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An Experimental Investigation into Factors Affecting the Soiling of Glass Mirrors

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Abstract. This paper describes experimental work performed at Cranfield University to investigate some of the factors that affect the soiling of glass mirrors. An experimental test rig was built and the factors tested were temperatures, particle size, relative humidity, the type of sand, and the drop height of the particles. The results showed that humidity had the largest effect on the amount of sand that stuck to the mirror. In addition whether the sand was natural or artificial also seemed to have an effect on the results, perhaps due to soluble materials.

INTRODUCTION

Regions most suited for CSP plants are typically arid and dusty, leading to high rates of soiling of the collector mirrors [1]. The local climate and environmental conditions can vary significantly between such sites and there can be differences between factors including temperature, humidity, and composition of the ground soil. All these factors will have an effect on the soiling rate of the mirrors, and so the frequency of cleaning required to restore the mirror reflectivity. With such locations being potentially water poor, it is important to reduce the amount of water that CSP plants use for cleaning. To provide preventative measures against the soiling rate it is important to understand the mechanisms and conditions that cause different rates of soiling. Once such conditions are understood it can be possible to reduce the soiling rates through mitigation means such as anti-soiling coatings, dust barriers or novel cleaning methods. Such mitigation methods are under investigation through the EU Horizon 2020 projects WASCOP [2] and SOLWATT [3]. These experiments aim to investigate some of the factors to understand which are potentially the most important to consider in predicting the soiling rates at any locations. While the soiling rate remains a local phenomenon, which will require careful measurement to provide accurate numbers, examining the existing climate and environmental conditions can at least give early indications of the likely behaviour.

METHODOLOGY

Experimental Equipment

An artificial soiling experimental rig, shown in Fig 1, was constructed and comprises of a plastic chamber, the temperature and relative humidity of which is monitored by a temperature and humidity sensor unit, and these can be controlled from 20°C to 40°C and 30% to 90% respectively. The temperature is increased by blowing hot air into the chamber and decreased by opening the chamber and allowing it to cool. The chamber is located in an air conditioned laboratory set to 20°C, with 30% relative humidity, which determines the lowest temperature and humidity possible. The humidity is increased by a steam humidifier, which is externally controlled to be either on or off.

Different length vertical pipes can be inserted into this chamber to allow for different drop heights of the sand. The pipes are located above a sample holder which holds the samples at a 45° angle from the horizontal to prevent

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excessive buildup of sand on the sample. Different types of sands, both artificial and natural, were sieved to different sizes and then dropped down the soiling tube onto Flabeg mirror samples.

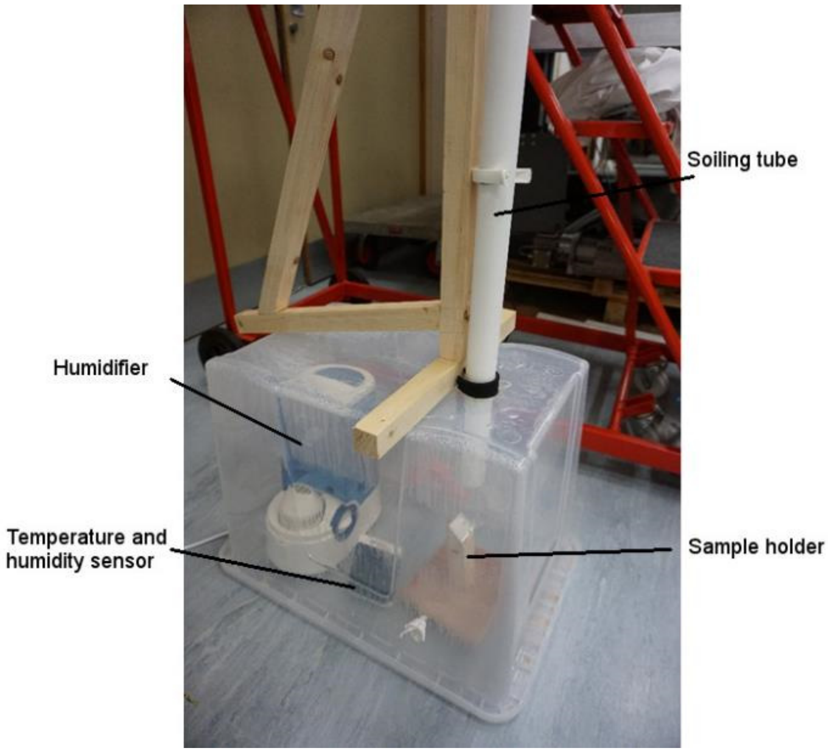

FIGURE 1. Soiling experimental test rig

Experimental Procedure

The factors chosen for the experimental investigation were temperature, relative humidity, type of sand, particle size range, and drop height of the sand; each factor with four levels, as shown in Table 1. The two natural sands were collected from Libya and Egypt, the two artificial sands were crushed quartz MIL E-5007C, and esqua DOR natural quartz. An L16 Taguchi table was constructed from the five factors and four levels to perform the experimental work. Each mirror was weighed on precision scales before soiling, and after soiling the mirrors were turned upside-down to remove any excess sand and reweighed. The mass of sand remaining on the mirrors could then be calculated.

TABLE 1. Factors and levels used in Taguchi design

Factor	Level 1	Level 2	Level 3	Level 4
Temperature (°C)	20	27	33	40
Particle size (μm)	<75	75-125	125-212	>212
R. Humidity (%)	30	50	70	90
Sand Type	Libya	Egypt	MIL	Quartz
Height (cm)	200	150	100	50

In addition to measuring the mass of sand remaining, microscopy was also performed at a number of locations on each sample to examine the particles stuck on the surface. Specular reflectance was attempted before and after using an Abengoa Condor reflectometer [4] at 650 nm, again at different locations on the samples.

RESULTS

Mass of Sand

The results of the experiments are shown in Table 2. Each run was performed with a new mirror sample.

TABLE 2. Taguchi experimental runs

Run #	Temp (°C)	Particle Size (µm)	Relative Humidity (%)	Sand Type	Height (cm)	Mass of sand stuck (mg)
1	33	>212	50	Libya	100	11.4
2	20	125-212	70	MIL	100	16.4
3	40	75-125	70	Libya	50	5.2
4	40	0-75	90	Egypt	100	43.3
5	27	0-75	50	MIL	50	6.0
6	40	125-212	50	Quartz	200	0.7
7	40	>212	30	MIL	150	0.7
8	33	0-75	70	Quartz	150	38.5
9	33	125-212	30	Egypt	50	1.5
10	27	75-125	30	Quartz	100	0.8
11	20	>212	90	Quartz	50	0.2
12	27	125-212	90	Libya	150	46.1
13	33	75-125	90	MIL	200	0.2
14	27	>212	70	Egypt	200	2.7
15	20	0-75	30	Libya	200	1.3
16	20	75-125	50	Egypt	150	9.5

From these results a main effects plot was calculated from the Taguchi design of experiments and is shown in Fig 2.

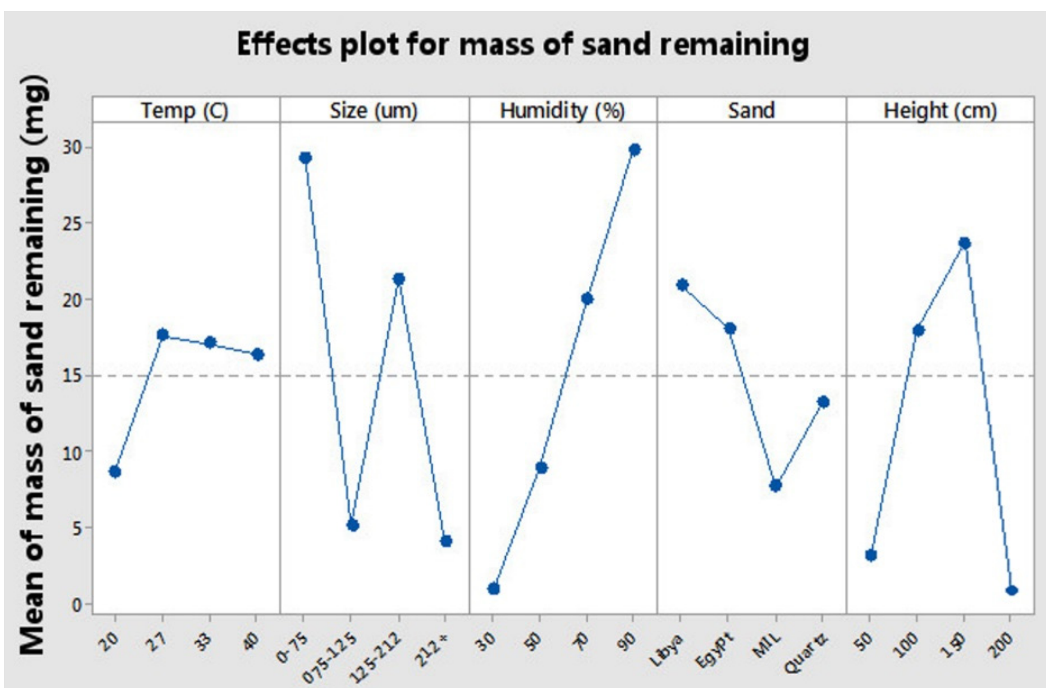

FIGURE 2. Taguchi main effects plot

The results suggest that:

- Temperature has little effect on the amount of sand that sticks to the glass. It should be noted though that only the air was heated, not the sand or mirrors.
- Relative humidity has the strongest effect on how much sand is sticking. As the humidity is increased the amount of sand sticking also increases significantly. There is more moisture in the air through which the sand travels, and this is absorbed by the particles increasing their adhesion potential.
- Sand type is important, there can be a significant difference in composition between two sands from different locations, as well as from artificial sand. In these experiments the natural sands stick better which may be due to more soluble compounds being present when compared to the manufactured quartz based sands.
- As the height is increased more sand sticks to the surface, except for the 200 cm height. As the height is increased, the velocity of the sand increases up to the terminal velocity. The sand is then more likely to break apart on impact and adhere to the surface of the glass.

Microscopy

Due to the non-homogeneous nature of the soiling on the samples, detailed analysis using microscope image processing is not useful due to the large ranges of results across a single sample, as shown in Fig 3.

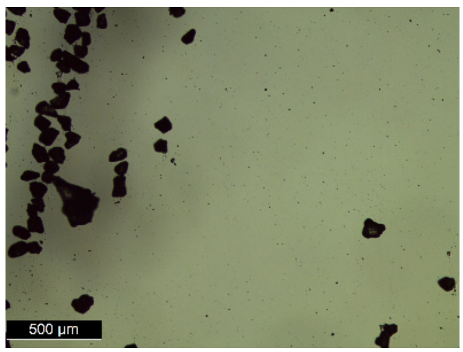

FIGURE 3. Microscope image of run 10 showing non-homogenous soiling

However, a general inspection of these images support some of the results found from weighing the samples after soiling.

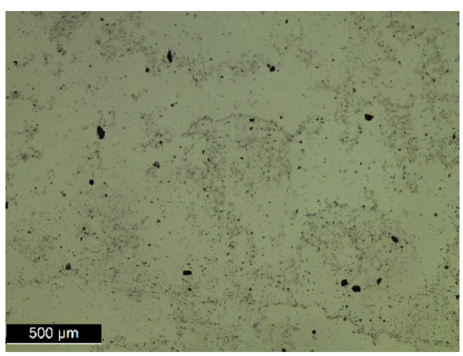

FIGURE 4. Microscope image of run 4 (0-75um, 90% humidity)

Figure 4 shows an image of run 4, done with the smallest particles at 90% humidity. It seems apparent that there was some condensation on the mirror sample, which aided in causing this fine sand to stick to the mirror. In this case, there is also a high coverage of particles across the image.

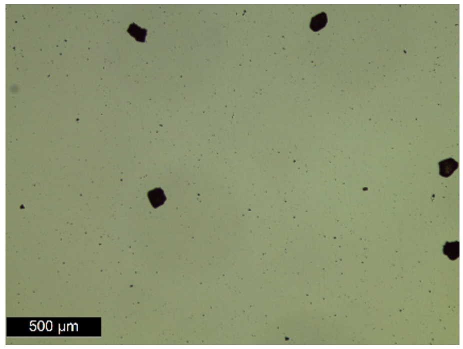

FIGURE 5. Microscope image of run 10 (75-125um, 30% humidity)

This contrasts with run 10, shown in Fig 5, which was done with larger particles and at low humidity. In this case there are very few particles stuck on the surface and none of the water patterning. Some background fine particles are noted, which are difficult to remove from the input sand in their entirety.

Reflectance

Due to the non-homogeneous nature of the soiling, shown in Fig 6, reliable reflectance measurements were not possible. The reflectance loss varied across the sample from no loss to total loss where there were patches of sand.

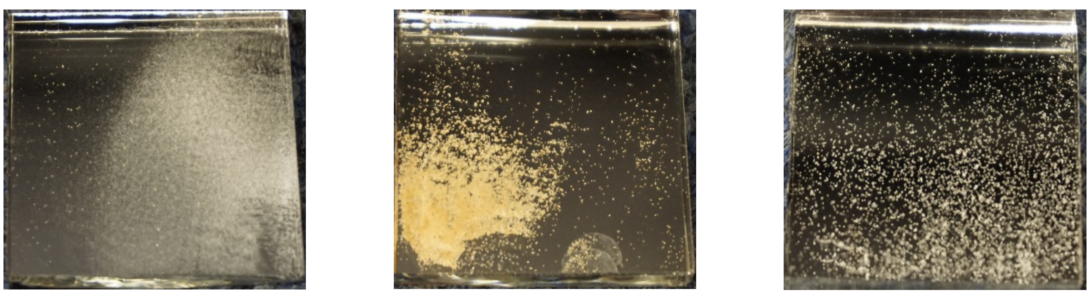

FIGURE 6. Examples of non-homogeneous soiling of samples

CONCLUSIONS

The results of the experiment have shown that there are a number of factors affecting the amount of sand that sticks to glass mirrors. The factor investigated with the most influence was humidity, where a higher humidity caused more sand to adhere. This is expected due to the higher moisture content of the air aiding in any dissolving of soluble materials and acting to cement the particles to the surface. In addition natural sands collected from desert environments appear to adhere more strongly that artificial quartz based sands, possibly due to the higher amounts of soluble materials present in natural sand.

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