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Characterization of Different Moroccan Sands to Explain their Potential Negative Impacts on CSP Solar Mirrors

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Abstract. During the life-time of Concentrated Solar Power (CSP) plants, optical performance of solar mirrors are affected by soiling phenomenon and surface degradations, especially in desert and oceanic environments such as those prevailing in North Africa. This optical loss results from the deposition of dust particles, salts, organic materials or any other contaminants present in the solar field or around the CSP installation sites. This phenomenon depends on the different exposure sites with every location having its own meteorological and geological characteristics. Moroccan CSP sites are planned in many locations with different environmental conditions: arid, semi-arid and Saharan, with or without oceanic influence. These environmental factors can have an aggressive impact on the CSP mirrors. Indeed, large particles will tend to degrade the mirror by scratching or breaking the glass surface, while small particles have more chance to deposit on solar mirrors and thus create a soiling layer. These particles are generated from many sources (sand storm, pollution, vehicular movements, etc.) and are transported through the air. This mode of transport is determined as a function of mineral, size, shape and hardness. In this paper, we present a simple methodology for analyzing the chemical and physical characteristics of the sand particles, characterization techniques, and their appropriate laboratory equipment. All the factors previously mentioned could be critical for the CSP mirrors. That is why analyzing these data may be a key point for the industry to understand the effects of soiling and degradation on the CSP mirrors in order to increase the global economic profitability of their solar plants.

1. Introduction

Solar energy is a renewable and carbon dioxide-free energy source to produce other forms of energy. Several technologies, such as photovoltaic (PV), concentrated photovoltaic (CPV) and concentrated solar power (CSP) systems, have been developed to create an alternative clean energy over the past decades. In CSP plants, sunlight is concentrated by solar reflectors on absorber tubes to heat a transfer fluid. This pressurized fluid can be used to directly drive a turbine to produce power or be combined with a heat exchanger to generate steam. This technology requires a high level of direct normal radiation (DNI) to be efficient. For many decades, the Deutsches Zentrum für Luft- und Raumfahrt (DLR) have made an inventory of operational, under construction or projected CSP plants thanks to several main parameters: a DNI higher than 2000 kWh/m²/year, a large open area as flat as possible, no property nearby, but the presence of a power distribution network and a great supply of water (Fig. 1). According to the Köppen-Geiger climate classification [1], the most suitable locations to install a solar power plants is generally an arid region or an area near the sea [2].

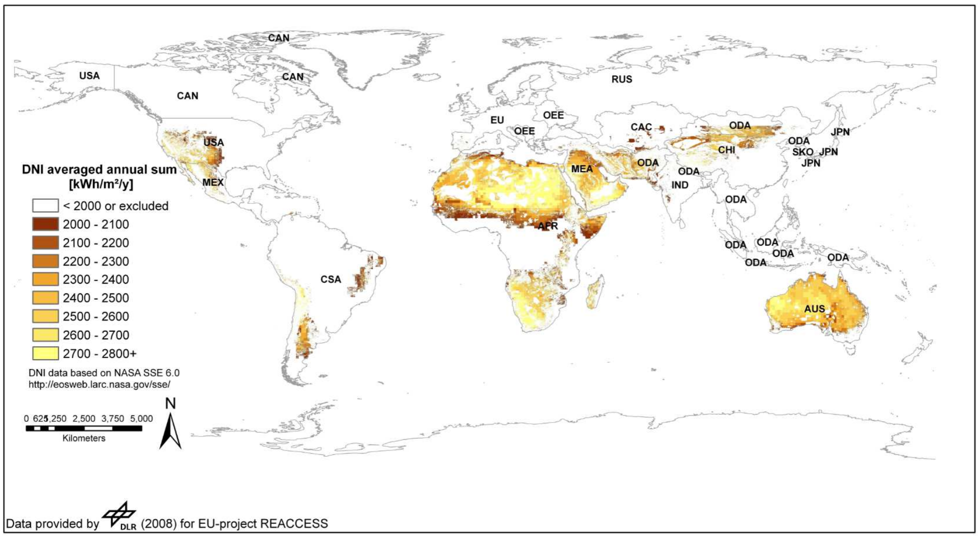


FIGURE 1. Map of potential locations for CSP plants [2]

However, desert and oceanic environments are subjected to aggressive stress factors: sunlight, high temperature, humidity, saline mist, wind, sand storms, etc. [3][4][5]. The more they are aggressive and repetitive, the faster exposed materials can degrade. Therefore, the durability of CSP components, is a key factor for the concentrated solar power. Indeed, if reflectors are degraded, the efficiency of the CSP plant could be seriously affected, whereas the lifetime of the solar mirrors is estimated at approximately 25 to 30 years [6][7].

The goal for the industry is also to minimize the cost of maintenance and the environmental impact of solar materials [8]. That is why solar mirrors must retain their optical properties during the life of the plant, and therefore, it is necessary to predict the risk of deterioration of the materials, before there is too much damage. Weather conditions can affect mirror surface and create a loss of their optical performances. According to their aggressiveness, these stress factors can generate serious damages: degradation of the different layers and coatings of the mirrors [9][10], chemical degradations as oxidation or corrosion [11], physical degradation causing cracks and erosion of the glass surface [12], etc. The airborne particles combined with light rains or strong winds could also create an important soiling layer on the glass surface and degrade initial optical performances of the solar reflectors [13].

Geographical location of a CSP site determines the nature of degradation and soiling effects on reflectors [14]. To lead a relevant study, the choice of the exposure sites must be representative of the actual on-site conditions. This study concerns North Africa, and particularly Morocco, which has a large economic development in terms of renewable energy for the last several years. Several solar plants are already operational while others are under construction or projected for future construction. Moreover, this country is characterized by a complex climate impacted by three main natural factors: the mountainous frame, the opening to the Atlantic Ocean and a Saharan position.

Furthermore, the Saharan region and particularly Morocco have a high level of fine particles ($PM_{2.5}$) in the air which is clearly shown by satellite measurement [15][16] and simulation [17]. $PM_{2.5}$, also called fine particulate matter, are airborne particles of 2.5 micrometers or less in diameter, which could be hazardous to health and volatile enough to deposit on the CSP mirror surface. Figure 2 represents a satellite map of the Earth with the average concentration of fine aerosol particles. The comparison of both maps (Fig. 1 and Fig. 2) shows clearly that the attractive sites for CSP are often plagued by high PM2.5, especially for Sahara's sites. Therefore, it is necessary to assess this risk in a more detailed way in addition to the sand analysis.

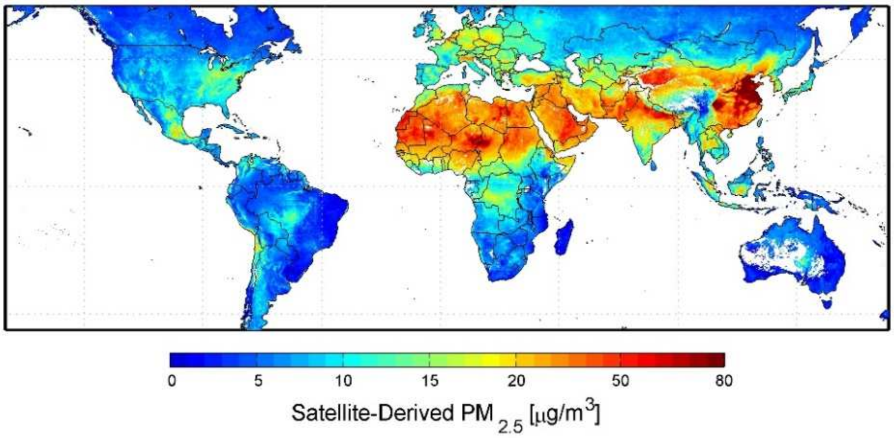


FIGURE 2. Global satellite-derived map of $PM_{2.5}$ averaged over 2001-2006 [15]

Five Moroccan locations have been considered for this study because of their different climate and topography of areas: Boujdour, Laâyoune, Ouarzazate, Skoura and Temara (Fig. 3).

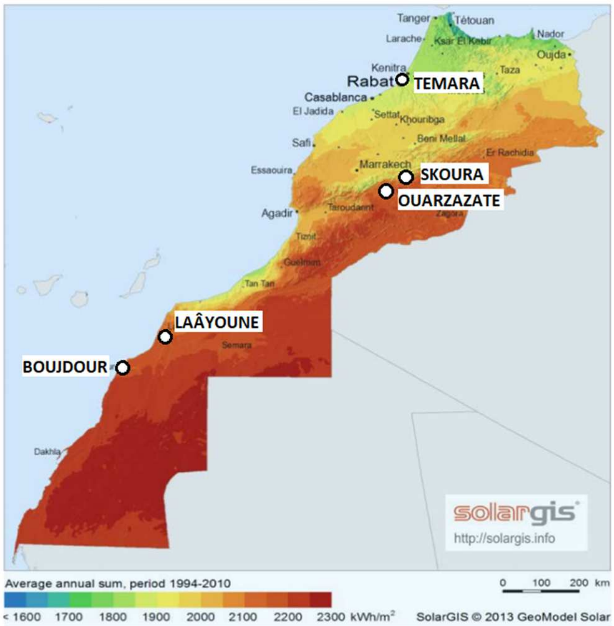
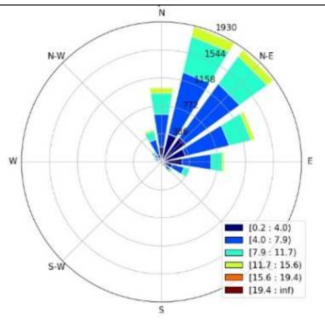
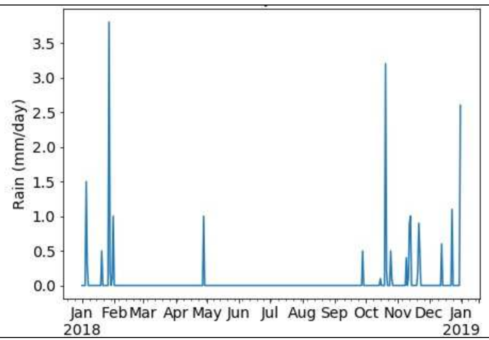
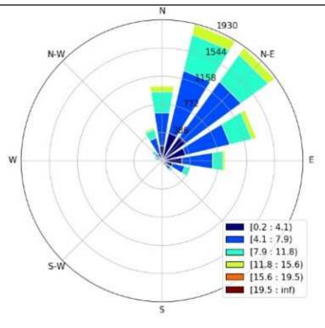
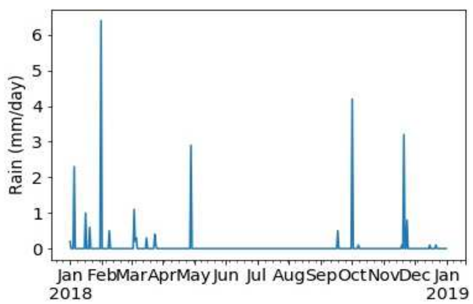
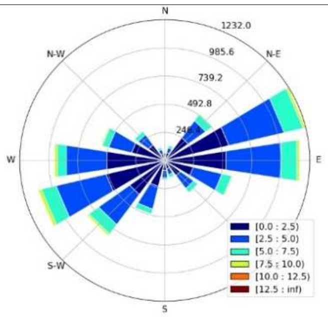
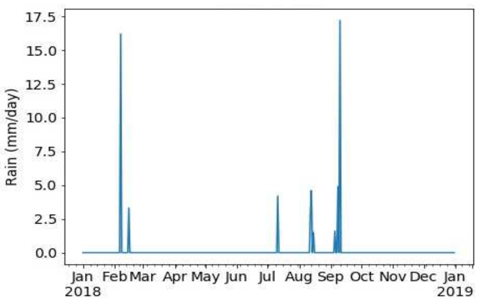


FIGURE 3. Moroccan locations of the different collected sand samples on the DNI map [18]

The goal of this work is to analyze the sand of different sites in Morocco with a simple methodology to determine the potential risk of soiling and degradations on the CSP mirrors. Knowledge of the characteristics of sands (particle distribution, morphology and composition) is necessary to have an idea of their impact on reflectors in operational plants and allows to improve all the installations around the site. These previous simple sand analyses could also be made on other sands around the world and could be a key point for the industry to know the best place to build future solar power plants, in order to increase the global economic profitability of the installed plants.

2. Presentation of the sites

Table 1 lists the main meteorological data of the five selected Moroccan sites. Boujdour [19] and Laâyoune [20] are both Saharan coastal places far from about 200 km with an estimated DNI of approximately 2150 kWh/m²/year. Rainfall in this region is low but the relative humidity of these sites is quite high all year round (~ 70%) because of the coastal climate. Winds come from NNE and NE directions with an average velocity of 7 m/s but they can reach a maximum speed of about 16 m/s. Temara [22] is an Atlantic coastal site in the North of Morocco with a lower DNI of 1720 kWh/m²/year. The relative humidity of this site is higher than 80% because of the coastal climate and the heavy rainfall. Winds come from ENE and WSW directions with an average velocity of 6 m/s and a maximum speed of about 13 m/s. The two last sites, Ouarzazate [21] and Skoura [22], are both arid or semi-arid places located in the Moroccan desert, far from about 50 km. The DNI of the sites are respectively of 2636 kWh/m²/year and 2128 kWh/m²/year. These areas are characterized by irregular rainfall and therefore a low relative humidity. Prevailing winds come from ENE and WSW directions with an average velocity of 3 m/s and a maximum speed of about 10 m/s.

BOUJDOUR			**DNI :** 2127 kWh/m²/year **Relative Humidity :** ~ 70 % **Wind speed (max) :** ~ 15.6 m/s
LAÂYOUNE			**DNI :** 2150 kWh/m²/year **Relative Humidity :** ~ 75 % **Wind speed (max) :** ~ 15.6 m/s
OUARZAZATE			**DNI :** 2636 kWh/m²/year **Relative Humidity :** 10 - 70 % **Wind speed (max) :** ~ 10.0 m/s

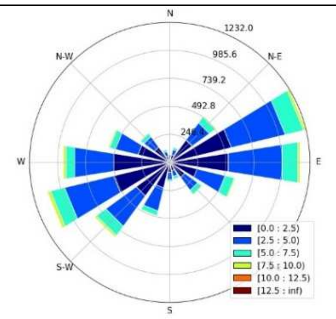
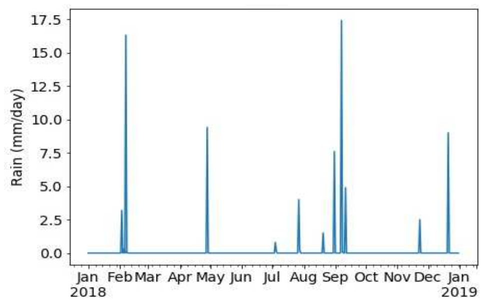
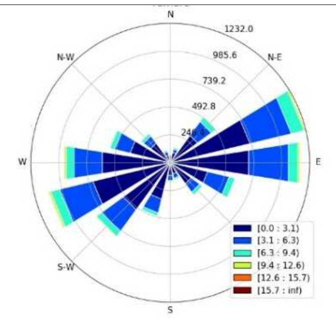
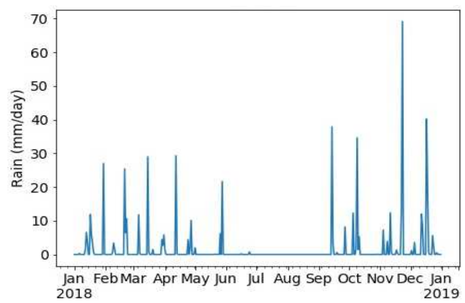
SKOURA			**DNI :** 2128 kWh/m²/year **Relative Humidity :** 25 - 65 % **Wind speed (max) :** ~ 10.0 m/s
TEMARA			**DNI :** 1720 kWh/m²/year **Relative Humidity :** ~ 80 % **Wind speed (max) :** ~ 12.6 m/s

TABLE 1. Meteorological data from the five Moroccan locations – Meteonorm database [22]

3. Experimental

3.1. Sample Preparation

For this study, five different sands have been collected from the ground of Moroccan CSP plants or other potential sites. About 500g of each sand were sampled manually by scraping the ground and avoiding pebbles. These sands look different in terms of their color, their texture or their particle size (Fig. 4). Sand samples are previously placed in a crystallizer (or possibly in a large beaker), itself placed in a heating chamber at 100°C for 24h to remove any trace of humidity in the samples. Measurement errors due to water molecules must be avoided during the analyses, so it is necessary to store the sand away from humidity.

Boujdour | Laâyoune | Ouarzazate | Skoura | Temara

FIGURE 4. Pictures of the five collected sands

3.2. Characterization and Analysis

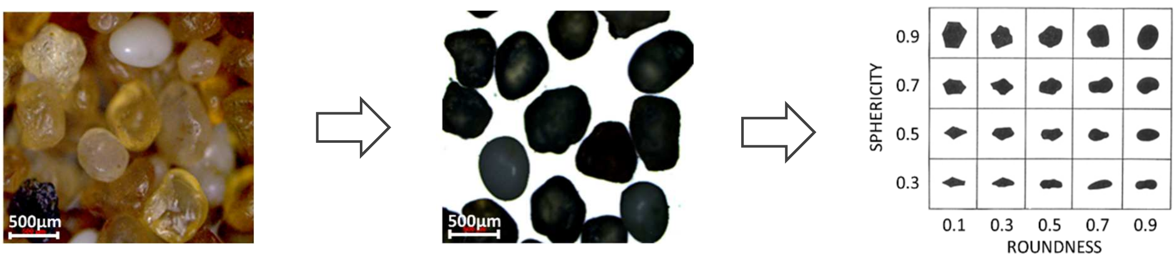
Currently, there are many different methods for characterizing sand and other particles. In this study, we have been looking mainly at the particle size distribution, the particle morphology and the mineralogical composition of sand samples. Only a few characterizations have been used during this study, but the goal is to undertake a preliminary soil survey in a simple way.

3.2.1. Particle Size Distribution

The first step after drying the sand samples is to obtain their particle size distribution (in wt %) by sieving method according to the standard AFNOR EN-933-2 [23]. Moreover, this characterization also allows to separate sand particles from other contaminants. For this study, several sieves with different mesh diameters (Ø50 µm, Ø100 µm, Ø200 µm, Ø400 µm, Ø600 µm and Ø800 µm) are stacked and placed on a vibrating table. The literature suggests that particles smaller than 63 µm have more chance to deposit on the mirror surface to create a soiling layer because they are transported more easily in the air. However, larger particles can also adhere differently to the mirror depending on the local climatic conditions (humidity, rainfall, wind speed and direction, etc.) and the mirror exposure conditions (tilt angle, direction of exposure, etc.) [13][24].

3.2.2. Sand Particle Morphology

The second step is to determine the morphology of the sand particles, as sphericity and roundness. Sphericity is a measure of the degree to which a particle approximates the shape of a sphere. Roundness is the measure of the sharpness of a particle’s edges and corners. Sphericity and roundness are ratios and, therefore, dimensionless numbers [26]. These two morphological parameters are studied by image processing with a Zeiss Axio Imager A.2m optical microscope. Thanks to a distinct contrasting effect, the shape of the particles seems much sharper. From the pictures obtained by optical microscopy and the visual chart of the morphology of minerals [27], sand particles of various size can be classified depending on their roundness and their sphericity, that are according to their smooth or angular surface, and according to their round or oval shape (Fig. 5). In the real CSP plant life and according to the impact velocity, the well-rounded particles could just cause slight damages (conical cracks) whereas the angular particles could create severe degradations (lateral and radial cracks) on the glass surface [28][29].



(a) (b) (c)

FIGURE 5. Classification process of sand particles according to the Chart of the morphology of minerals [27] (a) optical microscope image X20, (b) image treatment X20, (c) sphericity and roundness map

3.2.3. Mineralogical Composition

The third step is to identify the mineralogical composition of the sand samples. Mineralogical composition of sand is determined, at first by Fourier Transform Infrared (FTIR) spectroscopy by means of a Brüker Tensor 27 spectrophotometer with an Attenuated Total Reflectance (ATR) module. This qualitative analysis allows the identification of the main sand compounds due to the peaks situated between 4500 cm^{-1} and 250 cm^{-1} on the spectra.

Then, this analysis is fully completed by X-Ray Diffraction (XRD) by means of a Brüker D8 Advance equipment, in the Bragg-Brentano θ-2θ configuration. Powder diffraction allows a quick, qualitative and non-destructive analysis of the sample. In this analysis, scans are parameterized between an initial angle at θ_i=10° and a final angle at θ_f=75°, with an angle interval of 0.025° and a speed of 1.8 s/interval. The obtained spectra are then analyzed using mineralogical databases.

4. RESULTS

4.1. Particle Size Distribution

Granulometric distribution of the five sand samples collected manually by scraping the ground is illustrated in Figure 6. As a reminder, this analysis was made on 500g of sands by sieving method with six different mesh diameters. Therefore, seven fractions were obtained per sample and were grouped according to their size. Initial observations show that the size distributions of the five collected sands look very coarse. Indeed, 90 to 100% of the samples contain large particles (diameter >100 µm). Pebbles, granules and coarse sand (diameter > 600 µm) are important fractions for three Moroccan sites: Ouarzazate (64%), Skoura (54%) and Boujdour (40%). These particles are in smaller quantities (~20%) for the two other sites. The particles larger than 600µm are significantly influenced by the sampling process. These ones are not too dangerous because they are heavy and the wind is not violent enough to carried them to the mirrors. Moreover, fine sand and medium sand fractions with an average grain size between 100 µm and 600 µm are largely predominant in Temara (76.3%), Laâyoune (71.5%) and Boujdour (53.5%). The smallest particles (diameter < 100 µm) result from the normal erosion of bigger stones and rocks on the sites. They have been found in very small quantities (~6.4%) especially in Boujdour and Laâyoune samples.

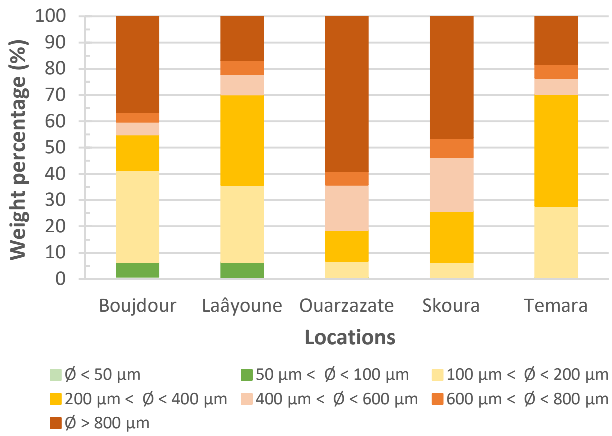


FIGURE 6. Particle size distribution of the Moroccan collected sands

4.2. Sand Particle Morphology

The analysis was made on the different size fractions of each sample. However, particles larger than 600µm might not be of any interest for the subject because they can be considered as "not dangerous" for the CSP mirrors. For each sand, all the size fractions are nearly identical in terms of roundness and sphericity. The results of this analysis are illustrated in Figure 7. Thanks to the Chart of the morphology of minerals [27], samples have been classified according to their sphericity and their roundness. The combination of these two parameters determines the shape of the sand particle and its potential effect on the mirror surface. At first sight, the sand particle morphology of the five samples looks generally similar with a sphericity index of 0.7 to 0.9. This index shows that particles approximate overall the shape of a sphere and not an oval form.

Roundness is the parameter which differentiates the morphology of all these samples. Indeed, they don't have the same roundness index, i.e. the same sharpness of edges and corners. Sand particles of Laâyoune and Boujdour are rather curved and smooth with a roundness index of 0.5 to 0.9. This kind of particles could cause slight scratches on the surface of the mirror. Sand grains of Ouarzazate and Skoura's samples are both smooth and sharp with a roundness index of 0.3 to 0.9. They could also create slight damages as scratches or small lateral cracks. The most dangerous particles are obviously those of Temara site. The roundness index of 0.3 to 0.5 shows that the sand particles have cutting edges and could seriously damage the glass surface of the solar reflectors. Violent impacts can create radial and lateral cracks with material removal, and therefore cause an important loss of performance [12][30].

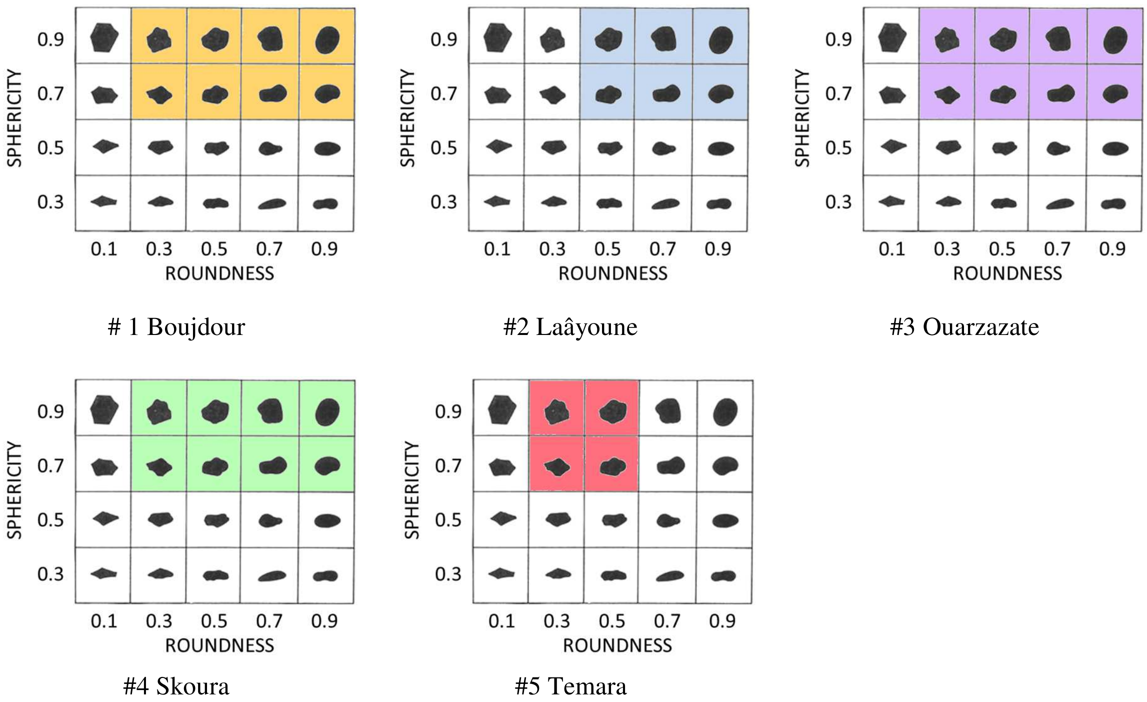


FIGURE 7. Sphericity and roundness of the particles from the Moroccan collected sands

4.3. Mineralogical Composition

4.3.1. FTIR-ATR spectroscopy

A first analysis consists of finding the main compounds present in the samples by FTIR-ATR spectroscopy. Major constituents of sand are Calcite ($CaCO_3$), Dolomite ($CaMg(CO_3)_2$) and Quartz (SiO_2). Their characteristic peaks are detailed below (Fig. 8).

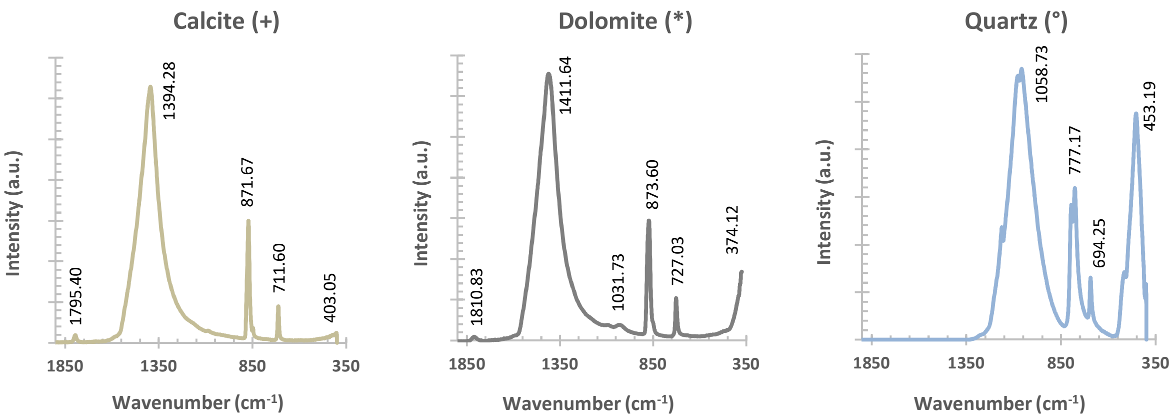


FIGURE 8. ATR Spectra reference of Calcite, Dolomite and Quartz [31]

Only the common size fraction 100µm < Ø < 200µm of the Moroccan sands has been analyzed by FTIR-ATR spectroscopy in qualitative terms. This equipment is provided with a diamond tip making noise in the spectra between 1900 and 2400 cm^{-1}.Thanks to a database for minerals [31], the peaks obtained between 2600 cm^{-1} and 350 cm^{-1} (Fig. 9) reveal the presence of these three main compounds. It can be noted that they appear in variable quantity for each sand sample according to the intensity of their peaks. Therefore, it can be shown that sand from Boujdour is a carbonate-rich sand, contrary of sand from Ouarzazate, which is a quartz-rich sand.

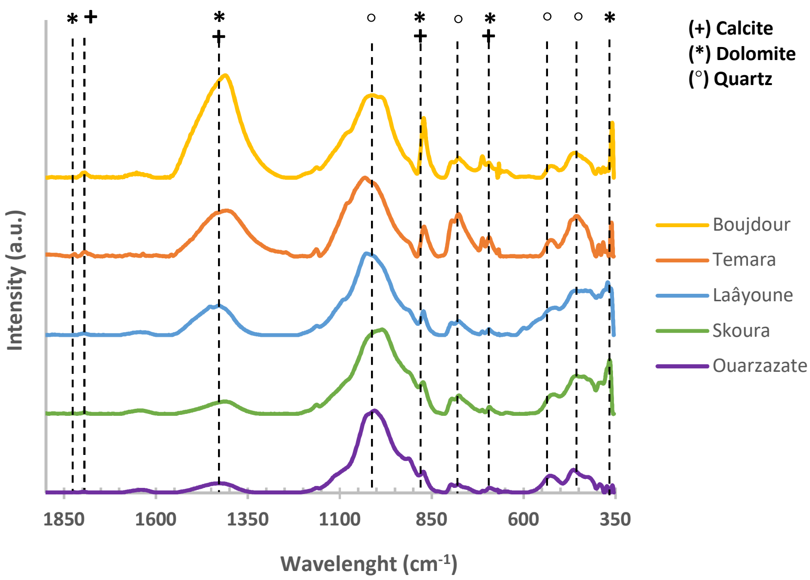


FIGURE 9. Infrared absorption spectra of the five Moroccan sands obtained by FTIR-ATR spectroscopy

4.3.2. X-Ray Diffraction

The second analysis is made by XRD to know the quantity of each mineral in every samples. The characteristic peaks for Calcite, Dolomite and Quartz are detailed below (Fig. 10). These three compounds can be easily differentiated because their main peak doesn't have the same position and the same intensity.

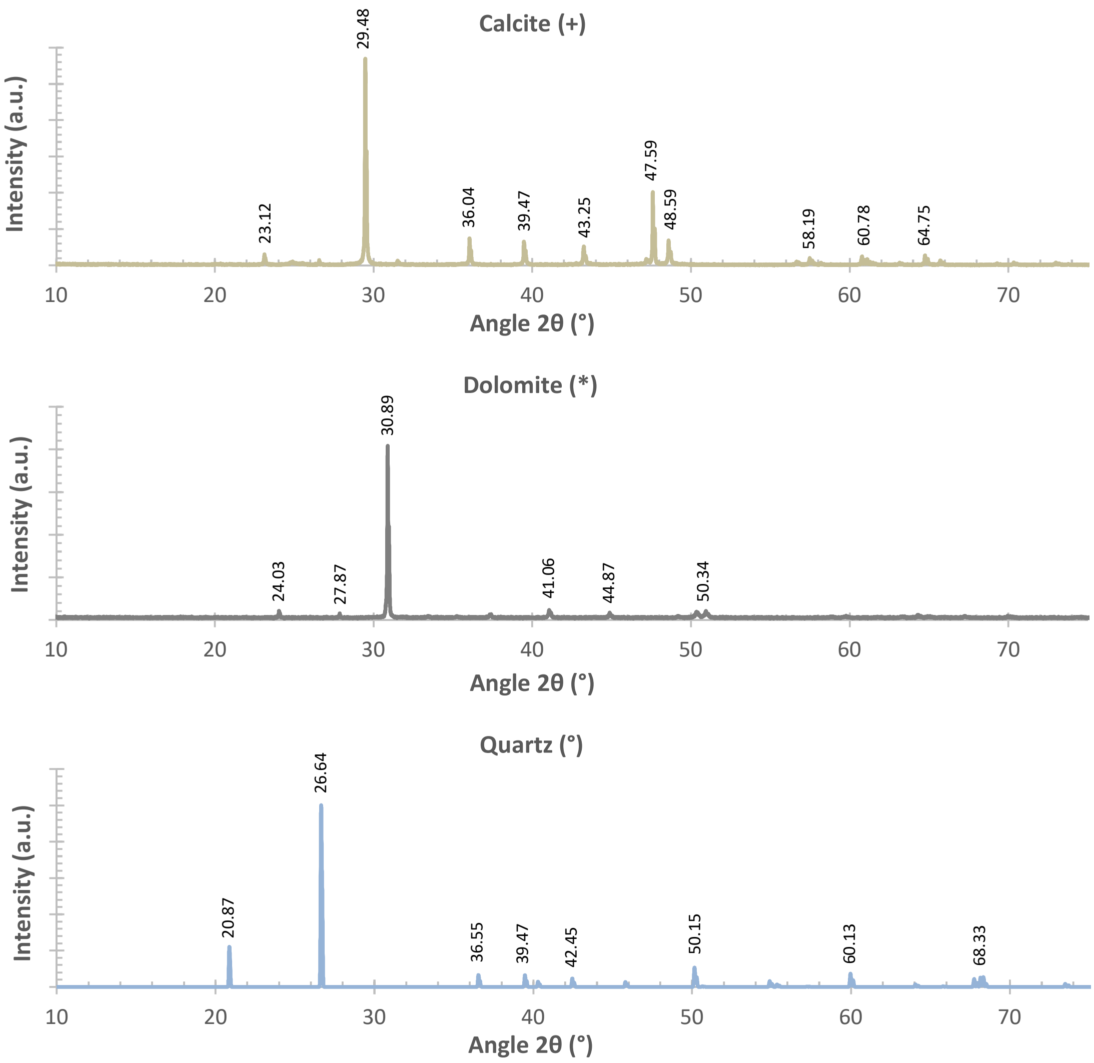
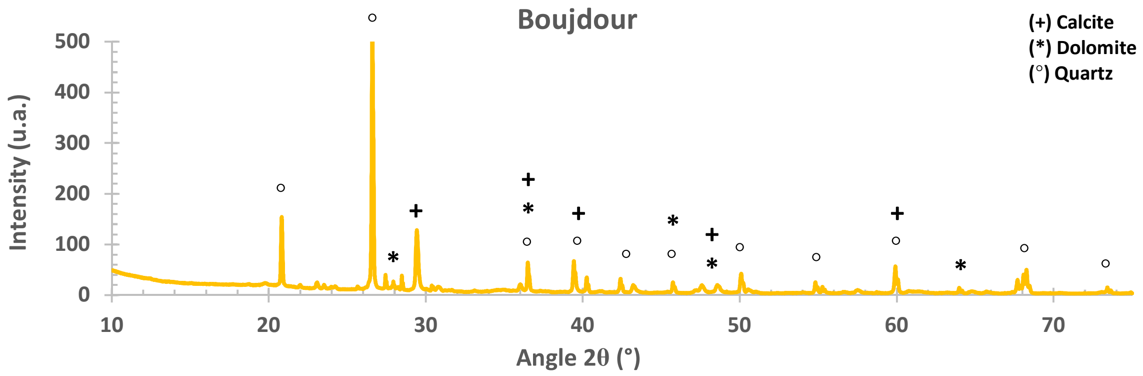
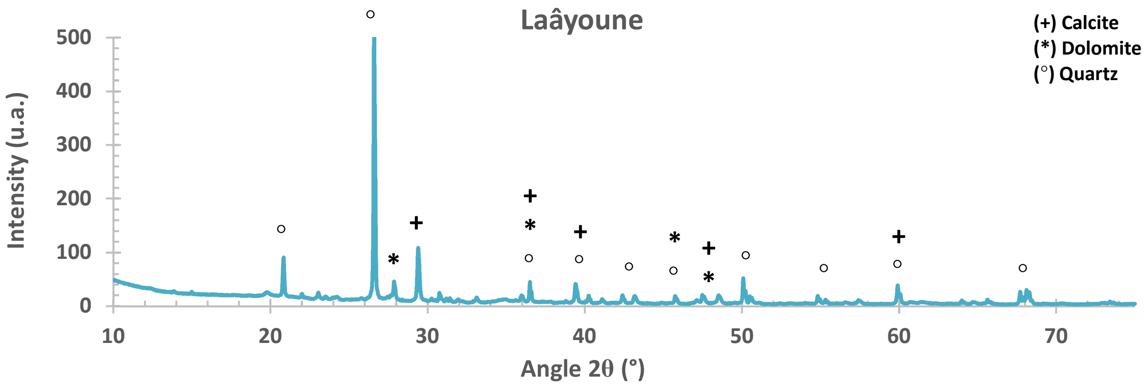
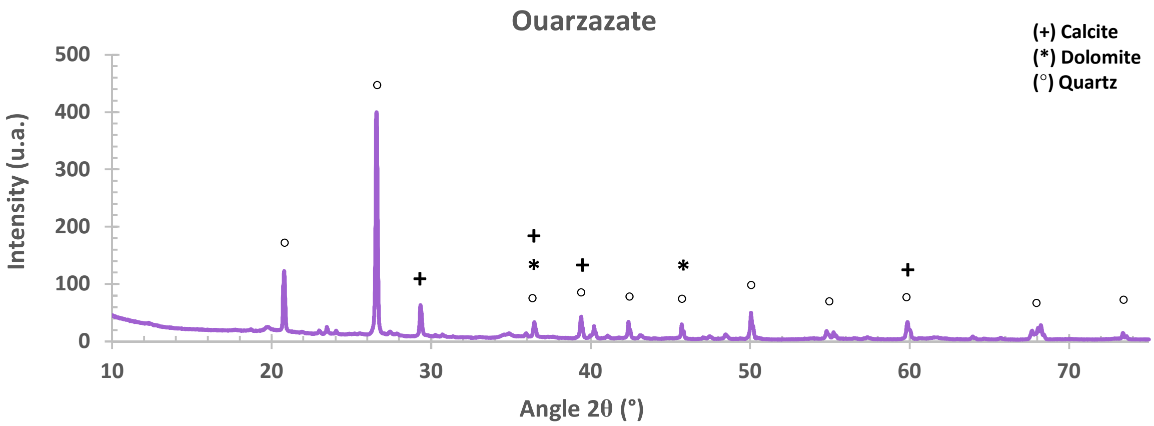


FIGURE 10. XRD diffractogramms of Calcite, Dolomite and Quartz [31]

Figure 11 illustrates the mineralogical composition of the Moroccan sand samples on the same size fraction as previously, analyzed by XRD. All the diffractogramms reveal the same peaks between 10° and 75°, but they appear with different intensity. Thanks to a database for minerals [31] and the intensity of the peaks, we can reveal the presence of the three main compounds and their approximate quantity. Therefore, it can be shown that sands from Boujdour, Laâyoune and Temara are carbonate-rich sands, contrary of sands from Ouarzazate and Skoura, which are quartz-rich sands. According to the Mohs scale [32], Quartz has a hardness of 7 whereas Calcite and Dolomite (carbonate) have a hardness of 3 to 4. Arid sites (Ouarzazate and Skoura) have a Quartz-rich sand, indicating that particles are hard and quite erosive. On the contrary, coastal sites (Boujdour, Laâyoune and Temara) have a carbonate-rich sand, which shows that particles are softer.


Boujdour
(+) Calcite
(*) Dolomite
(°) Quartz
Intensity (u.a.)
0
100
200
300
400
500
10
20
30
40
50
60
70
Angle 2θ (°)


Laâyoune
(+) Calcite
(*) Dolomite
(°) Quartz
Intensity (u.a.)
0
100
200
300
400
500
10
20
30
40
50
60
70
Angle 2θ (°)


Ouarzazate
(+) Calcite
(*) Dolomite
(°) Quartz
Intensity (u.a.)
0
100
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300
400
500
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20
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40
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Angle 2θ (°)

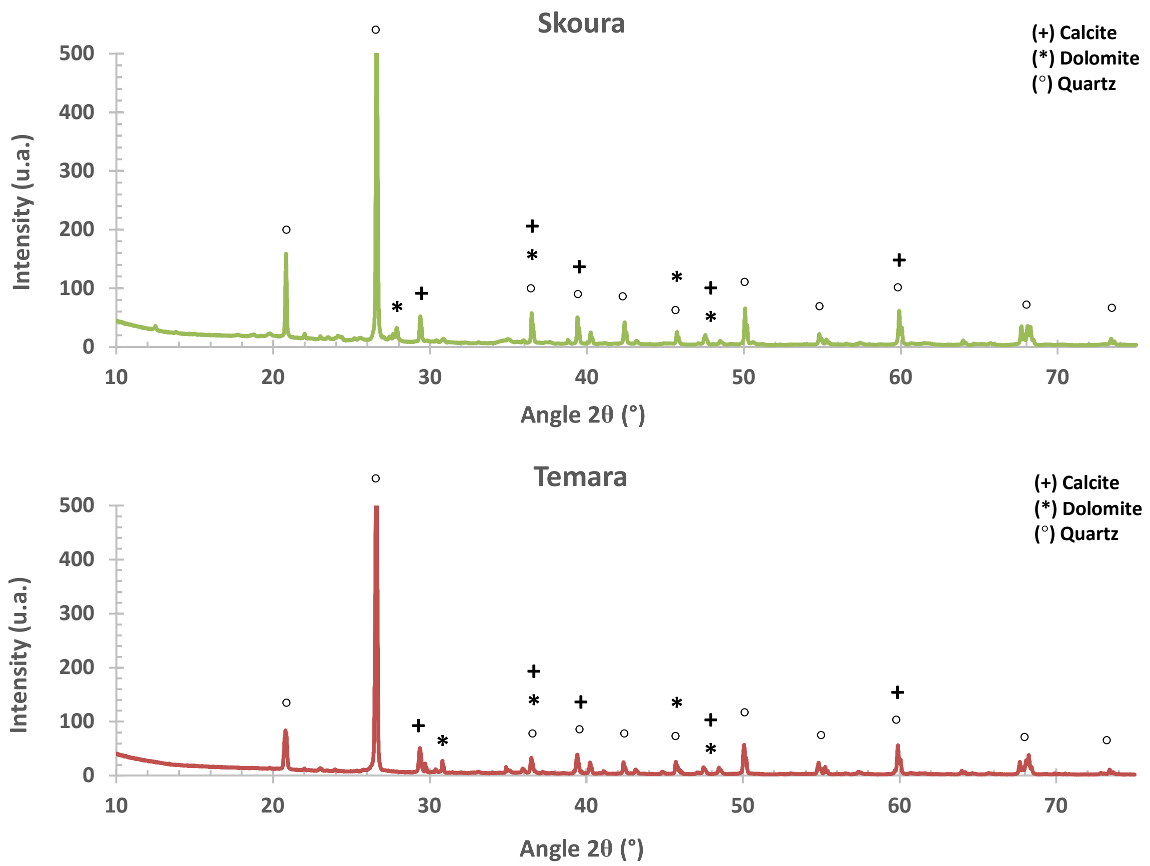

FIGURE 11. Mineralogical composition of the five Moroccan sands obtained by XRD

5. Discussion

As presented in the §4.1, the granulometric analysis has been influenced by the sampling process. The particles larger than 600µm are not of interest for the subject because they are not transported by the wind and therefore they can't cause damage to the mirrors. In this discussion, we are focused on the particles smaller than 600µm. The collected Moroccan sands are very coarse, especially those coming from desertic sites, with particles larger than 100µm. On the contrary, the smallest particles (Ø < 100µm) are particularly found in the coastal sites. In the literature, it is said that the particles with an average size greater than 63 µm will tend to degrade the mirror by scratching or breaking the glass surface, while the particles with the average size less than 63 µm have more chance to deposit on solar mirrors and thus create a soiling layer. According to the meteorological conditions and the direction of the exposed mirrors, the effect of sand on the CSP mirrors will be different. Indeed, in the coastal sites, the particles smaller than 100µm could be deposited on the mirror to create a soiling layer if the wind speed is high enough to transport the particles in the air and if the level of humidity allows to agglomerate the particles on the surface. Moreover, the particles with a diameter between 100µm and 400µm could become airborne with a high wind speed and could damage the mirror according to their morphology. In the desertic sites, the particles are globally coarse and the wind not violent but there may sometimes be sandstorms which could transport them in the air and cause damages to the mirrors. In addition, the low level of humidity prevents an important soiling phenomenon.

As presented in the §4.3.1 and the §4.3.2, ATR spectroscopy and X-Ray diffraction allowed to know the mineral composition of the Moroccan sands, and therefore the hardness of their particles. The analysis was made on the size fraction 100µm < Ø < 200µm, because this is an important common fraction to the five collected sands. According to the results of the analyses, the three main compounds are Quartz, Calcite and Dolomite on all the five sites. The intensity of the peaks reveals the proportion of these compounds in each sand sample, and their average hardness was defined thanks to the Mohs scale. By definition, the sand is a mixture of particles with dominance of one mineral. The main part of all the sands is composed of quartz but the carbonate-rich sands could be less aggressive than other. This is the case for the coastal sites. Indeed, Calcite and Dolomite have been detected in a larger quantity than the sand of desertic sites, thereby slightly reducing the global hardness. But the severity of the potential damages also depends on the morphology of the particles and their size.

As presented in the §4.2, the sphericity index of 0.7 to 0.9 shows that particles of every Moroccan sands approximate overall the shape of a sphere. However, the roundness index is quite different for the five sands. This analysis of shape must be correlated to the wind speed of the site to determine the level of potential impact on the mechanical damage of surface mirrors. Indeed, the sharpest particles won't deal any damage if they are either too large, to small or too soft. On the other hand, a perfectly spherical hard particle can deal noticeable damage to the glass surface of a mirror at a high velocity. The sand of desertic sites is composed of sharp particles which have a high hardness. However, the wind speed is relatively low so these particles could not create serious damages on the mirrors. The sand of Saharan coastal sites is composed of rather curved and smooth particles with a lower hardness. The wind speed is more important so these particles could cause slight scratches or even small lateral cracks on the mirrors. Finally, the sand of Atlantic coastal sites is composed of angular particles which could create severe degradations as radial and lateral cracks due to the violent winds. This analysis is coherent to the experimental results of another study [33] about the mirror surface damaged by sand from Temara and Skoura sites as function of wind speed. Results of this study show clearly a higher damage of the mirror surface for sand come from Temara site.

6. Conclusions

North Africa, and particularly Morocco, has a large economic development in terms of renewable energy for the last several years. This country has a high potential to produce energy from the sun thanks to a high DNI. Several solar plants are already operational while other are under construction. However, Morocco is characterized by a complex climate impacted by the mountains, the opening to the Atlantic Ocean and a Saharan position. Therefore, these power plants could be subjected to aggressive factors as irradiation, high temperature, humidity saline mist, wind, sand storm, etc. This last one generates two phenomena: the deposition of a soiling layer on the solar reflectors and the degradation of the glass or the silver layer which could cause a serious loss of optical performances of the mirrors and therefore decrease the profitability of the power plant.

Stress factors have a very strong environmental impact on the durability and the optical performances of CSP mirrors. Moreover, technologies and their maintenance are very expensive, so industry have to minimize the costs. In order to survive 25 to 30 years and optimize the CSP plant efficiency, it is necessary to predict the risk of deterioration of the solar materials. For that, it is essential to carry out this preliminary study on the sands to select the best sites for CSP Plants.

The study presented in this paper is a simple methodology to analyse the sand of different sites and evaluate the potential risks for the operational or future CSP plants. Five sand samples have been collected in Morocco to be representative of the different climates of the country and the actual on-site conditions: Boujdour and Laâyoune (Saharan coastal sites), Ouarzazate and Skoura (desertic sites) and Temara (Atlantic coastal site).

The three coastal sites (Boujdour, Laâyoune and Temara) are characterized by prodegradant geographical and weather conditions. Proximity of the sea induces a constant high level of humidity and saline mist that pose a serious corrosion risk for reflectors. This coastal climate is also defined by violent winds transporting a lot of suspended sand particles through the air, and provoking a silting phenomenon and heavy damage on the solar reflectors. Temara, for its part, is a very dangerous place for a CSP plant because of violent wind gusts, angular sand particles, and a serious risk of corrosion with a high level of saline atmosphere [34]. The two desertic sites (Ouarzazate and Skoura) are characterized by a low level of humidity and weaker winds. However, their coarse granulometric distributions with hard and angular sand particles don't make them dangerous sites because these particles can't be transported in the air and reach the reflectors. In addition, it could be interesting to complete the study with more data, as wind direction and exposure direction depending on the sites.

The results presented here are theorical assumptions which are going to be proved by the exposure of some reflectors in the same places (MASCIR, MASEN and WASCOP project). Moreover, several studies were carried out in worldwide laboratories using sand blasting setup to know the effects of sand on different surfaces (mirror, glass, etc.). A guideline is currently being written by the scientific community. Indoor and outdoor results should be correlated to explain the real effect of sand of CSP mirrors.

Finally, these results show that the CSP mirrors could be soiled regularly depending on the local meteorological conditions. These provided information could also be a key point to schedule cleaning sessions or to develop new cleaning technologies for CSP (WASCOP project).

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