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Investigation of soiling effect on different solar mirror materials under Moroccan climate

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Abstract

This paper presents some first results of the effect of dust on different solar mirror materials in Morocco. For this purpose, thirteen glass and aluminum mirrors were exposed at the University of Oujda (Eastern Morocco) for a period of three months (from April to June). For each type of the mirrors, one sample mirror was installed horizontally and twelve mirrors were installed in the so called "mirrors sphere" in four different directions (North, South, East and West) with three tilt angles relative to the vertical plane: +45°(facing the sky), 0° (vertical) and -45° (facing the ground). The drops in specular reflectance were measured after each month of exposition for both mirror materials. Furthermore, X-ray diffraction analyses were performed for the dust collected from the mirrors to identify the mineralogical components of the dirt settled on the mirror surfaces. For both mirror materials, the drop on cleanliness per time interval was quite the same for all the mirrors and over all the test periods. The highest average cleanliness drop per month for the horizontal mirrors was 45 % and 33 % for the glass and aluminum mirrors respectively. The +45° mirrors come in the second position with a cleanliness drop of about 14 % for both reflectors. However, the mirrors installed on the 0° and -45° angles remained cleaner with a cleanliness average of about 97 % for both mirrors. These first results can be of high importance to motivate scientists and actors in the field of solar energy to further investigate the soiling of CSP mirrors and add it as a parameter in solar resource assessment.

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*Keywords:*Dust effect; Soiling; Mirrors; CSP;Outdoor exposition; Eastern Morocco

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Nomenclature

DNI	Direct Normal Irradiance (W/m²)
$\rho_s(\lambda,\theta,\varphi)$	Specular reflectance (%)
λ	Wavelength (nm)
φ	Incidence angle (°)
θ	Acceptance angle (mrad)
ρ_d	Reflectivity of the dirty state of the mirror (%)
ρ_c	Reflectivity of the clean state of the mirror (%)
$\rho(SW,\theta,\varphi)$	Solar-weighted specular reflectance (%)
$\rho(SW,\theta,2\pi)$	Solar-weighted hemispherical reflectance (%)

1. Introduction

Soiling is the phenomenon of the deposition of dust on a surface during the exposition to the environment. It is considered a major critical issue for both solar technologies, CSP and PV [1,2]. Indeed, the dust accumulation causes an important reduction in the amount of solar radiation reaching the solar receiver, which influences significantly the power output of the plants. Soiling is a complex problem; it depends very much on the location and on the meteorological parameters (such as rain, wind, humidity …). In addition to that, it can cause serious trouble for the operators of solar power plants that have to find the best scenario for the cleaning cycles of the power plant in order to keep a high reflectivity/efficiency, without consuming a lot of water, fuel and working time. Such a problematic is especially present in desertic areas, as where most of the power plants will be installed in Morocco and in the MENA region [3]. Although this problem is extremely important and needs a deep understanding, very few studies have dealt with it, particularly for CSP [4,5]. Contrary to CSP, several papers have been published about soiling of PV panels [e.g. 6-8].

As a precaution to dust settling, e.g. the German mirror manufacturer Flabeg developed a coating for CSP glass mirrors which decreases the amount of soiling on mirror surfaces up to 50 % [9]. Although coating materials can reduce the losses due to soiling, the reduction of the plant performance for plants with such materials remains an important issue. Therefore, predicting the necessary amount of water for the cleaning of the solar field is of interest, as it allows the operators and maintenance teams to optimize the cleaning cycles. This is especially relevant for CSP power plants whose efficiency is more affected by soiling than PV according to [1].

Given this fact, and knowing that the Eastern region of Morocco will host the next power plant fixed by MASEN (Moroccan Agency for Solar Energy) in the Moroccan solar plan, we want to add soiling as a parameter in solar resource assessment and understand its effect on CSP mirrors installed in this region. In this paper we present the results of a short term study that has been conducted with the objective to find the effect of dust on glass cleanliness and aluminum mirrors exposed for a period of three months –from April to June– at the University of Oujda (Eastern Morocco). An X-ray diffraction analysis has been conducted as well to identify the mineralogy of the dust deposit on the mirror surfaces.

2. Methodology & experimental setup

2.1. Experimental setup

In this experiment we intend to study the effect of dust on specular reflectance of two different mirror materials, aluminum and 4 mm thin glass, under the climate of Oujda -North-East of Morocco (34.65°N, -1.90°E). For this purpose two stand-alone mirror mountings with spheroid shape were installed at the University of Oujda (one for the glass and the other for the aluminum mirrors).Both spheres are composed by a horizontal surface and four arms oriented in four different directions (North, South, East and West). Each sphere holds 13 mirrors, one on the horizontal surface and three mirrors installed on each arm at three tilt angels +45°, 0° and -45° with respect to the vertical plane, see figure 1.

Fig. 1.Stand-alone mirror spheres installed at the University of Oujda.

The mirrors of each type used in this outdoor exposition experiment are identical. The aluminum mirrors have a surface of 120 x 120 mm, while the glass mirrors were prepared to have a surface of approximately 100 x 100 mm.

2.2. Reflectivity measurements

For CSP power plants, one of the important parameters in the preliminary energy conversion process is the capacity of the collectors to redirect the maximum of the incoming solar irradiation to the receiver. This process is described by the specular reflectance, $\rho_s(\lambda,\theta,\varphi)$, which characterizes the quality and the performance of solar mirrors [10]. The specular reflectance is highly affected by the presence of dust and soiling. Several devices which measure the reflectivity exist on the market. We can mention for instance Devices & Services (D&S) portable 15R, the Surface Optics Corporation 410 Solar [11], the Abengoa Solar Condor [12] and the automatic TraCS (Tracking Cleanliness Sensor) [13]. The D&S 15R is maybe the most used instrument in CSP power plants [14] and it's developed based on the results from Pettit [15]. The D&S 15R measures the specular reflectance at a wavelength of $\lambda = 600nm$, with an incidence angle of $\rho = 15°$ at three acceptance angels ($\theta = 15, 25$ and 46 mrad). For the highly specular front reflectors, the specular reflectivity can be approximated with the solar-weighted specular reflectance $\rho(SW,\theta,\varphi)$ [10] by including the solar weighted hemispherical reflectance $\rho(SW,\theta,2\pi)$:

$$\rho(SW,\theta,\varphi) = \frac{\rho(\lambda{=}660nm,\theta,\varphi)}{\rho(\lambda{=}660nm,\theta,2\pi)}\rho(SW,\theta,2\pi) \quad (1)$$

In this study we use the D&S 15R-USB with an acceptance angle of 25 mrad to measure the drop of the specular reflectivity for both mirror materials in dirty and clean states.

2.3. Methodology

After exposing the mirrors for one month, the samples were collected and packed in boxes to protect the mirrors and to preserve the same dust distribution on the mirror surfaces. Then we measured the reflectivity in the dirty state (ρ_d). After cleaning the samples with non-mineralized water, we collected the dust for the X-ray diffraction test. Finally, we measured the reflectivity in the clean state (ρ_c). Tables 1 and 2 show the reflectivity values of both states (dirty and clean) for glass and aluminum mirrors respectively.

Table 1.Reflectivity measurements for glass mirrors in the dirty ρ_d and clean ρ_c states (%).

	Horiz		North						South						East						West					
			45°		0°		-45°		45°		0°		-45°		45°		0°		-45°		45°		0°		-45°	
	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c
Apr	33.5	95.1	73	95	82.9	95.1	90.8	95	78.9	95	90.9	95	83.5	95.1	74.3	95.1	82.8	95	87.5	95	76.9	95	91.1	95	86.9	95
May	71	95	89.6	95	93.6	95.1	93.9	95.2	89.4	95.2	92.9	95.2	94.2	95	88.9	95	91.6	95.1	93.4	95.1	88.5	95	93.2	95.2	93.5	95.1
Jun	53.4	95	80.3	95.1	92.1	95.1	94.8	95	81.1	95.2	92.9	95.2	94.6	95.1	85.8	95	92.7	95.2	94.4	95.1	85.5	95	93.4	95	94.5	95

Table 2.Reflectivity measurements for aluminum mirrors on the dirty ρ_d and clean ρ_c states (%).

	Horiz		North						South						East						West					
			45°		0°		-45°		45°		0°		-45°		45°		0°		-45°		45°		0°		-45°	
	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c	ρ_d	ρ_c
Apr	33.5	77.9	60.7	80.1	71.8	80	75.6	78.6	61.7	76.6	73.8	77.8	76.4	77	62	78.5	67	77.3	74.9	78.3	62.1	78.2	69.8	76.7	75.2	77.9
May	67.6	78.6	74.7	77.9	77.8	79.0	77	77.6	71.6	78.3	75	77.3	76.8	77.9	72.8	79.2	74.4	78.2	75.9	77.6	71.8	78.4	75.2	77.9	76.2	77.1
Jun	56.4	77.6	67.1	77.1	75.7	77.9	75.9	77.9	67.7	77.5	75.6	77.5	77.8	78.8	68.7	79.2	75.5	78.6	76.0	78.0	67.3	78.1	76.4	78	77.2	77.9

Dividing the reflectivity of the mirror in the dirty state by its reflectivity in the clean state we get the parameter defined as cleanliness. It gives the relative reduction of reflectivity of a mirror compared to its clean state (see Equation 2). This paper intends to demonstrate the drop of reflectivity by the parameter of cleanliness.

$$Cleanliness = \frac{\rho_d}{\rho_c} \qquad (2)$$

ρ_d and ρ_c represent the average values of the specular reflectivity that we measure with the D&S 15R on at least six spots on the mirror. The error bars (ξ) on figure 5 were calculated as follows:

$$\xi = \frac{Standard\ dev(\rho_d)\ +\ Standard\ dev(\rho_c)}{100} \qquad (3)$$

3. Results and discussion

Soiling of solar mirrors is a complex phenomenon. Several parameters influence the dust deposition and accumulation on the mirror surfaces, hence the drop of cleanliness/reflectivity. Weather and site exposition characteristics have a major impact on the mirror soiling; therefore it's crucial to highlight the climatic conditions during the exposure time as well as the properties of the dust accumulated on the mirrors.

During the three months of exposure-from April to June- we had three different weather conditions. On April we had a huge dust storm that remained for a whole day followed by a red rain event (a light rain when the atmosphere is loaded by aerosols). This dust storm caused a huge accumulation of dust on the mirrors (especially the horizontal ones), see figure 2.

Throughout the third week of May we had heavy rains for three successive days, which contributed in washing the mirrors, whereas in June, we did not observe any anomaly or special weather condition.

Fig. 2.Dust deposition on horizontal mirror surfaces after a sand storm. (a) Dust deposition on aluminum mirror; (b) Dust deposition on a 4 mm thin glass mirror; (c-d) Photo showing the high aerosol concentration in the atmosphere during a sand storm in Oujda City.

3.1. Dust chemistry

The city of Oujda is located in the North-East of the Eastern region of Morocco. With this location the dust settled on the mirrors can be transported from two potential emission sources of dust:

- the Mediterranean coast at the north
- the arid regions from the south

In order to identify the origin of the aerosols deposed on the mirrors, a number of analyses must be completed. The size and the mineralogical components of the dust layer on the reflectors are of relevance. This study will not deal with the origin of dirt, but it will only show the mineralogy of the dust on the mirrors after each exposition period. For this reason, we have collected the dirt that was washed off the mirrors and send the dust samples to the National Center of Scientific Research and Technology (CNRST) to perform the X-ray diffraction analyses.

Figure 3 shows the XRD patterns of the dust particles collected during April. XRD is an analysis that only presents the mineral components other than the quantitative analysis or the fluorescent XRD that gives the absolute quantity/weight of an element present in a sample. The semi-quantitative results of the XRD analysis revealed that the dust particles were composed by:

- Quartz SiO2
- Calcite Ca(CO)3
- Muscovite 2M1, syn KAl2Si3AlO10(OH)2

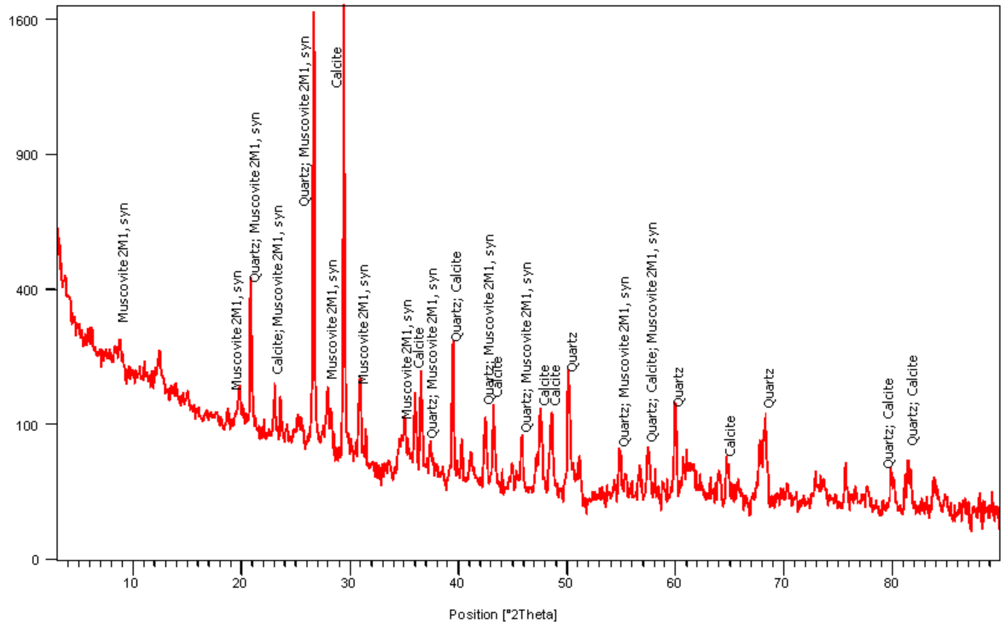

Fig. 3.The XRD pattern of the dust collected from the mirror surfaces during April.

As we have mentioned earlier, during May we had a heavy rain event that washed the mirrors, thus we collected a very small quantity of dust from the mirrors. Therefore, we collected dust from May and June and made only one XRD analysis for the samples collected in this period. The patterns of the analysis are illustrated in figure 4 and the particles compositions are:

- Quartz SiO_2
- Calcite $Ca(CO)_3$
- Dolomite $CaMg(CO_3)_2$
- Albite high $NaAl\ Si_3O_8$
- Muscovite 2\ITM\RG#1 $KAl_3Si_3O_{10}(OH)_2$

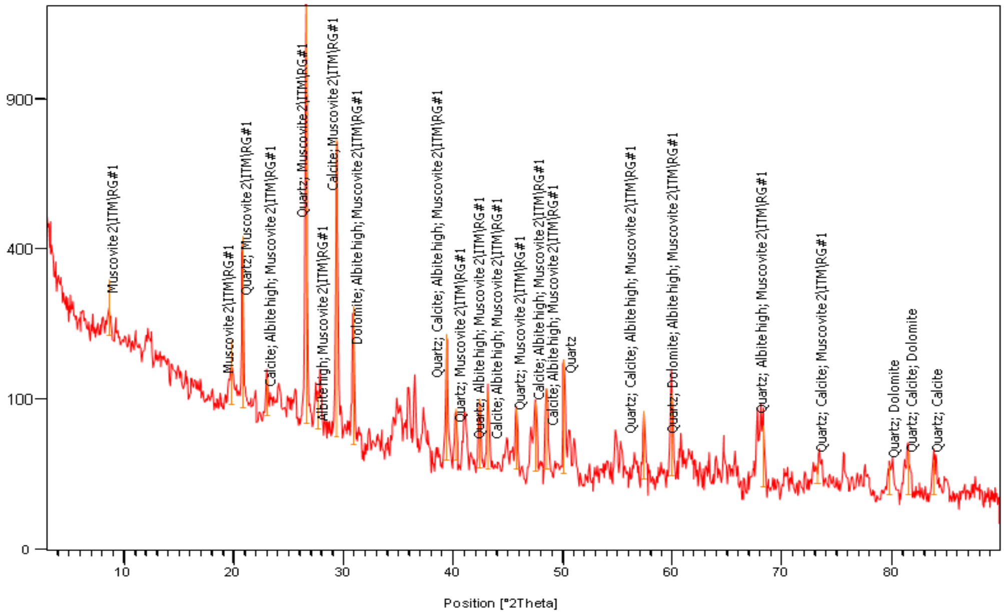

Fig. 4.The XRD pattern of the dust collected from the mirror surfaces during May and June.

3.2. Effect of dust on mirrors

Figure 5 illustrates the cleanliness drop of both mirror materials during the three months of exposure (April to June). One can see clearly that the cleanliness of the glass and aluminum mirrors were quite similar for all the directions and tilted angles, except for the horizontal ones. In fact, the horizontal mirrors were the most affected by dust followed by the +45° mirrors (facing the sky), while mirrors installed at 0° and -45° were quite clean for the whole exposition time. This is because horizontal and +45° mirrors are exposed upwards to the atmosphere and, consequently, dust and soil can deposit easily on their surfaces. However, the amount of dust deposition on the reflective surface of the mirrors installed at 0° and -45° is very low. This is mainly due to the nature of the ground in the exposition site (grass limits the emission of dust).

During April, the cleanliness drop for the horizontal mirrors of both materials was very high and absolute values are very hard to be measured as can be seen in figure 2: there are regions of almost zero reflectivity on both samples but of different size and distribution. The tilted mirrors seem to have the same susceptibility to dust deposition for both materials in the sand storm conditions observed in April. We can see from table 1 and table 2 that the vertically mounted glass mirrors facing towards North and East suffer a significantly higher soiling rate than the ones facing in other directions. One of the reasons might be the fact that the average wind direction measured in Oujda is North and East from where particles are more likely to impact and eventually stick to surfaces. This effect is not present in the aluminum mirrors nor other tilt angles and exposure months. The observation needs further investigation to be confirmed though.

Due to the heavy rain event in May, the difference between the +45° mirrors and the ones exposed at 0° and -45° decreased significantly if compared to the other months when no rainfalls occurred. It seems reasonable that the washing effect is greater on 45° exposed mirrors. The differences in losses on the horizontal mirrors were significant though with the glass mirror losing 25 % and the aluminum mirror 14 %. This is maybe because of the different mirror surface properties in relation with water polarity. We have not studied these mirrors' properties yet, but we are planning to make some contact angle measurements in the future.

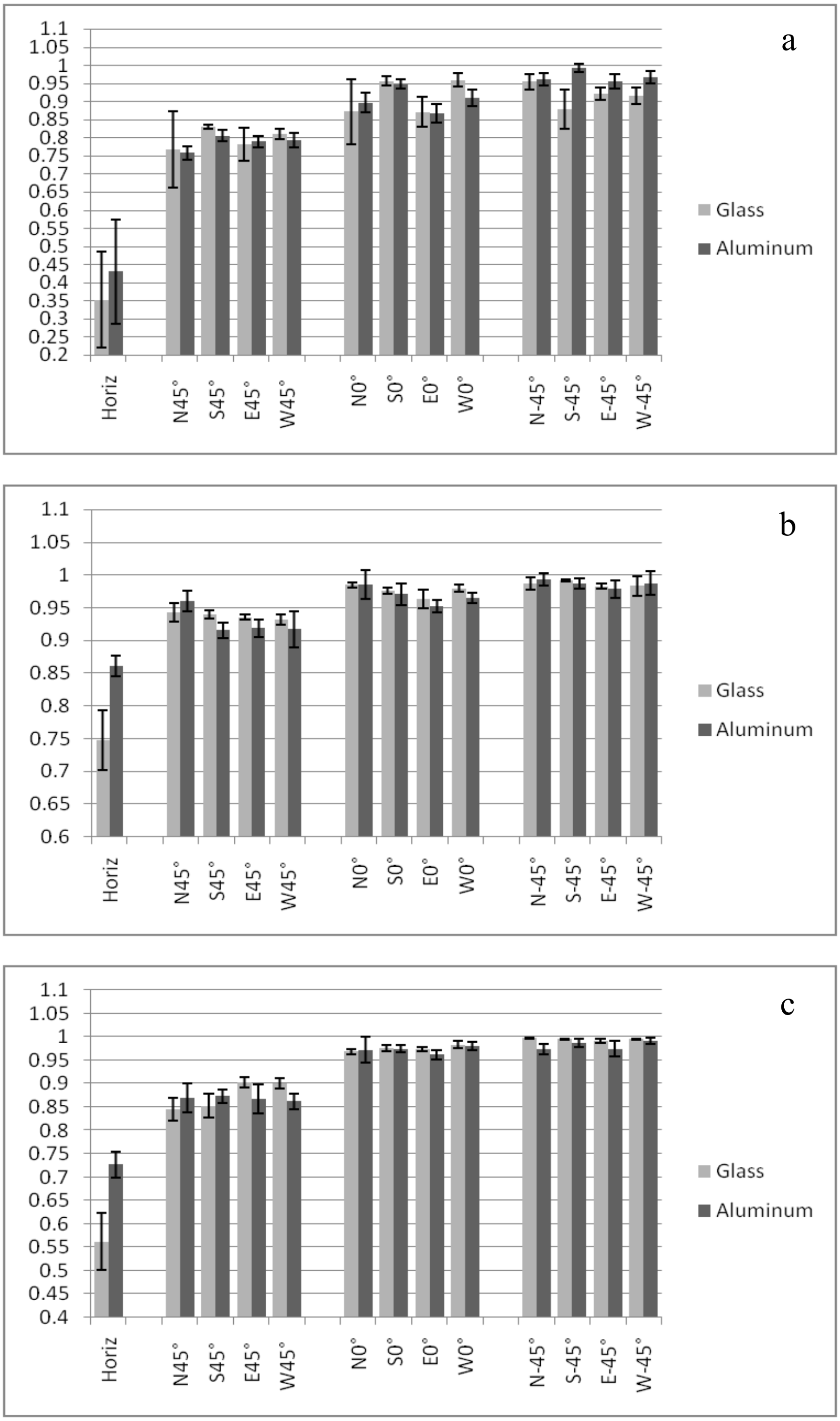

Fig. 5.Cleanliness values for glass and aluminum mirrors after one month of exposure. (a) April; (b) May; (c) June.

In June, the 0° and -45° mirrors were nearly not affected by dust as the cleanliness drop was about 2 % for both aluminum and glass mirrors. For the +45° glass and aluminum mirror losses were 10-16 %. At the same time, cleanliness losses on the horizontal mirrors were significant, the aluminum mirrors' cleanliness decreased by 27 % and by 44 % for the glass mirrors. Here again, the aluminum mirror performs better than the glass mirror. The averages of the cleanliness values of all mirrors over all the exposition period are summarized in table 3.

Table 3.Average cleanliness values (%).

	Average cleanliness values (%)												
	Horiz	***N45°***	***N0°***	***N-45°***	***S45°***	***S0°***	***S-45°***	***E45°***	***E0°***	***E-45°***	***W45°***	***W0°***	***W-45°***
Glass	0.55	0.85	0.94	0.98	0.87	0.97	0.95	0.87	0.94	0.97	0.88	0.97	0.96
Aluminum	0.67	0.86	0.95	0.98	0.86	0.96	0.99	0.86	0.93	0.97	0.86	0.95	0.98

In the graphs in figure 6, we can see that the average cleanliness values of both mirror materials (installed at the same position in each sphere) are quite similar. In general, the samples behave as expected with higher soiling rates for mirrors facing increasingly towards the sky. There is a very small difference of only a few percentage points between the 0° and -45° tilt angles. Thinking of heliostats this might take away the need to design the heliostats to be able to go to a face-down position for stow. There is nearly no difference between glass and aluminum mirrors. For the horizontal mirrors the average cleanliness values of the three months of exposure were of 55 % and 67 % for glass and aluminum respectively.

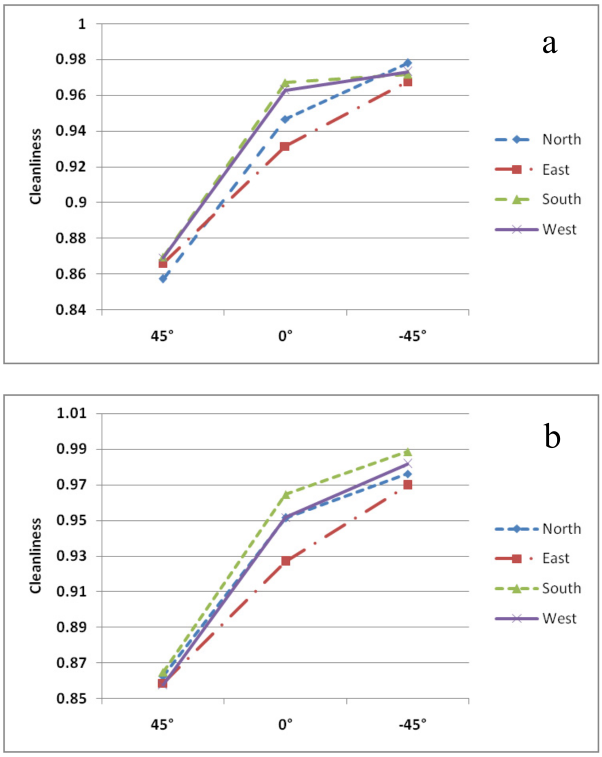

Fig. 6.Cleanliness average values for the whole exposition period. (a) glass; (b) aluminum.

4. Conclusion and outlook

This paper presents some first results of the effect of dust and soiling on glass and aluminum mirrors exposed for three months, on different orientations (North, South, East, West) and tilt angles in the so-called “mirror sphere” at the University of Oujda (Eastern Morocco). The first results show that the drop of cleanliness was the same for all mirrors’ materials installed at same positions. Horizontal mirrors were the most affected by dust (with an average cleanliness drop of 45 % and 33 % for the glass and aluminum mirrors respectively) followed by the 45° ones. However, the 0° and -45° mirrors were not affected by dust. The effect of dust can be more important during sand storm periods and less important during rainy periods.

X-ray diffraction analyses were made to identify the mineralogy of the dust settled on the mirrors. The dust particles were mostly composed by Quartz (SiO_2), Calcite ($Ca(CO)_3$) and Muscovite ($KAl_3Si_3O_{10}(OH)_2$).

As a follow up to this work we would like to extend the test period to at least 12 months and add weather parameters, especially rainfall and airborne aerosol concentration to the study in order to investigate their effect on dust deposition and thus the cleanliness of the mirrors. Since soiling is site specific, we are planning also to add a new site of exposition in an arid region (Ain Beni Mathar, Eastern Morocco) and to compare the results for both materials from both exposition sites. The final results of this research would be important for investors and actors in the field of energy, since the Eastern region of Morocco will host the second CSP power plant in the Moroccan solar plan after the Noor complex installed in Ouarzazate.

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