oceanside sand particles; (b): Desert sand particles; (c): Normalized sand particles.

To evaluate the impact of the sand particles granularity, two different fractions of natural sand particles are used, namely sand particles with diameter ϕ_{sand} higher than 150 µm to simulate the sand storm and sand particles with diameter lower than 150 µm to simulate the dust storm. This classification was done according to the military standard MIL-STD-810 which classify the windstorms into sand storms (150 µm < ϕ_{sand} < 800 µm) and dust storm (ϕ_{sand} < 150 µm) **[10]**. For the normalized sand particles, only the coarse sand fraction was used for tests.

It is worth to note that during natural sand transportation, bigger sand particles need higher wind speed to be transported in comparison with lower particles. In order to simulate the real conditions of exposure and simplify the tests matrix, it was decided to simulate the surface erosion by the fine sand particles at wind velocities of 3.8; 6.3 and 9.2 m/s, and by the coarse sand at wind velocities of 6.3; 9.2 and 15.1 m/s, see. Fig.6.

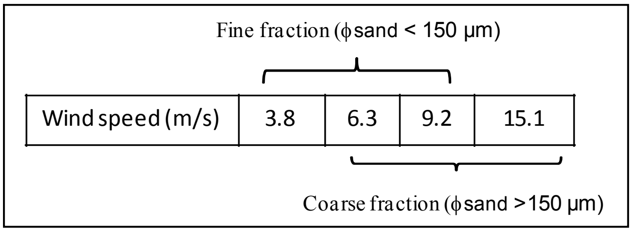

Fig.6: Sand fraction used with each wind velocity during aging tests in controlled environment.

2.3. Characterization techniques

For the characterization techniques of mirrors tested in both natural aging sites and in controlled environment, the optical performances are followed by measuring the specular reflectivity at 660 nm under an incidence angle of 15° and an acceptance angle of 25 mrad, ρ_s(SW, 15°, 25 mrad). This measure is ensured using a portable reflectometer 15R-USB from Devices & Services.

The surface roughness was characterized by a stylus profiling system Dektak XT provided by Brucker. The obtained results from the surface scanning are analyzed by ImageJ software in order to determine the impacts properties (impacts number, impacted area, impacts size diameter). An optical microscope Leica is also used to observe the different shapes of generated impacts upon mirrors surfaces.

3. Results and Discussion

Mirrors samples are exposed in the Oceanside site from August 2013 and from May 2013 in the desert site. During this period, no degradation other than surface erosion was identified on the exposed mirrors. Therefore, the decrease measured in specular reflectance can be directly related to the effect of surface erosion. The difference between all measured mirrors is represented in the graph by bars. After 240 days of natural aging, the measured loss in relative specular reflectivity, *Rr,* is lower than 0.4%, see. Fig.7:

$$Rr = \frac{(Ri-Ra)}{Ri} \quad (1)$$

With:
Rr: Relative loss is specular reflectivity
Ra: Specular reflectivity after aging
Ri: Initial specular reflectivity

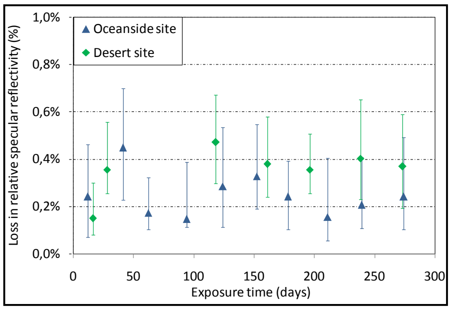

Fig.7 . Irreversible losses in relative specular reflectivity Rr of exposed mirrors samples in both natural aging sites.

Regarding the effect of the climatic parameters, no conclusion can be deduced from the graph since the loss in relative specular reflectivity is still low in both sites.

According to the results of aging in controlled environment, tests show that mirror's tested at 90° present the maximum loss in specular reflectivity which fits with the literature, see. Fig.8 **[13]**. The surface characterization of the tested mirrors at 20° and 90° shows that the samples tested at high impact angle, 90°, presents higher impacts properties (roughness parameters, impacts number, impacted area, impacts size diameter) than those observed on samples tested at low impact angle, 20°. This trend is confirmed in the literature **[13]**. Results also show that the optical performance decreases by increasing the wind velocity in the sandblasting chamber, see. Fig.8.

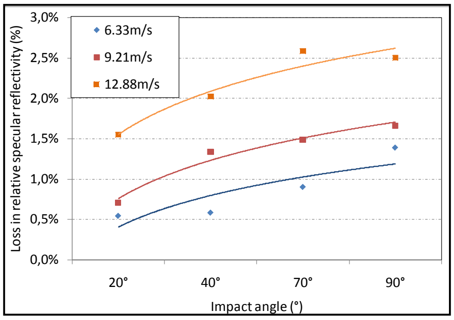

Fig.8: Effect of impact angle and wind velocities on the surface wear rate of glass mirrors tested at 2 g of sand particles during accelerated tests in laboratory. Logarithmic trend curve.

The effect of wind speed observed during testing in controlled environment can be compared to those observed on natural aging tests. Two shapes of impacts are distinguished and can be directly related to the wind speed in the region. In the desert site, where wind speed is low with approximately 80% of wind values below 5 m/s, the generated impacts are presented as ring cracks, see Fig. 9.a. In Oceanside site, where the wind speeds are higher and up to 22 m/s, the generated impacts are normal cracks with direct removal material, see Fig. 9.b. This was confirmed by the results obtained in controlled environment when the observed impacts on mirror tested at high wind speed present impacts with removal material, see. Fig. 9.c.

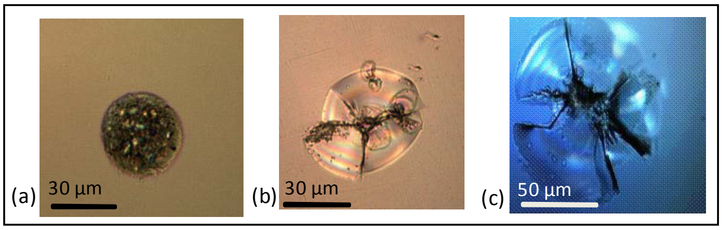

Fig.9. Observed impact upon exposed solar mirrors; (a): Mirror exposed in desert site, (b): Mirror exposed in Oceanside site, (c) Mirror tested in controlled environment at 90° and V=9.21 m/s.

In desert site, the wind speed is not high enough to create normal impacts with direct material removal such as those observed on surface of Oceanside's site mirror. In this case, the generated impacts are presented as a ring crack where the material removal caused during the shock between sand particle and the mirror's surface remains on the middle of the impact as showing below see. Fig.10.a. For the mirror exposed on the Oceanside site, the observed impact presents material removal which is presented as a hole on the middle of the impact during the surface scanning by the stylus profiling system, see. Fig.10.b.

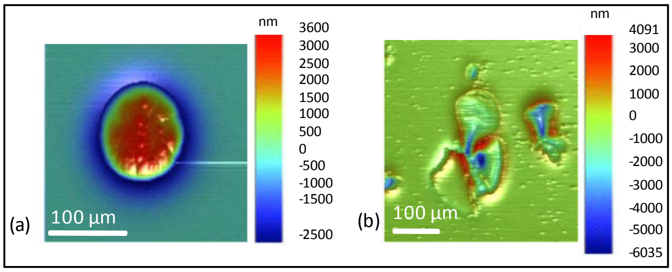

Fig.10: Observed impact upon exposed solar mirror in both sites analyzed using stylus profiling system, (a): Impact on desert's site mirror, (b): Impact on the Oceanside's site mirror. Resolution X=1µm and Y= 0.1 µm.

The effect of sand properties on the surface erosion phenomenon is evaluated by making a comparison of the roughness parameters and impact properties of two mirrors exposed in both natural aging sites. The main obtained results are reported in the table below.

Table 3: Surface roughness properties of two mirrors exposed in different sites for 240 days of natural aging.

Exposure site	Roughness parameters			Impacts parameters	
	R_a (nm)	R_v (nm)	R_p (nm)	Impacts number	Impacted surface (%)
Oceanside site	1.17	-1900	2630	3298	1.6
Desert site	1.22	-2284	2925	1358	1.1

The roughness parameters compared in this study, namely R_a, R_v and R_p are defined as:

- R_a: The average arithmetic gap of the roughness profile
- R_v: The maximum height of the projection in the analysed profile
- R_p: The maximum depth of hollow in the analysed profile

For the same aging time, desert's site mirror presents higher roughness parameters than Oceanside's site mirror. However, the impacts parameters (impacts number, impacted area and impacts size) calculated upon surface of Oceanside's site mirror are higher than those calculated on surface of desert's site mirror. This difference should be due to the variety of the sand particles properties present in both sites or to the difference in the wind speed. From the geological analyses, it was shown that desert's site sand particles are harder and smoother than Oceanside's site particles which are softer and sharper. By correlating this information with the obtained results, we can make the hypotheses that the hardness impacts on the roughness parameters and the sharpness influence the impacts parameters or that the wind speed is influencing on the impacts properties.

In order to confirm these hypotheses, two mirrors were tested at the same wind velocity, the same impact angle and the same size particles range and with sands extracted from both natural aging sites. Results show that the roughness parameters of mirror's surface tested by desert sand particles are higher than those calculated upon mirror's tested by Oceanside sand particles, see Table.4. However, the impacts parameters (impacted area, impacts size, impacts number) are higher for mirror's tested by Oceanside sand particles. This confirmed the hypothesis emitted for the obtained results from the natural aging tests that assumed that this difference is directly related to the sand particles properties.

Table.4: Surface roughness properties of two mirrors tested by fine sand particles extracted from studied sites; V= 6.33 m/s and at impact angle of 90°.

Used sand particles	Loss in specular reflectivity (%)	Roughness parameters			Impacts parameters	
		Ra (nm)	Rv (nm)	Rp(nm)	Impacts number	Impacted surface (%)
Oceanside site	1.7	2.3	-460	270	2860	2.6
Desert site	1.5	2.4	-780	620	1880	1.3

To evaluate the effect of size particles on surface erosion, both sand fractions, fine and coarse, extracted from the natural aging sites are used for tests. Results show that for the same sand mass and the same wind velocity, mirror tested by the coarse sand fraction present higher decrease in specular reflectivity in comparison with mirror's tested by the fine sand fraction, see. Fig.11.

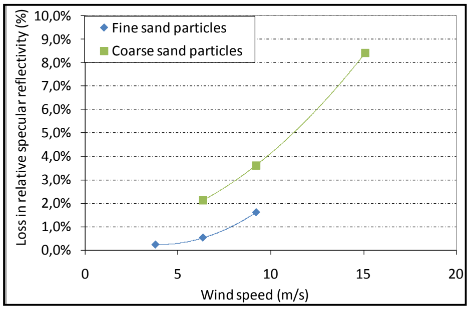

Fig.11. Effect of particle size on surface wear phenomenon at an impact angle of 90° and at received mass of 1g during accelerated tests in laboratory: Example of mirrors tested by desert sand particles, fine particles (Diameter < 0.15 mm) and coarse particles (Diameter > 0.15 mm). Polynomial trend curve.

4. Conclusion

Surface erosion is among phenomena responsible of optical performance decrease of mirrors optical performances and then on decrease in global yield of CSP plant. In this paper, the influencing parameters, climatic (wind speed and direction), geological (sand properties), on surface erosion were monitored and analyzed in two different sites in Morocco. The objective is on one hand to evaluate the effect of these parameters on the observed degradation phenomena during the natural aging tests and on the other hand to define the conditions for the aging tests in controlled environment in sandblasting chamber.

The correlation of results from natural aging tests and tests made in sandblasting chamber indicates that the loss of specular reflectivity is increasing with the wind velocity. Two different impacts shape can be distinguish as function of wind velocity, namely ring cracks formed at low wind speed and normal cracks that generate direct material removal in case of high wind speed.

Regarding the impact angle, the aging tests under controlled environment show that at normal impact angle, the loss in specular reflectivity presents a maximum rate.

In order to evaluate the effect of sand properties on surface erosion, tested mirrors in both natural and controlled environment are analyzed by stylus profiling system. It was found that the sand hardness affects the roughness parameters, while the sharp forms influence on the impacts properties (roughness parameters, impacts number, impacted area, impacts size diameter).

Other aging tests in controlled environment are planning in order to compare between surface erosion caused by sand particles extracted from studied sites and those caused by normalized sand particles.

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