

Soiling Particle Interactions on PV Modules: Surface and Inter-Particle Adhesion and Chemistry Effects

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Abstract — The understanding of the fundamental physics and chemistry of dust and the interaction of these soiling fragments with the PV module surface *and* each other is potentially important to developing viable mitigation approaches. This paper builds on our previous reports and observations investigating individual soiling particle adhesion on PV module glass using microscale proximal probe techniques. Specifically, in this presentation we report on the refinement of those adhesive force measurements by gaining and including information on the contact area of those particles with the surface, the specific chemistry of interactive surfaces, and the quantification of the force values using materials standard. We also investigate the adhesive forces holding the soiling particles together and the effects of the critical parameters of surface compositional properties, moisture (humidity), and hydrocarbons. This allows for the comparisons of the inter-particle adhesion to the adhesive force holding the particle to the glass module surface. These evaluations are performed on soiling particles collected from operating modules in differing climate zones in Brazil and Middle-East Gulf regions.

I. INTRODUCTION

The integrity of the first surface of interaction for the incoming solar photons remains an area of concern for PV module reliability and performance. Soiling of this topmost layer has been identified as a high-priority problem that needs to be addressed over many past decades during the development of solar electric and thermal systems. With the opening of the solar markets in the sunbelts and desert areas of the world, areas that have not only the highest solar resource availability but also the most critical dust issues, the *understanding and mitigation* of this problem become crucial for avoiding any showstopper for rapid and widespread deployment. The soiling issue is not, of course, confined to these harsh-climate areas. Significant losses can also be encountered in areas that have more temperate environments.

The number of studies and publications documenting the effects of soiling throughout the world have been growing rapidly in the last 5 years [1,2]. Many of these have focused on the effects on performance, important for establishing cleaning cycles, providing information for siting, and sometimes giving evidence for the effectiveness of mitigation approaches [3]. A growing interest has been on the *science* of the soiling process, aimed at gaining understanding of the fundamental and controlling mechanisms that might uncover better or new approaches to dust-accumulation prevention or more-effective and less-expensive restoration methodologies [2-7].

This paper continues toward this understanding, examining the fundamental physics and chemistry of dust and the interaction of these soiling particles with the PV module surface *and* with each other. We build on our previous report and observations [2] of the investigation of single soiling particle adhesion on PV module glass using proximal probe techniques. Specifically, with these studies we report: (1) the refinement of those adhesive force measurements by gaining and including information on the contact area of those particles with the surface. This includes (for the first time) the important relationship to the specific surface chemistry of those same particles at the microscale. Surface analysis confirms the concentration of soluble salts on the surface of the grains; (2) the measurement of the adhesive forces holding soiling particles themselves together. This again includes the investigation of the effects of the surface chemistry and morphology properties, moisture conditions, and (in some cases) effects of hydrocarbon presence. These studies include the successful mapping of the compositions from the exact separated particle surfaces. (3) The comparison of the inter-particle forces with the adhesive forces between the particles and the module glass surface. The studies are performed on soiling particles primarily collected from different climate zones in Brazil and from the Gulf-region.

II. SUMMARY RESULTS AND DISCUSSION

Previously, we have reported the the initial measurements and technique “proof-of-concept” of the adhesion of individual dust/soiling particles to the surface of module glass at the microscale [2]. We had also identified several limitations of the methodology. In this study, we provide some refinements of the measurements in order to improve the interpretation of the adhesive properties of the particles. This paper also compares the inter-particle adhesion with that between the particles and the glass PV module surface. A primary focus is to gain insight between these adhesion properties and the chemistry of the soiling constituents.

A. Soiling Particle-Module Glass Surface Adhesion

As reported [2], an atomic force microscope (AFM) was configured and adopted as an optical lever detection microscope to determine the adhesion of individual soiling microparticles to the module-glass surface. Because this methodology determined the *force* holding the particle in place,

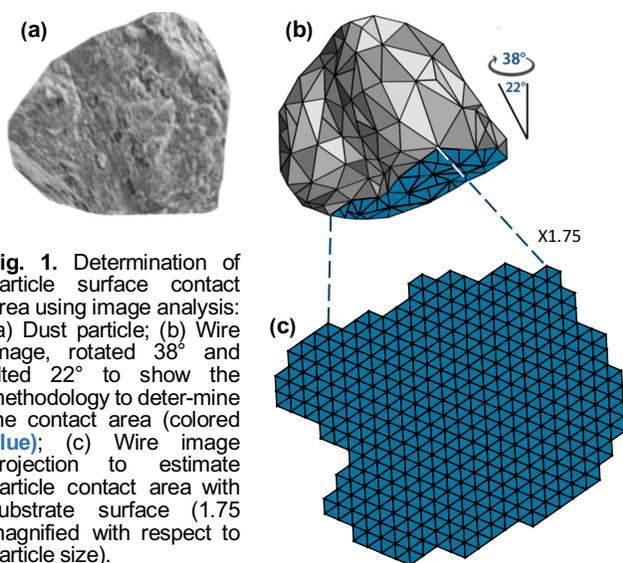


Fig. 1. Determination of particle surface contact area using image analysis: (a) Dust particle; (b) Wire image, rotated 38° and tilted 22° to show the methodology to determine the contact area (colored blue); (c) Wire image projection to estimate particle contact area with substrate surface (1.75 magnified with respect to particle size).

the question of reproducibility and consistency in interpretation and comparison of results were identified as limitations. In the previous studies, particles with similar geometries were selected to minimize measured-force differences. We have now included special image processing into the measurement system in order to provide a first-order estimation of the contact area of the particle with the substrate. A representation of the result is shown in Fig. 1, which shows the image of the particle from the camera attached to the system and the 3-D wire image produced. To accomplish this, we image the particle from 3 aspects, and the specially developed image processing program reconstructs this to provide the result. This can then be rotated to expose the bottom portion (partially shown in Fig. 1, with the reconstruction rotated 38° and tilted 22° just to expose the bottom surface)—and an automated, in-situ measurement of the area in contact with the substrate (highlighted in “blue” Fig. 1b). From this and the measured force [2], we can gain a force/unit contact area.

The effectiveness of this technique is shown in the adhesive force measurement (Fig. 2) for two particles of large differences in geometry (and contact with the substrate). The particles are

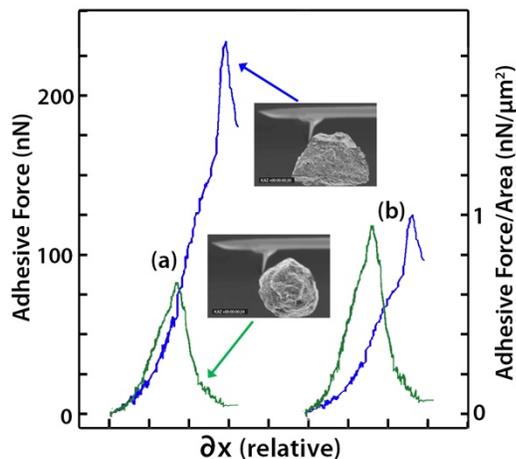


Fig. 2. Comparison showing the normalization of the (a) adhesion force going to the (b) force/unit contact area for particles of smaller (green) and larger (blue) contact areas.

taken from the same module and location—and have about the same average surface composition (the chemistries are discussed in detail in the final presentation). Though the force measured to move the particles differs considerably, the force/unit area is nearly identical (some differences are encountered because in the bottom surface is not completely flat, and this morphology also affects the force/unit area).

This paper also provides the direct correlation between the chemistry and composition of the *same* surface particles evaluated in the adhesion measurements with the determined adhesive force/unit area. We have been able to collect these same particles for the chemical and compositional determinations. These correlations are shown to be determining adhesion-strength factors in the adhesion, especially organics (under UV exposure and high temperature), some soluble minerals over dry silicates, and in some specific cases, hydrocarbon species from vehicle emissions.

B. Particle Chemistry

The chemical composition of the particles has been reported to be a primary factor in the soiling process [1,2,8-10]. In the extreme, the “cementation” process has been demonstrated to be associated with the ambient humidity, moisture conditions, and the presence of other vapors or emissions. The chemical and physical nature of the particles, the particle surfaces, and the module glass itself can all be determining factors in the severity of the soiling. Soluble minerals, salts, and some organics in the presence of UV radiation have been identified or raised as fundamental concerns in module soiling.

In this paper, we have focused on particles that have the typical chemistry and surface compositions summarized in Table 1. These particles were collected from the surface of modules under 3 specific and different climate conditions. “A” and “B” are from high-temperature zones (desert conditions), but with arid- and high-humidity ambients, respectively. The basic composition of these particles is dominated by primary silicates. “C” is from an urban area (array adjacent to a heavily traveled highway) in Brazil. The fundamental bulk composition is associated with Fe-compounds and secondary silicates. The ambient is moderate temperature and annual moderate humidity.

The reason for selecting these particular samples is associated with the comparisons between in the bulk chemistries and the surface compositions. All three are typical of the regions. The methods for analysis (electron dispersive spectroscopy-EDS and x-ray photoelectron spectroscopy-XPS) have been describe in our previous reports—and the data are quantified using material the surface layer is removed. Complement this, the Si (from SiO₂) signal increases—as expected from the volume of the grains that are dominated by SiO₂. We have successfully analyzed the surface chemistry of individual particles that are evaluated for their adhesion properties and directly linked this composition with the adhesion.

standards. EDS provides volume or bulk information on particles composition; in contrast, XPS examines the topmost layers of the sample—giving the composition and chemical state information of the surface region.

Table 1. Compositional information on soiling particles collected from module surfaces from several climate zones. Analysis is done on a collection of several mg of particles. The EDS data provide information on the volume compositions and the XPS on the near surface region. The surface concentrations of soluble salts and organics for “B” and the hydrocarbons for “C” are evident in comparing the techniques.

Technique	Detected Elemental Species (%)												
	C	O	Na	Mg	Al	Si	S	Cl	K	Ca	Ti	Cr	Fe
A. Dry “sand” dominated by primary silicates (Dry desert region in Saudi Arabia interior)													
EDS	5.0	52.5	2.2	2.8	7.6	21.9	ND	0.8	1.7	1.8	0.7	ND	2.8
XPS	6.9	51.1	2.8	2.7	7.4	20.0	ND	1.1	2.1	2.3	0.4	ND	2.7
B. Dry “sand” dominated by primary silicates (Humid desert region Saudi Gulf region)													
EDS	6.6	52.8	3.1	2.1	7.5	21.4	ND	1.8	2.8	1.9	0.5	ND	2.1
XPS	7.8	52.9	8.2	1.1	6.4	19.6	Trace	9.2	4.6	2.5	0.3	ND	1.6
C. Particles from highway region exposed to hydrocarbon vehicle emissions –secondary silicates (Brazil)													
EDS	11.2	41.9	1.9	2.4	5.3	11.2	2.1	0.8	1.9	9.2	Trace	0.1	8.2
XPS	19.8	49.8	3.2	2.9	4.9	8.8	6.2	1.2	2.2	10.8	Trace	0.4	6.9

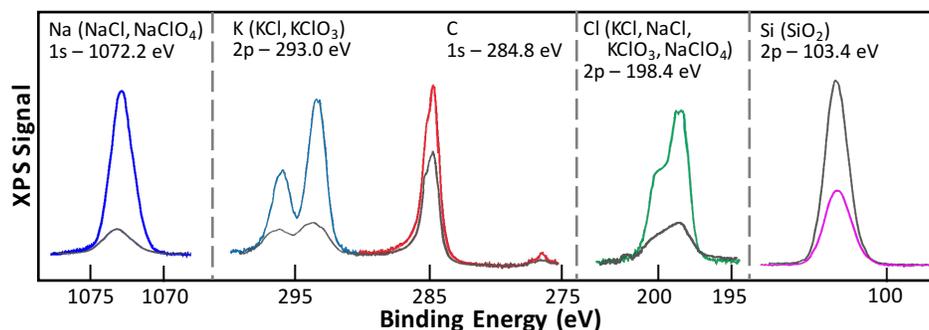


Fig. 3. X-ray photoelectron spectroscopy (XPS) data showing signals from Na, K, C, Cl, and Si before (colored characteristics) and after sputtering for removal of the surface region (dark grey characteristics), indicating the surface accumulation of the soluble minerals.

In Table 1, “A” (averages from 4-different samples collected from 4-regions of the same module surface) have essentially the same bulk and surface compositions (with some minor differences in the C at the surface and the Si). In contrast, samples “B” have surface compositions significantly different than the bulk, with soluble minerals and C dominating the near surface region. The origin of these is from the salts and organics that typify the near-sea environment. Finally, the sample from Brazil

different in composition from the particles having bases with primary silicates just described (“A” and “B”). These dominated by Fe-O compounds and secondary silicates in the bulk—but the surfaces indicate the presence of hydrocarbons and emission components (S, Cr) likely from the high diesel traffic. Examples of the comparative EDS for bulk and XPS for surface compositions are presented in Fig. 3 for “sample B” from Table 1. The data show the XPS signals for Na (from NaCl, NaClO₄), K (from KCl, KClO₃), C, Cl (KCl, NaCl, KClO₃, NaClO₄), and Si (SiO₂). The color traces represent the data from the as-collected samples (indicating the presence of NaCl, KCl, and some organics from the carbon signal). We then lightly sputtered the sample, removing the top surface—exposing the underlying bulk region. The resulting signals are shown in black. One can observe the Na, K, Cl, and C signals diminish because the concentration of these soluble minerals (that lead to cementation under moisture conditions) is on the surface of the grains. Correspondingly, the Si signal increases from the primary silicate that represents the bulk interior of the particles.

C. Inter-Particle Adhesion

The adhesion of the soil particles to the substrate is *one* factor in the dust accumulation process. The *inter-particle* interaction is equally significant. This interaction can be both chemical

(why the knowledge of the surface chemistry and composition of the particles just discussed is important) and charge related. This inter-particle adhesion has now been evaluated using the AFM technique—initially for particles collected from the field and agglomerated or joined by the “cementation” process [8,9].

In this procedure, a cluster of grains is isolated for examination. Fig. 4 shows a sample of two grains, with the AFM tip applying the force to the contact zone—this time instead of scanning in the x-direction, rather we moved the probe via the piezoelectric in the z-direction. As the cantilever is lowered, it bows (as before) in proportion to the applied force. With the proper cantilever spring constant (k), the applied force separates the two particles. Fig. 5 presents the results for two sets taken from operating PV modules: (a) for particles with

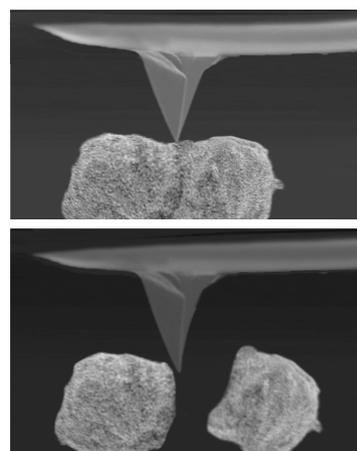


Fig. 4. Illustration of method to measure inter-particle adhesion (shown for two particles having high surface soluble mineral content and exposed to moisture on the PV module glass surface).

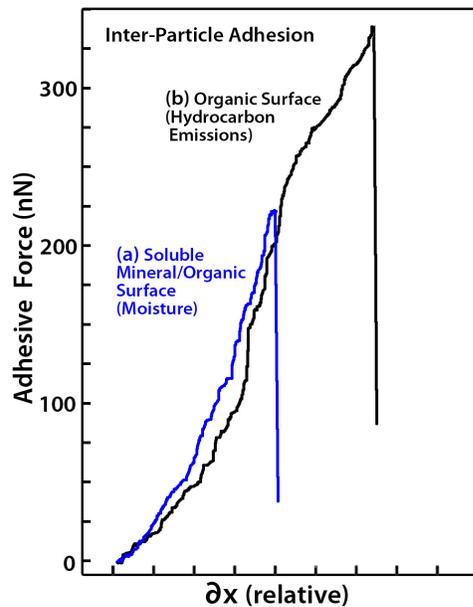


Fig. 5. Measured inter-particle adhesion forces for two difference cases: (1) Particles having soluble mineral/organic surface chemistry and exposed to moisture, and (b) particles taken from module exposed to hydrocarbon fumes (high vehicular traffic). The parameter Δx is a measure of the bowing of the AFM cantilever that relates directly to the force [2].

soluble mineral/organic surfaces, and (b) for particles exposed to hydrocarbon fuel emissions (from vehicular traffic near the PV installation). The characteristic shows the increasing force as a function of the bowing of the cantilever (represented by the angle parameter Δx [2]) The estimated adhesive forces shows that (1) the forces holding the grains together are typically significantly higher than those holding the grains to the bare glass module surface; and (2) the adhesion of grains from the hydrocarbon exposure is much stronger than the former case. The reasons for this are discussed in terms of the surface chemistry of the soiling particles—with subsequent direct evaluation of the fragmented surfaces of the recovered particles.

III. SUMMARY

This paper has built on fundamental information for the adhesion properties of dust particles collected from operating solar PV modules in the field. The investigation *first* refines the previously introduced method that determines the *adhesive force* of a single soiling particle to the PV module-glass surface [2]. This refinement now includes determining the contact area of the particle with that surface using specially developed (in-situ) image analysis techniques resulting in the normalization to the *force per unit area* of contact. *Second*, the study extends the adhesion determinations to the other important mechanism—the *inter-particle coupling*. The same proximal-probe method is used to provide this first-time microscale information. The

examples are given for samples collected from modules that had incurred cementation (e.g., from moisture and from exposure to hydrocarbon emissions). The differences show that the moisture-induced cementation typically have much lower adhesion forces than those from the fuel emission exposures. Finally, the inter-particle adhesion forces are typically an of magnitude higher than the particle-module glass adhesion. In many cases, we were also able to recover the particles in order to determine the surface compositions and relate those chemistries to the adhesion mechanisms.

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