

The Effect of Dust Hygroscopicity on Soiling and Self-Cleaning Processes in a Condensing Environment

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Abstract— Dew promotes chemical interactions between soilants and glass that lead to increased soiling rates and cleaning costs. Anti-soiling coatings have been developed to address these issues, and prior experiments have quantified the soiling impact of several categories of particle chemistries. In this paper, the impact that the hygroscopicity of a soilant has on soiling and cleaning values was measured on hydrophobic coated glass and compared to bare glass samples. Results will be presented from UV-visible direct transmittance and optical image processing measurements to characterize soiling and self-cleaning of surfaces as a function of particle hygroscopicity in a condensing environment, mimicking natural dew conditions.

Keywords—soiling, hygroscopic, hydrophilic, hydrophobic coating, self-cleaning, anti-soiling, solar cover glass

I. INTRODUCTION

Dew can promote chemical interactions between dust and the solar cover glass of photovoltaic panels which can lead to increased cleaning difficulty and expenses [1]. Accordingly, the severity of soiling is reported to be greatest when dew is present [2]. Even in dry and arid environments, a significant amount of dew can form, as the lower nightly temperatures facilitate dew formation [3]. For example, dew formation has been reported to occur around 200 nights per year in the northern Negev desert and on 73% of measured nights in the Taklimakan Desert in China [4,5].

To combat these phenomenon, various anti-soiling coatings have been developed. Our group has shown that Hydrophobic surfaces reduce soiling compared to hydrophilic Bare Glass surfaces [6]. This lower soiling rate is caused by a dust herding mechanism, where the highly mobile drops on the Hydrophobic surface can sweep dust particles into multiple concentrated piles as the drop evaporates. In addition, we have also shown that water collection from dew can be increased by over 36% by creating a hybrid surface, containing an array of hydrophilic features at the top, with the remainder of the surface being hydrophobic [7]. These optimized hybrid surfaces were shown to increase cleaning efficacy for several soilants tested compared to hydrophilic or uniformly coated Hydrophobic surfaces [8]. However, an experiment has not yet been performed to determine whether the hygroscopic nature of soilants effects the soiling and cleaning rates of a surface.

A useful metric to evaluate the hygroscopicity of a mineral is deliquescence relative humidity (DRH). The DRH of a

substance is the relative humidity value at which the mineral will absorb sufficient water to spontaneously become an aqueous solution. Hygroscopic minerals are abundant in nature and usage. NaCl deposition occurs frequently in areas near oceans, and CaCl₂ deposition is common in agricultural areas. Our hypothesized salt soiling mechanism is as follows. Salts are typically deposited onto solar glass surfaces via wind from the ocean or agricultural fields. After dew condenses on the soilant, with more dew condensing on more hygroscopic soilants, the soilant dissolves. The water then evaporates as the sun comes up, causing the salts to precipitate into larger particles, while also forming a thin film haze on the surface, both of which obstruct sunlight and reduce solar panel efficacy.

II. EXPERIMENTAL PROCEDURE

A. Materials

Low iron glass substrates from Pilkington, 3 mm thick, were cut to 50 mm x 57 mm and thoroughly washed. Hydrophobic coatings on glass were prepared by thermally laminating a fluorinated ethylene-propylene (FEP) layer onto the glass, followed by peeling as described previously [6,7,8]. An array of hydrophilic channels was formed in Hybrid samples by selectively abrading away the coating as shown schematically in Fig. 1. Contact angle measurements were taken of every sample using a model 250-fl contact angle goniometer (ramé-hart Instrument Co.) Ten measurements per sample were automatically performed using 5 μ L droplets of DI water to determine the contact angle. The soilants used were Arizona Test Dust, CaCO₃ NaCl, and CaCl₂ as described in Table 1. Prior studies have shown that particles soiled on photovoltaic panels usually have an average diameter of 16 μ m [9]. All soilants used were milled to ensure large outlier particles were not present. The soilant particle size distribution was determined by taking several images using a Nikon SMZ 1500 with an INFINITY2-1C camera after the soilant was applied to a Bare Glass surface.

TABLE I. SOILANT TYPE, SOLUBILITY, DRH, REACTIVITY, AND SOURCE

Soilant	Solubility in Water	DRH	Source	Median Particle Diameter
Arizona Test Dust	Negligible	Negligible	PTI Inc.	5 μ m
CaCO ₃	0.047 g/L	Negligible	Sigma Aldrich	5 μ m
NaCl	360 g/L	76%	Table Salt	6 μ m
CaCl ₂	811 g/L	31%	Cabisco Chem	6 μ m

B. Experimental Methods

Glass surfaces were coated with one of the selected soilants in the accelerated soiling chamber [6]. This apparatus was designed to replicate soiling conditions in the Arizona desert [10]. The dust holder was surrounded by a 50°C heater to prevent the hygroscopic soilants from absorbing moisture and dissolving within the dust holder. For each trial, 40. mg of soilant was weighed and placed in the holder. Two glass samples were placed adjacent to one another on a Pelitier plate at the bottom of the soiling chamber, and four soiling cycles were run as detailed in previous articles [6,7,8]. The environment was kept at 70% RH, and water was allowed to condense on the glass surface at 10°C for two minutes prior to dust ejection. For each self-cleaning measurement, a single soiled sample was placed in the artificial dew condensation chamber for two hours as detailed in previous articles [6,7,8].

C. Analysis

Transmittance measurements from 350 - 850nm were taken with a Lambda 650 UV-vis spectrophotometer (PerkinElmer) at three locations (4 mm x 15 mm) on each sample (Fig. 2) at three different time points: before any soiling cycles; after 4 soiling cycles had been completed; and after the cleaning process had been completed. The representative solar weighted transmittance (RSWT) spectrum was calculated from the transmittance measurements. [11]

Microscopy images were taken of each sample at five locations (Fig. 2) using a Celestron 5 MP Digital Microscope concurrent with the UV-vis measurements. The size of each microscopy image was 80mm² (10mm x 8mm). A python program was used to analyze these images and quantify the surface area covered (SAC) by dust.

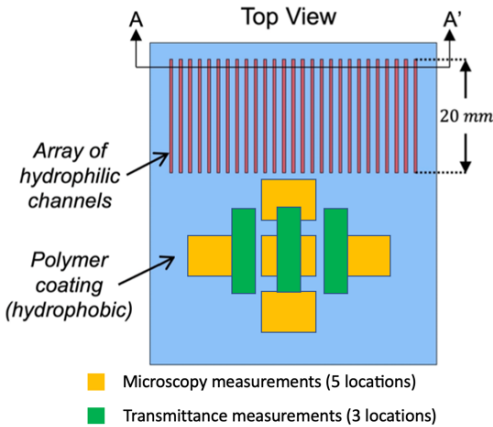


Figure 1. Hybrid surface with microscopy measurement locations (orange) and transmittance measurement locations (green).

III. RESULTS

A. Surface Characterization

The average contact angle for the Hydrophobic surfaces was $126.2^\circ \pm 1.8^\circ$, demonstrating the non-wetting nature of the surfaces. Previous measurements taken on hybrid surfaces revealed that the average distance between adjacent hybrid features was 1.6 mm, and the average width of hydrophilic features was 0.4 mm.

B. Artificial Soiling

The percent direct transmittance (%T) loss from soiling depends on both surface coating and soilant type. The overall decrease in %T after four applications of each soilant type is shown in Fig. 2. On Hydrophobic surfaces, soiling levels were significantly lower than on Bare Glass surfaces. The average %T loss for Hydrophobic surfaces was $3.4\% \pm 0.7\%$, while the average %T loss for Bare Glass surfaces was $6.6\% \pm 2.1\%$.

On Bare Glass surfaces the %T loss increases with increasing hygroscopicity of the soilants; Arizona Test Dust resulted in the lowest soiling ($-4.8\% \pm 0.2\%$) whereas CaCl₂, the most hygroscopic soilant, resulted in the largest %T decrease ($-10.2\% \pm 0.6\%$). On Hydrophobic surfaces, all types of particles soiled similarly, however %T reduction on CaCO₃ ($-4.5\% \pm 0.2\%$) was larger than the other soilants (average of -3.0%).

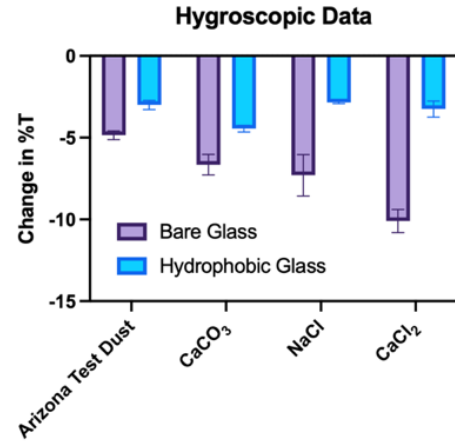


Figure 2. Change in RSWT %T as a function of surface coating and soilant type after four soiling cycles, averaged over n = 4 trials.

Soiling was also evaluated using microscope images as shown for both types of surfaces and the four types of soilants in Fig. 3. Confirming the %T measurements, Bare Glass surfaces qualitatively appear more highly soiled than Hydrophobic surfaces. In addition, the trend between soiling level and the hygroscopic nature of the soilant can be seen on Bare Glass surfaces. On these Bare Glass surfaces, the average size of the highly scattering areas was 16 μm², 22 μm², 37 μm², and 121 μm² for Arizona Test Dust, CaCO₃, NaCl, and CaCl₂ respectively. On Hydrophobic surfaces the same trend is observed, but on a smaller scale, with the average size being 15 μm², 19 μm², 20 μm², and 25 μm² for Arizona Test Dust, CaCO₃, NaCl, and CaCl₂ respectively.

C. Soiling Reproducibility and Uniformity

Both transmittance and SAC data demonstrated soiling uniformity within samples, and reproducibility between samples. The average difference in %T within samples was $1.9\% \pm 1.2\%$, and the average difference in %T between samples soiled using the same soilant was $1.0\% \pm 0.8\%$, inferring both high uniformity and high reproducibility. The average difference in SAC between samples soiled using the same soilant was $4.6\% \pm 1.5\%$. As the hygroscopic nature of the soilant increased the reproducibility and uniformity decreased.

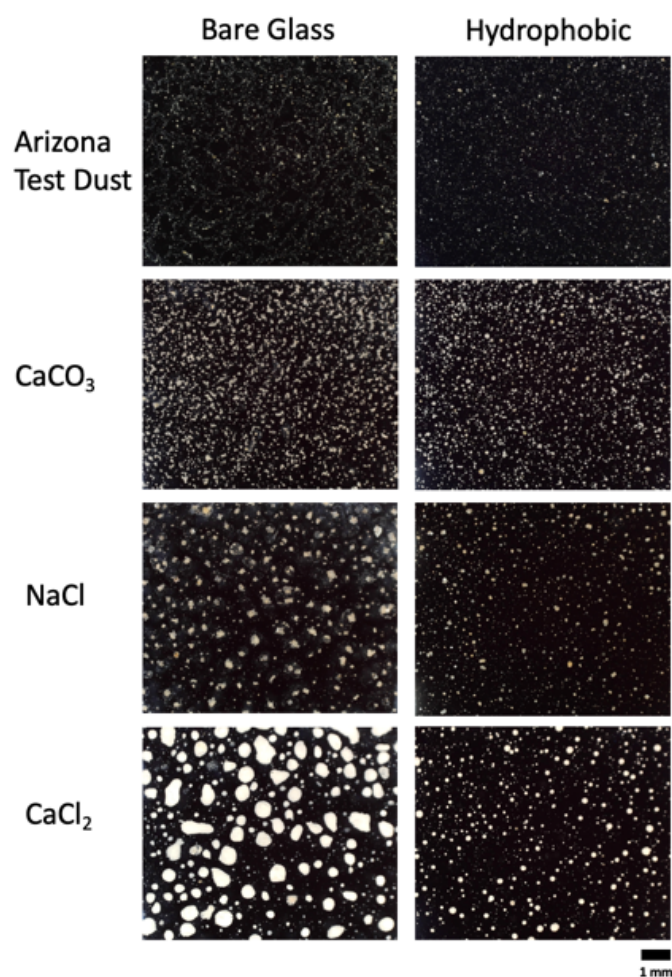


Figure 3. Microscopy images of each soilent type after four dust applications on Bare Glass and Hydrophobic surfaces.

D. Artificial Dew Cleaning

Artificial dew cleaning trials are underway and will be presented at the conference.

IV. CONCLUSION

A correlation between wetting properties of a glass surface and soiling levels was observed. Surfaces with a Hydrophobic FEP coating soiled significantly less than Bare Glass hydrophilic surfaces by both %T and SAC metrics. Using Hydrophobic surfaces as opposed to Bare Glass reduced the %T loss by as much as 68%, from 10.1% to 3.2%, when using the most hygroscopic soilent, CaCl_2 . A correlation between soilent hygroscopicity and soiling level was also observed. On all surfaces a decrease in %T, and increase in SAC, was observed as the DRH of soilants increased. However, this effect was more apparent on Bare Glass than Hydrophobic surfaces.

We hypothesize that the superior performance of hydrophobic coatings results from the condensation mechanism and droplet mobility. Water condenses in a dropwise manner on Hydrophobic surfaces, as opposed to a filmwise manner on

hydrophilic Bare Glass surfaces. On a Hydrophobic surface, the droplets shrink laterally as the liquid evaporates, further consolidating the soilent by the previously reported dust herding mechanism [7]. Thus the fraction of surface obscured by the soilent is relatively low and the %T decrease is minimized. On Bare Glass, the more soluble salts fully dissolve in the larger area liquid films. The salts precipitate to form larger crystals and/or films as the surface is dried. Unlike liquid drops on hydrophobic surfaces that shrink laterally, the area covered by liquid does not shrink during evaporation on Bare Glass because the liquid-solid contact line is pinned to the hydrophilic surface. The increase in soilent coverage as the DRH of a soilent increases is readily apparent in the optical micrographs, especially on Bare Glass substrates.

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