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Impact of Soiling Physicochemistry on Mirrors With CSP Applications at the Plataforma Solar Del Desierto De Atacama, Chile

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Abstract. The context of global economic instability and armed conflicts has caused fossil fuels to reach unprecedented levels. In this sense, Concentrating Solar Power (CSP) technology has proven to be an excellent option to diversify the energy matrix dependent on fossil fuels, especially in places where there is a good quality solar resource, such as desert areas. These good qualities can be overshadowed by local phenomena such as soiling that can affect the viability of a project. In this paper, the effect of soiling on CSP mirrors installed in a cold desert climate in the Atacama Desert, Chile, is presented. During the 202 days (continuous) of outdoor exposure, atmospheric parameters such as humidity and temperature, as well as reflectance were evaluated daily. At the end of the experiment, the chemical composition of the material deposited on the mirror surface was analyzed by scanning electron microscopy (SEM) and elemental analysis (EDX). The characterization of the material detected the presence of Gypsum (soluble salt), which was shown to have the ability to cement the deposited material. The atmospheric parameters showed that the relative humidity at the site can exceed 60%, sufficient values to solubilize the Gypsum, producing the cementation process. The reflectance values showed that the effect of the cemented material, for 202 days of exposure, can reach a 47% loss of its reflective capacity. This means that the longer the exposure time, the greater the effect of the cementation and the more energy will be needed to clean the mirrors.

Keywords: Soiling, Mirrors, Cementation, Desert, Concentrated Solar Power, CSP, Solar Energy

1. Introduction

The current context, due to world economic instability and war conflicts, has caused fossil fuels to reach unprecedented levels. These problems are added to those already existing because of global warming, which generates a complex scenario in energy issues. For these reasons, nonconventional renewable energies (NCRE) are emerging as an alternative to conventional fuel sources due to their potential as a competitive and environmentally friendly energy supply and are seen as a real option to solve this energy crisis. In this sense, concentrated solar power (CSP) technologies have proven to be a viable option for solving energy supply problems. CSP plants have the advantage of storing energy in the form of heat, do not generate CO2 emissions. These advantages mean that they have a good factor capacity (between 50 and 80 %) and are environmentally friendly [1]. CSP technology is also versatile, as it can be combined with other types of NCRE. For example, it is possible to combine it with photovoltaic solar energy so that the latter works during the day and the CSP works at times when the solar resource is not available, thus reducing energy costs.

However, being based on the concentration of solar rays, CSP technologies depend on the availability of solar direct normal irradiance (DNI), so CSP is highly affected by the presence of clouds. Therefore, the major interest of the CSP industry is focused on the sunbelt where mainly desert areas abound. The Atacama Desert, located in Chile, is an example of this. With an area of 105,000 km^2, values in excess of 9.2 kWh/m^2 direct normal irradiance per day (DNId) have been recorded [2],[3]. Its cloudiness index is 3%, so it has clear sky conditions during most of the year, ensuring the availability of solar resources [4]. The Atacama Desert has a natural potential that has allowed the insertion of CSP technology, being Cerro Dominador the first project in Chile. However, these territorial advantages and the high solar resource can be overshadowed by the effect of local desert conditions, such as soiling. Soiling is defined as the process by which dirt formed by organic (pollen, bird droppings, silver debris) and inorganic (minerals, salts and sand) particles accumulate on the surface of the mirrors [5], [6]. The presence of deposited material drastically reduces the amount of light that the mirrors can reflect generating optical and energy losses. Uncertainty about the values of these losses can make a project economically unfeasible. However, knowledge about the composition and rate of fouling of solar technologies can help generate locally adapted plans to mitigate the effects and costs associated with fouling and cleaning. In addition, cleaning methodologies that are not commensurate with the deposited fouling can cause irreparable damage to mirror in the field. All these issues affect the profitability of a CSP project and must be considered both in the economic study and design stage, as well as during the operation of the plant.

This problem has become an opportunity, because different researchers have stated in their publications that the study of the impact of local environmental conditions on CSP and PV technologies in the Atacama Desert represents a tentative and novel field of research. For example, knowledge of the effects of fouling for each location in the Atacama Desert allows us to know the frequency of cleaning, type of cleaning and mechanisms to mitigate fouling. The accelerated development of solar CSP technology and its irruption in Chile and worldwide, demands answers and solutions that are in line with the speed with which these are being installed and developed.

In this work, the results of the physicochemical characterization of the material deposited on flat mirrors with solar tracking used in CSP plants, installed in a site with solar potential for the development of this type of projects, are presented. The focus of the paper is on elemental chemistry, morphology and their interaction with local atmospheric conditions.

2. Methodology

The study was conducted at the Plataforma Solar del Desierto de Atacama (PSDA). This site is a natural laboratory to study and test different solar technologies. It is located at 1,000 m.a.s.l. in the Atacama Desert (24.09°S , 69.93°E) and has a Köppen climate classification of type BWK, corresponding to a cold arid desert zone [7],[8]. It has clear sky most of the year, with a cloudiness of less than 3% and high levels of solar radiation, which can reach 9.2 kWh/m^2 of direct normal solar irradiation per day [3]. Due to these climatic conditions, the PSDA is a suitable place to test this type of technologies. Currently, the PSDA is under the management of the Energy Development Center of Antofagasta, which belongs to the University of Antofagasta.

To study the effect of deposition and soiling on mirrors with CSP applications, a Solys 2 solar tracker capable of measuring global, direct, and diffuse solar radiation, coupled to a reflecting mirror, corresponding to the TracCS of the company CSP Services, was used. The mirror was left dirty for 6 months (from November 2020 to May 2021) and its reflectance was constantly measured with a resolution that provides the value per minute. Ambient temperature (T_{amb}) and relative humidity (RH) were measured with a Young thermometer and hygrometer, models CS215-L11 and HMP60-L11, both measurements with a resolution per minute.

To analyze the physiochemistry of the material deposited on the CSP mirrors, samples of dirt deposited on the mirrors were collected after six months of exposure. For the collection of material, soft filament brushes were used to remove all the deposited material, which was stored in a plastic sample holder. The collected samples were analyzed by scanning electron microscopy (SEM) with a Joel JSM-6360 LV X-ray spectrometer (EDX) coupled with an energy dispersive spectrometer (Oxford inca c200). For greater representativeness of the analyses, 3g of spatula were removed from the stored material for analysis.

3. Results

3.1 Physiochemistry of soiling

The morphological analysis of the deposited soiling is shown in Figure 1. Figure 1 A), corresponds to a surface view of the soiling collected from the mirror. It can be observed how the particles have a random geometry with the presence of prismatic and spherical particles. Another important observable is the presence of particles with the ability to generate agglomerates, such as those shown in red. A more detailed analysis of the agglomerated material is shown in Figures B) and C), where the presence of prismatic particles with the capacity to generate agglomerates can be observed.

Figure 1 b) shows the presence of prismatic crystals with sizes between 9.63 um and 8.82 um respectively. Another important aspect to emphasize are the particles surrounding these prisms, which have random geometry and the presence of well-defined spheres is highlighted. Figure C) shows the same phenomenon described in B), but in another random section of the sample. The results show the presence of well-defined prismatic particles with the ability to generate agglomerates, in addition, a phenomenon of welding between particles (red circle) can be observed in a better way. This phenomenon occurs when the cementation process is present and occurs very frequently due to the presence of hygroscopic soluble salt and high levels of relative humidity (above 70%) [9],[10].

To verify the presence of the cementation process in the mirror, an elemental analysis (EDX) was performed exclusively on the agglomerated material as shown in Figure 1 D). The results indicate the following elemental percentages: 0.46% Mg, 0.78% Al, 1.68% Si, 0.24% S, 0.30% Ca, 0.22% Fe, 0.21% Cu, 0.12% K and 0.22% Na, the rest corresponds to oxygen and carbon. These results confirm the presence of Gypsum ($CaSO_4$ *$2H_2O$), as shown in Figure E) and F), material documented in other investigations carried out at the site (ref). This implies that Gypsum (hygroscopic) has the ability to generate dirt crusts that trap different types of compounds (soluble and insoluble), causing the dirt crust to begin to grow as exposure times increase[11].

3.2 Atmospheric Parameters

Atmospheric parameters were evaluated for the 6 months of outdoor exposure of the CSP mirror. The measurements started on November 11, 2020, and ended on May 30, 2021. The results are shown in Figure 3, which corresponds to the frequency of relative humidity (RH) and temperature (T_{amb}) events for the exposure period of the mirror. Figure 3 a) shows the frequency of relative humidity, where the desert behavior and the influence of relative humidity on the PSDA can be observed. The desert characteristics are observed in the first important frequency peak, which is found at 18% RH. The second important peak is observed at 70% RH. It should be noted that for a desert area, values that can reach 100% RH are recorded, this is due to a local humidity phenomenon called Camanchaca [12]. This is a phenomenon of coastal fog, dynamic and copious that is produced by the heat capacity of the sea. In the mornings, the sea absorbs the heat given off by the sun, and during the night and early morning, this heat is released, producing vapor that is inserted into the interior of the desert [13].

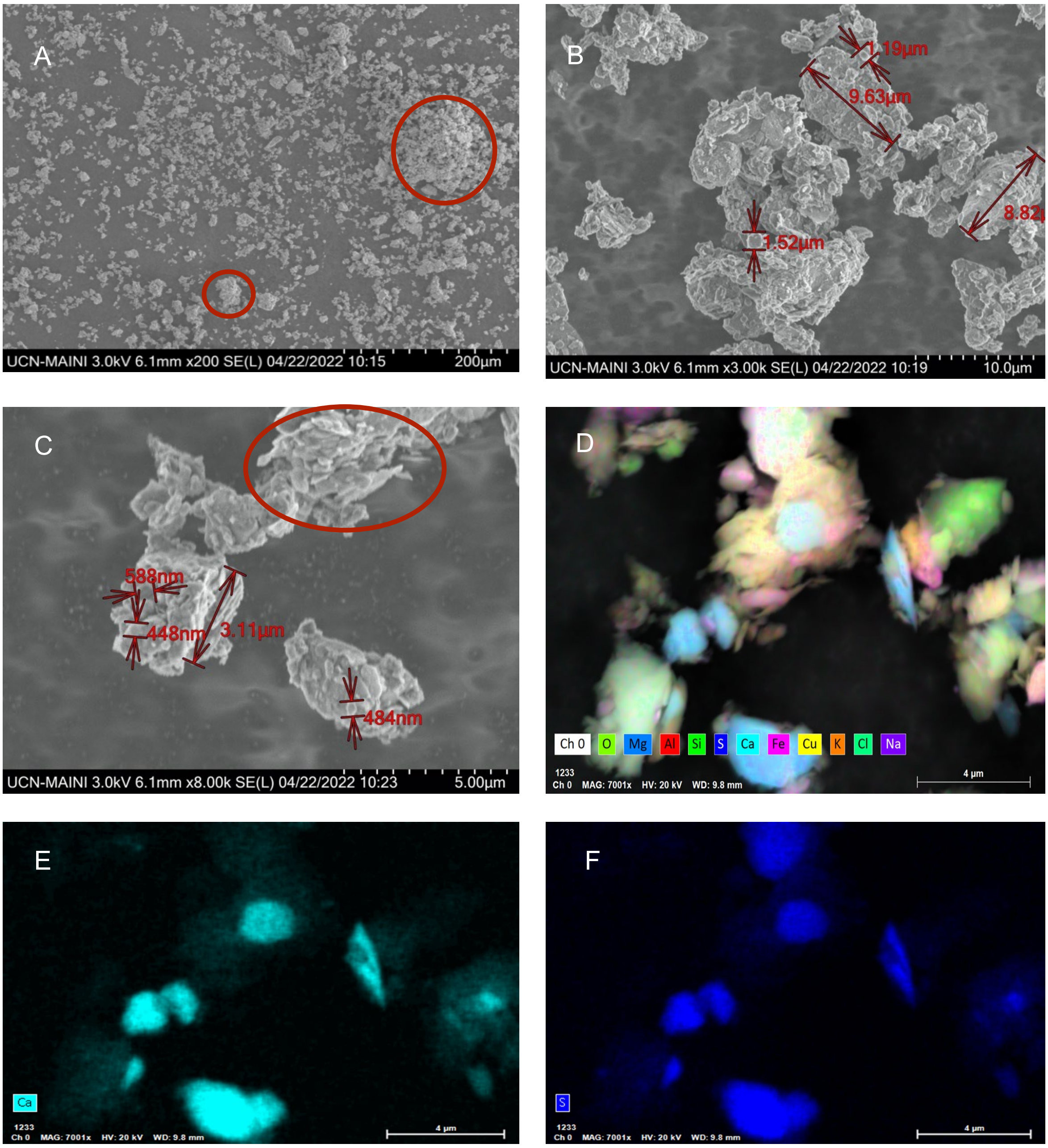

Figure 1. Morphological analysis by scanning electron microscopy (SEM).

The temperature frequency is shown in Figure 2 b). It shows the desert-like behavior of the site. The temperature in PSDA has a great oscillation, which can vary from -4ºC and reach a maximum of 40ºC. This difference in extreme values occurs during the night, where the minimum values are found, and during the solar midday, where the maximum values are found [14]. The importance of these variables is their influence on the cementation process. This process is caused by the interaction of relative humidity, ambient temperature and the chemical composition of the deposited material. In the case of PSDA, we have humidity conditions above 60% which causes hygroscopic material such as gypsum to solubilize partially or completely. This solubilization process occurs at night when temperatures are at their lowest and humidity values are at their highest [14]. Then, the next day the increase in temperature of the site causes the material to recrystallize again, a process in which the soluble material traps crystals of the insoluble material, as observed in the SEM images in Figure 1. This phenomenon is called the "desert rose", and is a phenomenon that occurs when the Gypsum is partially or completely solubilized, and then recrystallize trapping sand grains in the process [15]. This process is repeated day by day, so there is an increase of cemented material as exposure times increase [16].

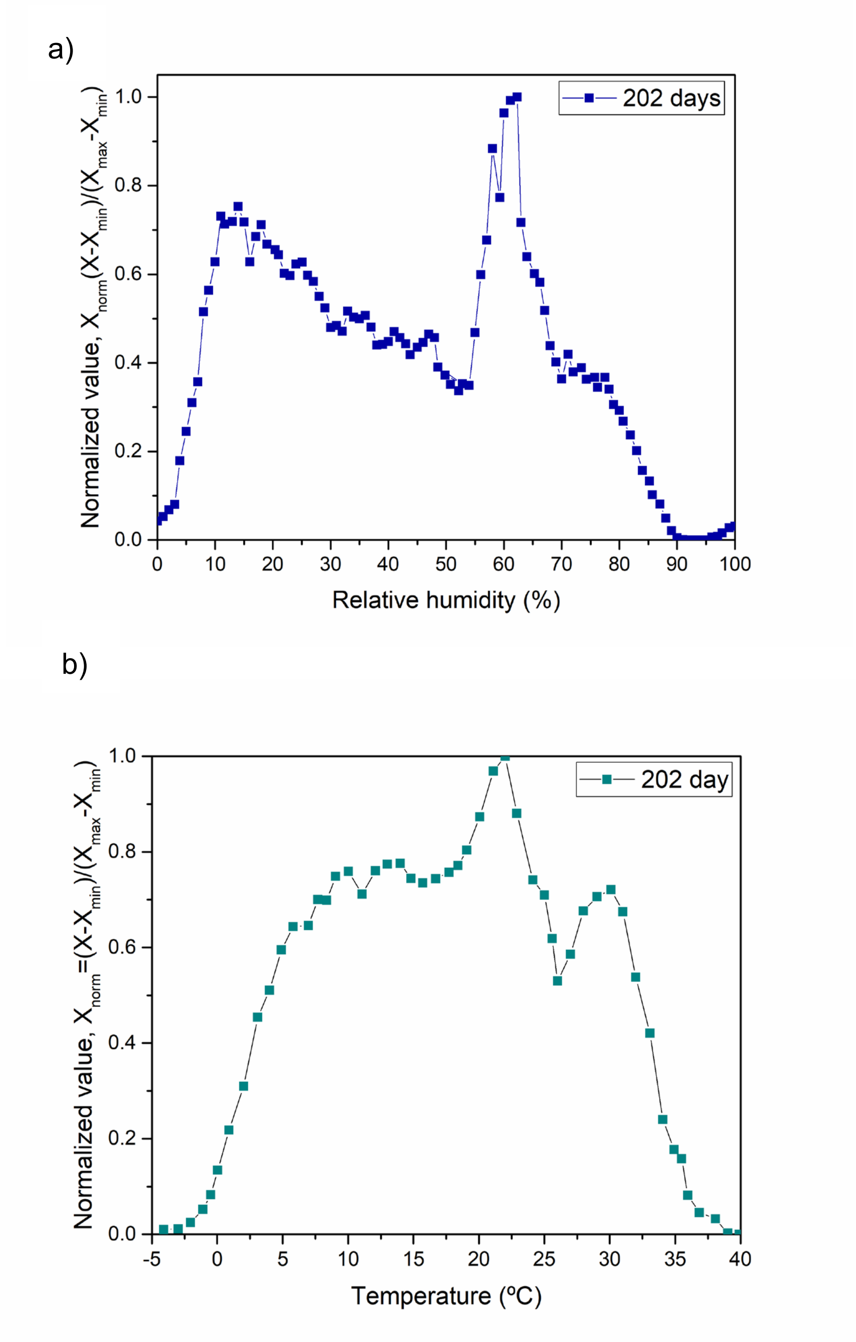

Figure 2. Atmospheric parameters measured for 202 days of exposure. a) relative humidity (RH) and b) ambient temperature (ºC).

3.3 Effects of the soiling on the optical properties of the CSP mirror

Figure 3 shows the reflectivity measurements of the mirror exposed to the environmental conditions of the Atacama Desert during the 202-day campaign. The measurements were taken around solar noon with a temporal resolution of 1 second and were averaged to obtain the daily values. The graph shows how the mirror loses reflectivity as time passes and dirt accumulates on its surface, mainly cemented material. On the first day of exposure the reflectance of the clean mirror measured was 90%, while by the end of the measurement campaign the reflectance dropped to 48%. This means that at the end of the measurements there was a 47% loss in the reflectivity of the mirror, which corresponds to almost half of the efficiency in its optimum state. In Figure 3, the reflectance decays with time, fitting a polynomial of degree 2. The 0.96 value of the correlation coefficient, R^2, indicates a good fit of the model with the measurements. The reflectance decays more rapidly in the first few days, so it can be interpreted that, as soiling accumulates, its effect is smaller, although it still has a cumulative effect.

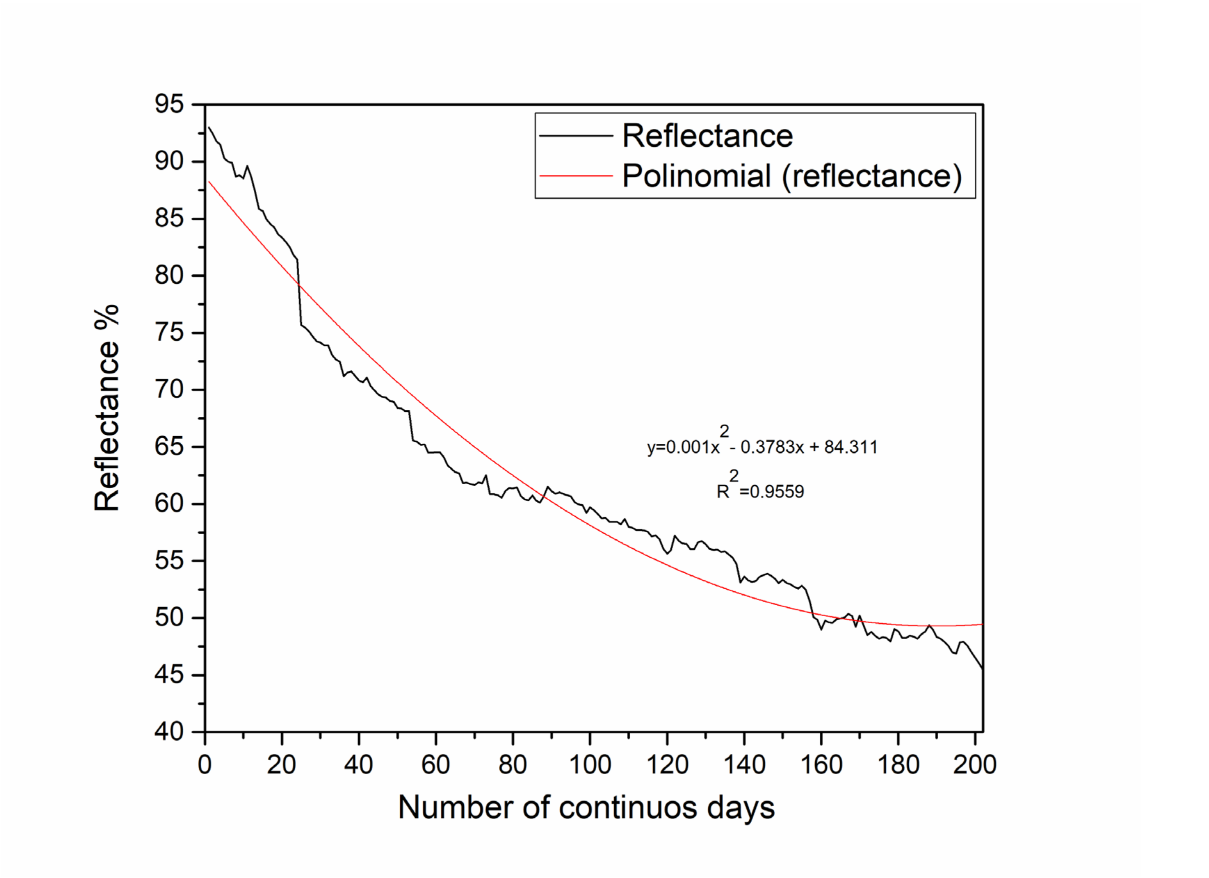

Figure 3. Daily mirror reflectance values during the 202 days of exposure. The dotted line shows the exponential fit function.

Another important aspect to consider is the involvement of local meteorological variables in the fouling and cleaning processes of the mirrors. As explained in the previous section, in the PSDA there are RH events that can exceed 90%, because of fog events. The effect of rain is ruled out, since no such events were recorded on the measurement dates. Figure 4 shows the daily reflectance losses. The Camanchaca has a positive effect in cleaning the exposed mirror, where a value of 90% was recorded (03:00 am). It should be noted that on day 79 a cleaning effect was obtained because of the humidity, in which an 8% improvement could be obtained compared to the previous day, other important days to be highlighted are day 115 and 119.

A comparison between the graphs in Figure 3 and 4 shows that the Camanchaca does not play a predominant role in the cleaning of CSP mirrors, at least in the configuration of the sample installation in the experiment. Although it can be observed that it plays a positive role on some days, the graph in Figure 3 shows that its contribution is not important. This indicates that the humidity phenomena, by promoting cementation, plays a negative role. The results confirm that as exposure times increase, the size of cemented dirt crusts increases, therefore, if the formation of cemented crusts is not avoided, the energy required for cleaning will increase and the reflective capacity of the mirror will be higher [16].

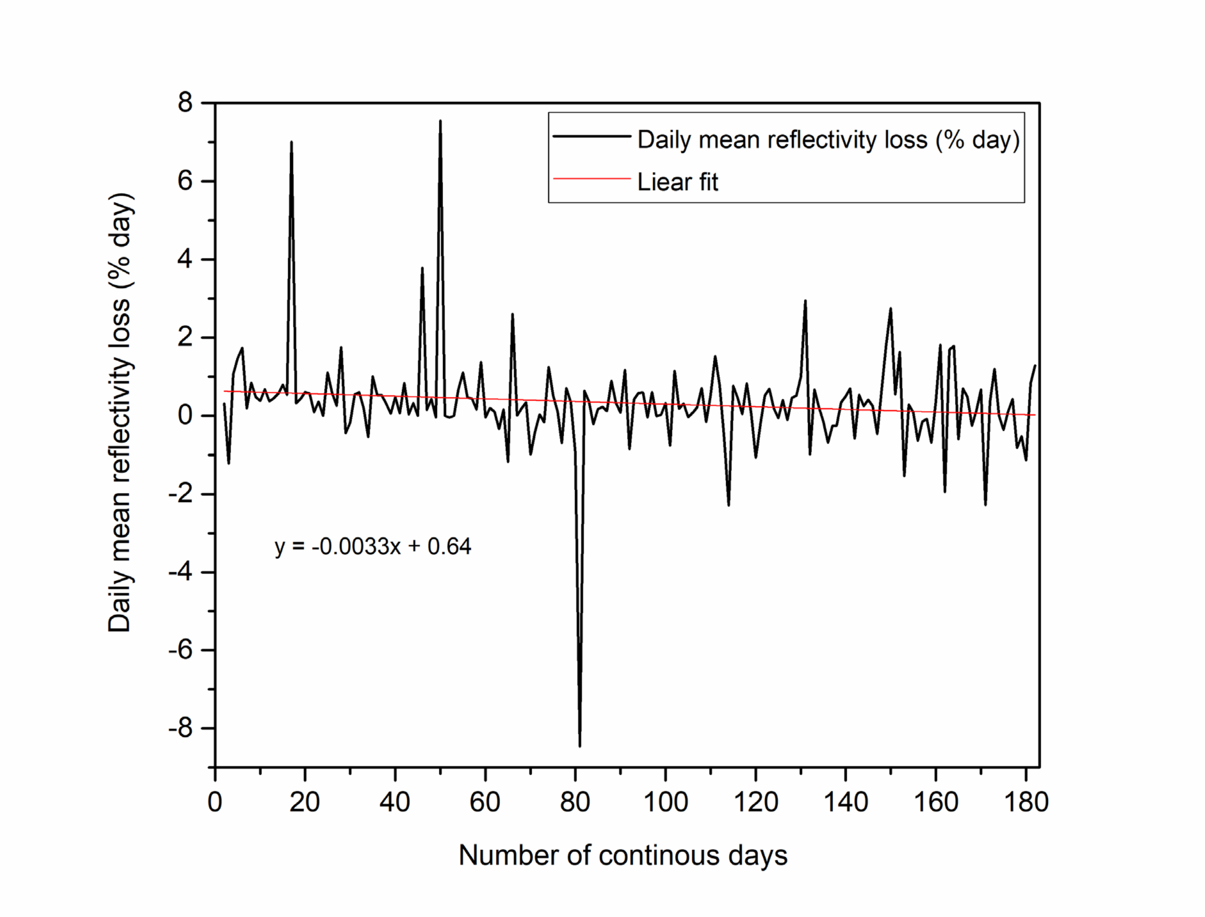

Figure 4. Daily reflectance losses in CSP mirrors for 202 days of exposure.

The obtained results can be compared with other solar potential locations such as those presented by El Boujdaini et al. [17] in the Sahara Desert. In this study, a similar experimentation was conducted in the city of Oujda, northwest of Morocco. The author shows that for a 196-day exposure period, reflectance losses of approximately 80% were observed, and a single rainfall event improved the response, reducing the soiling losses to 20%. These results demonstrate that the Atacama Desert exhibits a lower level of soiling for the same exposure period. This can be attributed to the specific meteorological conditions of each location. Oujda experiences a climate known as "Mediterranean," characterized by recurrent hot winds and sandstorms. In contrast, the Atacama Desert has an arid desert climate with the presence of crusty and compact soils. The differences in the results of the two papers, despite being from desert areas, highlight the local nature of soiling mechanisms and the importance of considering local environmental conditions to define and understand the mechanisms of deposition and adhesion of materials, such as cementation.

4. Conclusions

This study evaluates the effect of soiling on CSP mirrors installed in the Atacama Desert, particularly in the Plataforma Solar del Desierto de Atacama. For this purpose, a morphological and elemental analysis of the soiling deposited on CSP mirrors during 202 days of exposure has been carried out, in parallel with the monitoring of atmospheric parameters such as relative humidity and ambient temperature, as well as the reflective properties of the mirror.

Characterization analysis of the deposited material confirmed the cementation process produced by the gypsum. The images showed that prismatic crystals corresponding to gypsum encapsulated the material of different geometry. This phenomenon can be tested with the analysis of atmospheric parameters such as relative humidity and ambient temperature. The results showed that the relative humidity values at the site can exceed 70%, allowing the gypsum to solubilize. In addition, the temperature values can reach 40ºC, which means that the moisture is dried by the high temperatures, allowing the solubilized salt to recrystallize, a phenomenon that is repeated daily.

The effect of the cemented material on the optical properties of a mirror was analyzed for 202 days of exposure. The results showed that for the study time a 47% decrease in mirror reflectance was obtained. In addition, it was observed that the camanchaca local humidity phenomenon influences the cleanliness of the mirrors, but this quality is affected by its ability to generate cementation, a phenomenon that is more prevalent in the place. These preliminary results will allow to generate appropriate cleaning plans for mirrors according to local climatic conditions, as well as to determine the frequency and type of cleaning methodology.

Data availability statement

This article refers to information that includes strategic knowledge generated by the Universidad de Antofagasta through research results. This information allows generating new strategic lines of research and or projects that can be susceptible to be protected either as intellectual or industrial property, with the potential to be transferred, according to national legislation (Chile), so that this information acquires the character of confidential and is only allowed to be shown in the form of graphics.

Author contributions

Conceptualization: Douglas Olivares.

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Competing interests

The authors declare that they have no competing interests

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