

Fundamental Studies of the Adhesion of Dust to PV Module Surfaces: Chemical and Physical Relationships at the Microscale

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Abstract— Soiling of the PV module is a growing area of concern for performance and reliability. This paper provides evaluations of the fundamental interactions of dust/soiling particles with a several PV module surfaces (glass and glass with mitigation coatings). The purpose is to investigate the basic mechanisms and relationships between soiling particles chemistry, morphology, and their interaction and adhesion to that first photon-incident surface. The first-time evaluation of the chemistry and morphology of single dust particles taken from operating PV module surfaces is presented—including the microscale mapping of the composition on the particles' surfaces. The first direct measurements of the adhesive force of individual grains are reported, including correlations to the specific surface chemistry. Special nanoscale techniques using atomic force microscopy (AFM) are adapted to determine the force between the grain and the surface. Results are presented for various samples under dry and moisture-exposed conditions confirming the effects of cementation for surfaces having organic and soluble mineral concentrations. Additionally, the effects of hydrocarbon fuels on the enhanced bonding and adhesive force of soiling particles to surfaces are determined for samples from urban and highly trafficked regions (i.e., displaying cementitious-film formation). Comparisons between glass and superhydrophobic and superhydrophilic coatings are presented, showing the effectiveness of the lower-surface energy conditions on the particle adhesion. The effectiveness, limitations, and future research potential of this novel proximal probe technique are discussed in terms of the results and initial, proof-of-concept experiments.

Index Terms—Adhesion, Characterization, Dust, Microscale, Mitigation, Module, Nanoscale, Performance, Photovoltaics, Reliability

I. INTRODUCTION

Soiling, the sedimentation of particulate matter on the exposed surfaces of solar collectors is a growing area of

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concern for solar-system performance and reliability. In the case of photovoltaics (PV), the condition of this first-surface of interaction of the incident photons is critical for ensuring that the maximum-possible light reaches the conversion devices. Historically, this important issue has received intermittent research attention over the past 70 years, with studies mainly focused on the relationship of dust accumulation to electrical and thermal performances [1]. The well-known NREL efficiency chart [2] is one indication of the success of needed research investments—the improvement of research solar-cell conversion efficiencies over time. Researchers have invested considerable expertise and time to discover the mechanisms to increase the efficiency of these devices perhaps fractions of a percent to provide pathways to improved performance. The condition of this “surface of first interaction” however, is critical because dust inherently disrupts the intended function at that first surface/light interface, which can significantly reduce (by 10%-50% or more!) the power output and efficiency or can completely terminate system operation. With mounting deployment of this solar technology, especially into areas that have both significant solar resource and ambient dust conditions, studies relating to the fundamental nature of the particle adhesion may provide both increased understanding and new pathways to the mitigation or prevention of this adverse soiling effect [3,4].

Dust (or soiling particles) is defined as any particulate matter less than 500 μm in diameter (about 10 times the diameter of a

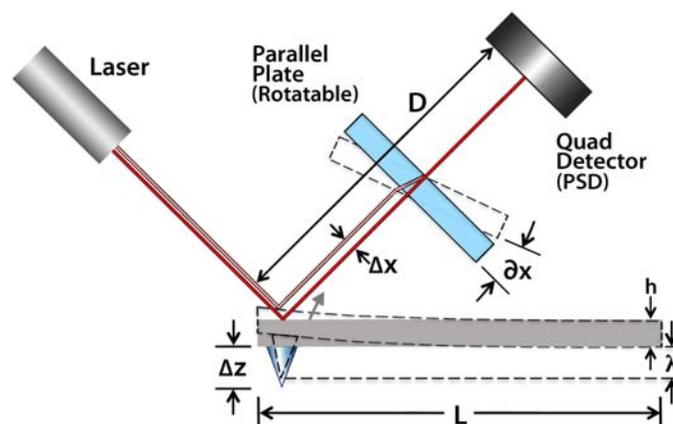


Fig. 1. Schematic representation of the AFM configured as an “optical lever microscope,” with the critical instrument parameters identified. The adhesion of a particle can be calculated from the bowing of the AFM cantilever as the tip “pulls” (or “pushes” – see Fig. 2) the particle [after Ref. 9].

human hair or 50 times that of an optical fiber) [1]. The composition can include amounts of pollen (vegetation, fungi, bacteria), human/animal cells, hair, carpet and textile fibers and other micro-fiber, and, most commonly, organic minerals from geomorphic fallout such as sand, clay, or eroded limestone. The chemistry of dust varies from geographical region-to-region, with the silicon-oxide based sand particles typically dominating in the desert regions of the Middle East, contrasted to the soil/fertilizer/plant products of the agricultural areas of the US and South America or possibly the vehicle or power plant fuels that might dominate the urban environments. The severity of dust or soiling also depends critically on the climate zone and weather conditions [5].

Though dust research for solar collectors has spanned more than 7 decades, the fundamental properties of dust and its control are still not fully understood [1,5,6]. The science and technology investment in this problem has increased substantially in this past decade—with exceptional work directed at understanding the issue. The purpose of this paper is to investigate the *most fundamental* mechanisms and relationships between soiling particles' chemistry, morphology and the adhesion of individual particles on the module surface. The objective is to gain insight on the interaction between these particles and their adhesion to that first photon incident surface, providing foundational information on the basic mechanisms that might help in developing the paths—potentially new ones—toward mitigation. This paper provides evaluations of the fundamental interactions or dust particles on several PV module surfaces (glass and with dust mitigation coatings). This extends previous studies of the chemical and physical properties of the dust material from various geographical regions and climate zones worldwide. This includes first-time measurements of the adhesion of individual dust particles to PV module surfaces using nanoscale (proximal probe) techniques with the first complementary microscale chemical mapping of compositional and surface distributions that relate directly to adhesion and soiling particle agglomeration. A goal is to establish proof-of-concept for using these nano- and macroscale techniques for the fundamental evaluation of determining the adhesion of soiling/dust particle to solar PV surfaces.

II. EXPERIMENTAL METHODOLOGIES

A. Compositional and Morphological Characterization

The particles and soiling samples were characterized for chemical and physical properties using various conventional microscopies and spectroscopies [6]: Electron dispersive spectroscopy (EDS), scanning Auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS), secondary ion mass spectrometry (SIMS), and scanning electron microscopy (SEM). The elemental mapping of particles (for chemical and elemental distributions) was provided through EDS, AES, and SIMS.

B. Particle Adhesion and Force Measurements

An atomic force microscope (AFM) was configured to determine the adhesive properties of individual particles to the

surface. The particles were selected after determination of specific chemical properties. The surfaces were uncoated and non-textured module glass, identical glass, coated with superhydrophobic (SHB) [7] and superhydrophilic (SHL) [8] “dust mitigation” coatings, and module glass with some antireflection coatings.

The schematic configuration of the AFM used to evaluate the adhesion of the particles to the substrate (module surface material), sometimes termed an optical lever detection microscope, is shown in Fig. 1 [9,10]. The probe can be configured to “pull” or “push” the particle on the surface (Fig. 2).

If the particle is adhered to that surface or if the friction between the particle is strong enough to hold it in place, the cantilever of the AFM bends or bows—and this physical change can be related to the force holding the particle to the surface. In these studies the “pull” configuration was used because concave bowing of the cantilever seemed to yield more reproducible

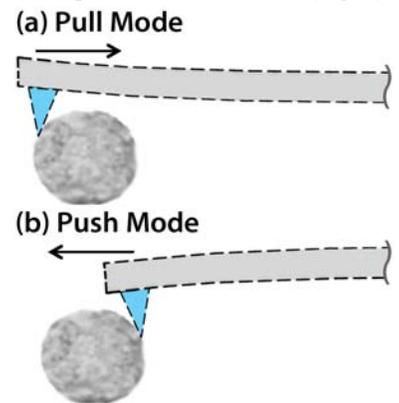


Fig. 2. The adhesion measurement can be performed with the AFM tip either pushing (cantilever bows upward) or pulling (cantilever bows down) on the particle.

results than the convex bowing for the “push” configuration, although this has not yet been investigated in detail. The system was operated in two modes: (1) *Angular increment Δx* . The inclusion of the rotatable parallel quartz plate allowed for the redirection of the beam onto a fixed detector. This angle relates to the change Δx (essentially the change in location where the beam would have intercepted the detector surface if the plate were not in place) and ultimately to the lateral adhesion force. The detector is a split photodetector with four identical quadrants (quad detector). Thus the parallel plate is operated as a beam “positioner” to keep the primary light focused on the “target” center. And (2) *Position sensitive detector*. This approach used special, linearly configured multiple micro-photodetectors and can determine Δx directly. However, is not sensitive for the smaller values of this lateral change due to resolution of our detector(s), the spread of the incoming laser light, and the distortion of the Gaussian distribution of the beam. This technique was only used to compare and validate some values of Δx . The lateral- and transverse-forces holding films and inclusions to a surface have been treated by several groups [9-15]. Bhushan et al. [9, 16-18] have provided several excellent evaluations and summaries of the techniques, including a calculation of the lateral force. This has been adapted as the underlying methodology to determine the relative forces holding the “dust” particles on the surface of interest in our studies. As the AFM tip pulls (or pushed) on the particle, it will bend until the force holding the particle in place is overcome. As it bends, the laser ray reflected from the top of the AFM cantilever is redirected and moves along the detector surface by an amount

Δx . Using the *Angle δx* method, the parallel quartz plate is used to keep the laser spot at the same point on the detector surface, and to do this, moves by an increment δx . This angle relates to the geometrical and mechanical properties of the AFM tip and cantilever, the geometrical position of the detector, and the deflection Δx . With the AFM operating in the constant force mode, only small Δx of the laser spot occurs—with all other movements compensated by the AFM feedback loop. In general, the lateral force is [9-11, 16-18]:

$$F_y = -k\Delta x, \text{ and} \quad (1)$$

$$k = Gbh^3/(3L\lambda^2) \quad (2)$$

where k is the cantilever spring constant, the AFM and cantilever dimensional parameters [b (the cantilever width), h (the cantilever thickness), and λ, L defined in Fig. 1] and G is the modulus of rigidity for the cantilever.

The solutions to the lateral (and normal) force equations have complex solutions, but for the cases under consideration here, the angular increment can be approximated by [9,16]:

$$\delta x \sim F_y \lambda L / (\beta G b^3 h) \quad (3)$$

F_y is the lateral (adhesion) force (Eq. 1) and β is a cantilever constant that is a function of the ratio h/b and Young's modulus ($\sim 2h/b$ for our case). Consequently, the adhesion force can be estimated from the AFM dimensional parameters and the measured value of δx as the cantilever bows. Thus the bowing can be used to indirectly evaluate the adhesion force holding the particle in place.

III. RESULTS AND DISCUSSION

A. Physical and Chemical Nature of Dust

The chemical and morphological differences of soiling particles throughout most of the world have been investigated [19-22]. Dust particles gathered from module surfaces in the desert regions of Middle East, North Africa, and India are dominated by silicon-oxides (e.g., sand or quartzite) materials, along with lower elemental concentrations that primarily relate to local environmental conditions (e.g., local industry, military operations, etc.). Those from the rural regions of Europe, South/North America, and Asia are usually commonly composed of soil and fuel components (if the arrays are near highways)—as well as other organic and mineral matter. Comparative examples are given in Fig. 3, with the composition from the dry, desert area in Saudi Arabia contrasted with samples from a module from a rural area in Brazil and one near a heavily trafficked highway area. Typically, the dust found on modules from the Gulf desert regions have 80-90% quartz and primary silicate minerals, with the remainder other minerals, organics, and area specific compounds. The samples from rural areas such as Brazil have 15% or less quartz and primary silicates, with the majority of the components from secondary silicates, agricultural products, and area-specific minerals. Components from the fuels (diesel) are evident in the sample taken near the highway, a factor that can have significant implications for both adhesion and cleaning. Even in the Middle East, the mineralogy varies substantially for various geographic locations and climate zones (Fig. 4).

The dust that deposits or accumulates on the module surface

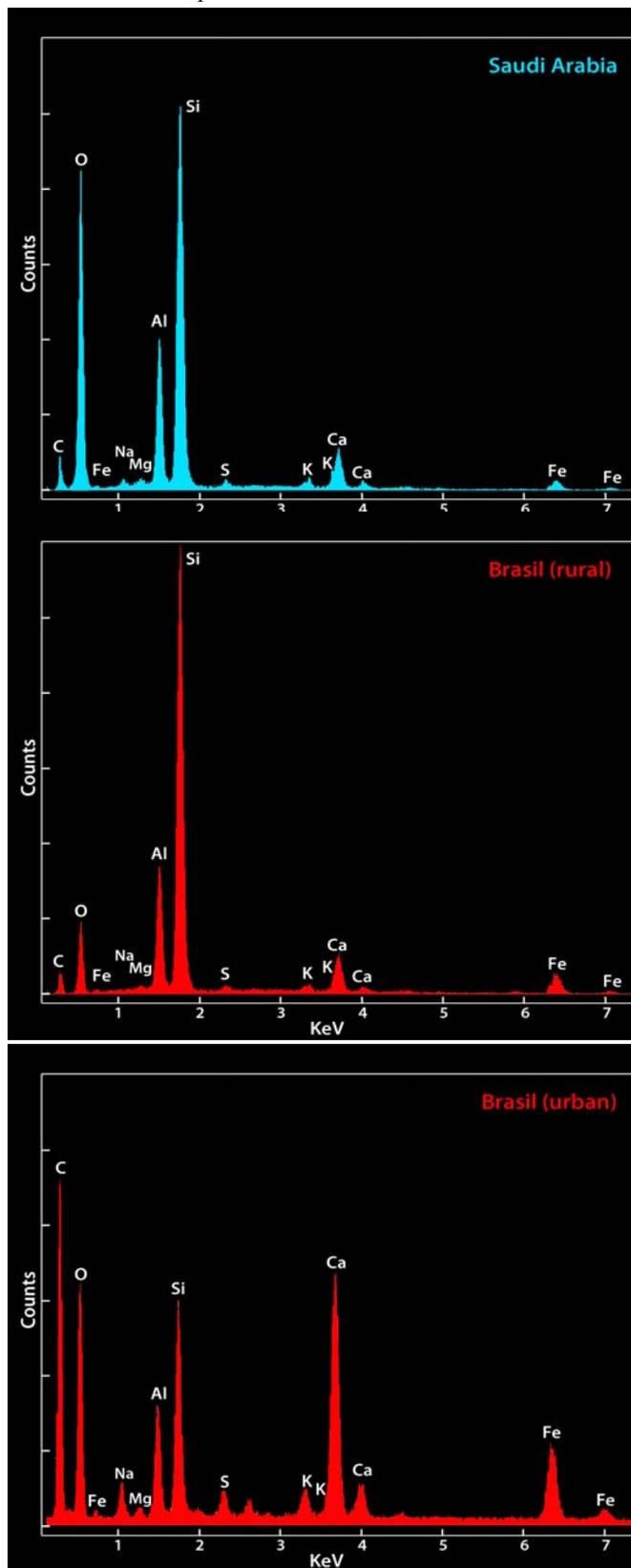


Figure 3. Comparison of the chemistry and composition of dust particles samples from modules in Saudi Arabia and Brazil. The Saudi Arabia sample is from Riyadh: dry and hot climate zone. The composition is dominated by quartzite and primary silicates. The samples from Brazil are from two different locations. The first is from a rural location and dominated by some quartzite but mainly secondary silicates and iron (soil). The second is from an urban area, where the hydrocarbons from the vehicular traffic are very high and different from the rural case.

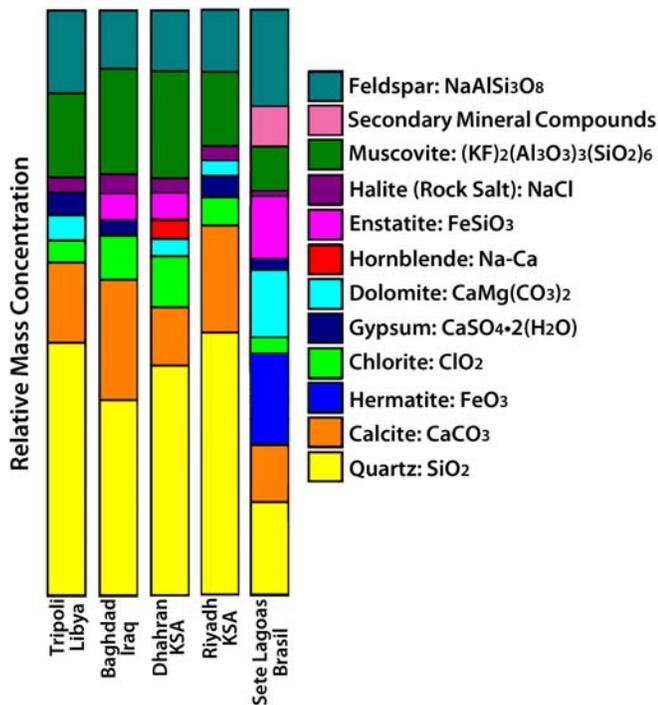


Fig. 4. Mineralogy evaluations from MENA region and Brazil, comparing differences in quartz, primary silicates secondary silicates and minerals distributions.

is, in most cases, significantly different that the airborne particulate matter carried by the wind, for example [23,24]. Such differences have been evaluated previously. Variations in morphology can be substantial. Figure 5 presents such cases for Riyadh, KSA with reproducible differences between the airborne and module components. The collection of airborne dust was from 1-3 meters above the module and is compared to that on the surface for morphology and chemistry.

Of special interest is the distribution of chemical species on the surface of the dust particles themselves. Figure 6 provides one example—a particle collected from the hot-humid region in Saudi

Arabia. The data show an SEM image of a particle, and EDS scans for Si, C, and Cl. The particle is primarily SiO_2 based, but the distribution shows C and Cl decorating distinct regions. Further examination provides evidence that the particle is composed of several quartzite-dominated grains—held together with organic material. The organic material on the surface reacts with moisture (e.g., humidity) to agglomerate the grains into large particles on the

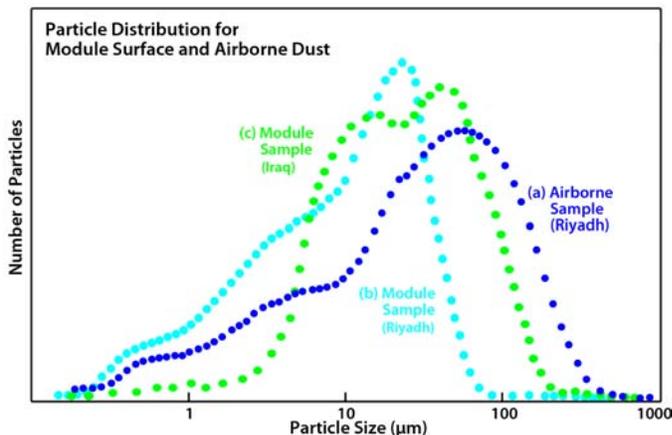


Fig. 5. Comparison of the particle distribution for dust particles collected from module surface to that collected as airborne particles (1-m above module).

surface. This paper provides this and further chemical mapping evidence that supports the Roth characterization [25] and Cuddihy model [26] of cementation of dust under these conditions. Figure 7 shows the mapping of specific impurities on the surface of a soiling particle from a sample collected from a module surface near a highway (urban area) in Brazil. The distribution of impurity species associated with diesel is evident for such samples. Also, the soil in Minas Gerais (mining region) has a very high Fe content—also shown in the mapping sequence. Thus, the surface chemistry differs from region to region—and this critical surface chemistry underlies the adhesion-force studies in the following section.

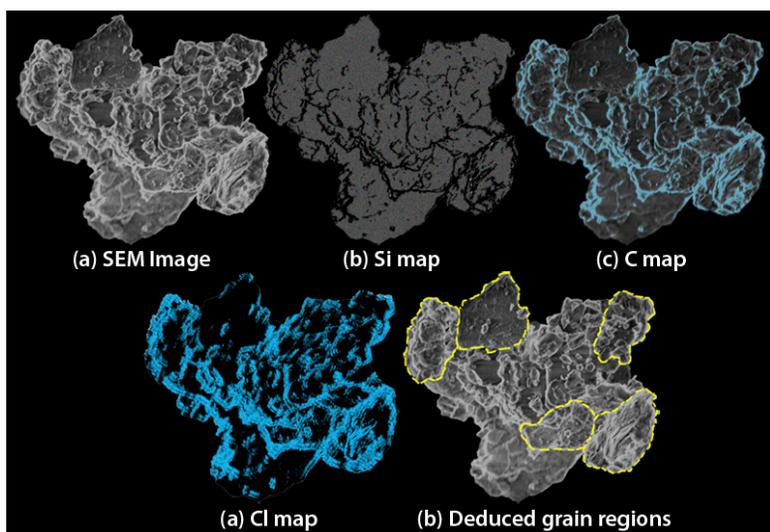


Fig. 6. Secondary electron image and color-coded elemental maps of various compositional components on a particle composed of agglomerated grains bound by organic and soluble salts. (From KSA)

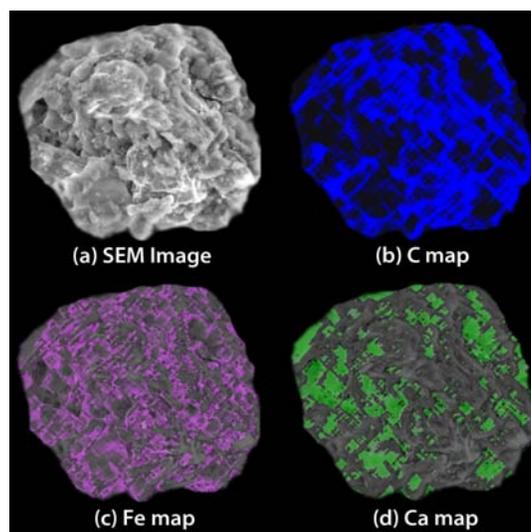


Fig. 7. Secondary electron image and elemental maps of typical grain from urban site in Brazil—showing high C content from hydrocarbon sources.

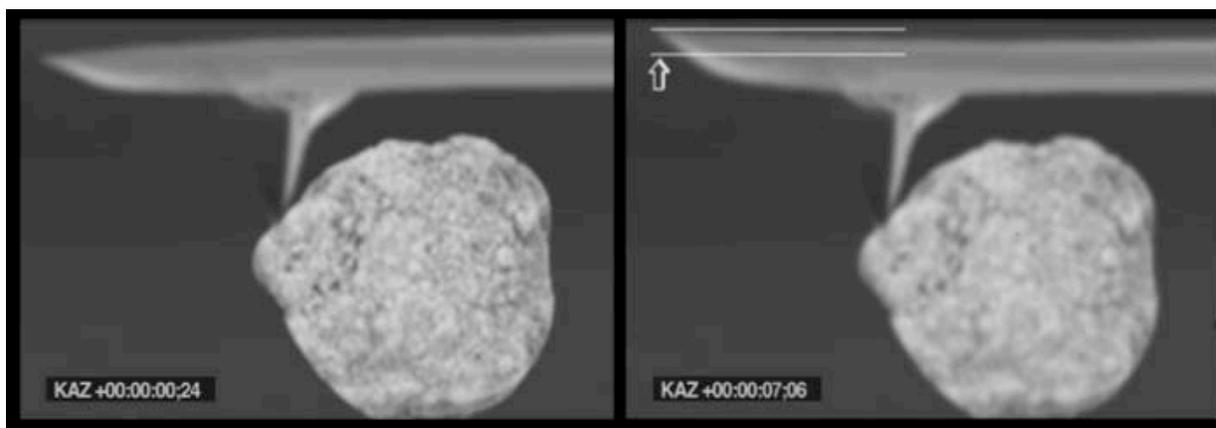


Fig. 8. Novel AFM particle adhesion measurement showing cantilever at start of movement (left) and bowed cantilever at maximum tip pull on particle (right) indicated by arrow. Laser deflection from top of cantilever with other AFM parameters is translated into the force holding the particle in place⁷.

B. Fundamental Evaluation of Dust Particle Adhesion

The interaction of the particle with the surface depends on several key parameters. These include the charge on the particle and the surface, the chemical and physical states of each (e.g., the cleanliness of the surface, hardness and roughness of each, presence of soluble salts or other organic matter, and relative energy level of the surfaces), and the ambient conditions including humidity, wind conditions, temperature, and relative energy level of the surfaces) [26]. There have been studies of dust adhesion using AFM [30], but these have focused on macroscale and not on single particle reactions nor considering the microchemistry. This paper investigates the mechanisms and extent of how many of these parameters affect the adhesion of single dust/soiling particles to the PV module surface. Particles taken from specific geographical locations are fully chemically characterized before conducting the adhesion experiments. A variety of PV module surfaces (glass, ARC-prepared, and anti-dust coatings) are used and compared for these first direct evaluations of the adhesive properties and forces holding the individual grains to these PV module surfaces utilizing the special proximal probe techniques described in Section 2.2.

The first set of comparative AFM studies are presented in Figs. 8 and 9, which show a view of the atomic force microscope tip on a single particle and the results calculated from the angle ∂x technique in Section 2.2, respectively. The particle is pulled to the right. In this process, then flexible AFM cantilever bows (compare Fig. 8a and 8b with the bowing indicated by the arrow) until the force holding the particle in place or to the surface is overcome and the particle moves (or in some cases, is actually propelled away). [NOTE: Videos of the AFM technique in operation are posted on our program website: www.PVReliability.org]

The characteristics in Figure 9 present the relative adhesive force as a function of ∂x for several particle and surface-condition cases. Figures 9a-c compare responses on a module-glass surface. Figure 9a shows the adhesion for a typical particle having low (or no) organic surface content under dry conditions. In comparison, a particle having significant organic surface content is represented in Fig. 9b, displaying relatively higher adhesive force (adhesion to the glass surfaces). These differences associated with the dissimilar surface chemistry are measured consistently between these particle types and validate the 4th and 5th of the “Cuddihy Principles;” that

is low surface-energy (less chemical interaction between particle and surface) and chemically clean surfaces (less sticky) and particles are less likely to adhere to the glass [26,27].

The “cementation” process is clearly exhibited in the characteristic of Fig. 9c, that of a particle with high surface organic-content (the same particle as in Fig. 9b), except that it was exposed to a high humidity (water moisture) conditions and allowed to dry before the adhesion was evaluated. The measured adhesive force is significantly higher—indicative of the organic

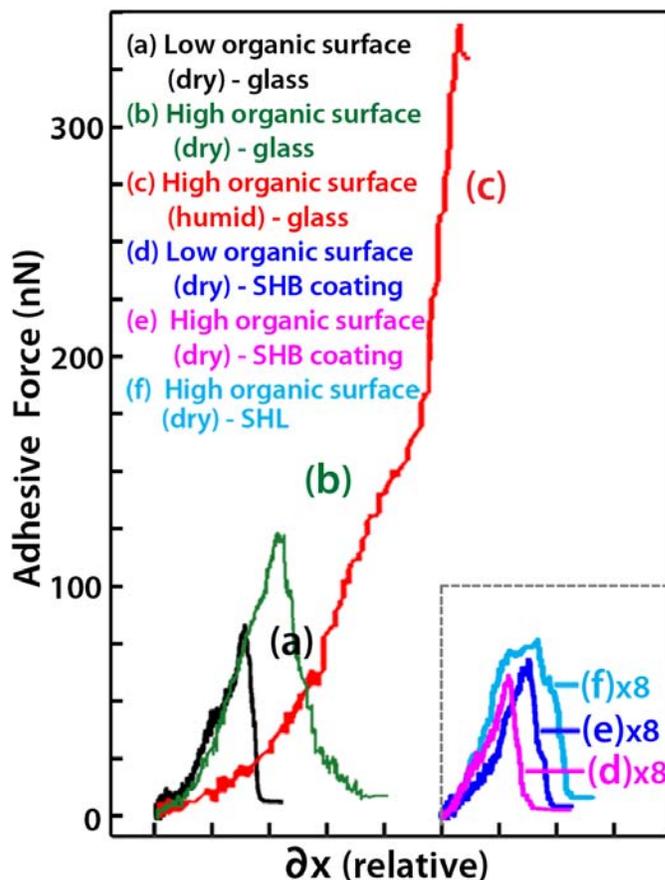


Fig. 9. Comparison of adhesive forces of various single dust particles on various PV module surfaces. Insert on bottom left shows data for superhydrophobic (SHB) and superhydrophilic (SHL) coatings (on glass) – at 8x enhancement.

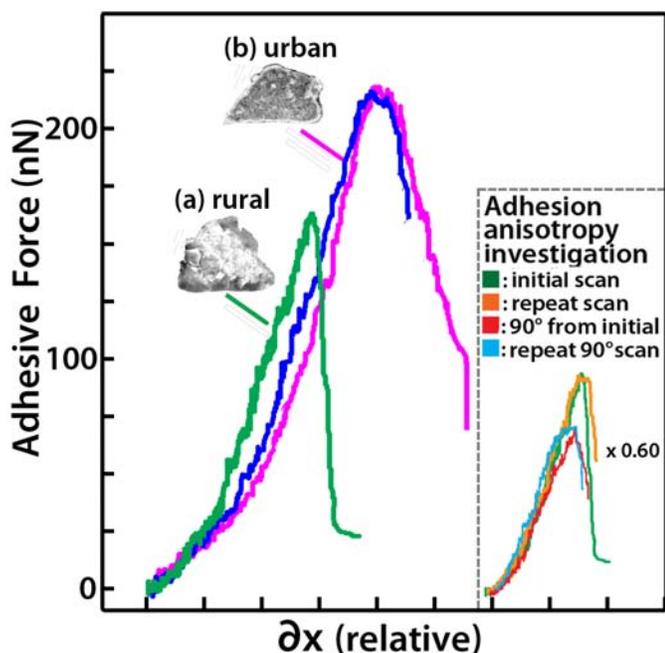


Fig. 10. The adhesive force characteristics comparing particles from rural and urban (containing hydrocarbons on surface) areas. The blue characteristic in (b) is a re-measure of the same particle. The insert presents some initial anisotropy investigations that are inconclusive at this point.

component at the particle surface bonds to the glass under the influence of the additional moisture condition. This is exactly the process that such dust encounters as it is exposed to morning dew, high humidity, or light rain and allowed to dry, forming a cementitious layer that is very difficult to remove [1,27,28]. One process toward mitigating the dust issue is to use coatings that have low surface energy [26], such as hydrophobic and hydrophilic layers on the exposed module surface. The recent development of *superhydrophobic* (SHB) and *superhydrophilic* (SHL) materials has guided new R&D soiling investigations, especially to alleviate the compounding (deleterious) effects of moisture [29-32]. The effectiveness of this approach is exemplified in Fig. 9d,e,f for low and high organic surface content particles on dry, coated superhydrophobic and superhydrophilic surfaces. A significant reduction in the adhesive force is noted (by almost an order of magnitude; the characteristics are presented with 8-times vertical scale enlargement). Exposing the high-organic particle to moisture then positioning it on the surface and letting the system dry showed that the adhesive force remained low, and no linking of the organic particle to the surface was evident. This measurement was quite difficult to complete because the particle tended to slide off before the probe could be positioned. Exposing the whole system to moisture was not possible because the water rolled off (high contact angle [33]) taking the dust particles with it. Thus to even get some idea of the adhesion and the force, the particle had to be wet before placed on the surface then dried—a condition that really does not mimic the environmental process experienced in the field. The corresponding dry case for a similar particle on the superhydrophilic surface is presented in Fig. 9f. Again, this coating provides low surface energy—and the adhesive force is small.

The peak-measured adhesive force (as extracted from the bowing of the cantilever, Eqs. 1-3)) provides one quantitative

feature of the characteristics in Fig. 9. The change in ∂x (i.e., the slope of the characteristic line) also indicates the extent of the adherence. The more the cantilever bows, the higher the measured value of ∂x —and this is routinely observed in these measurements. The value of $dF_y/d\partial x$ (the slope of the characteristic line) is expected to be constant for a given cantilever. But the changes in the slope (i.e., for the characteristic of Fig. 9c) can give information on the possible change in k , G , h and λ with $d\partial x$. Also, the change can also reflect some dragging of the AFM tip or change in contact on a securely held particle surface (cases in which these changes are more prevalent). These changes may provide additional information on the adhesion mechanisms, but have not been investigated in this initial study.

One interesting case is illustrated is that of dust particles that are exposed in urban areas or possible for PV arrays close to heavily-trafficked highways/refineries/fuel processing stations. In this case, the soiling can also be complicated by the constant and high exposure to hydrocarbon fuel emissions—such as diesel. This was already illustrated in Fig. 3, for two such soiling particles taken from two areas in Brazil. Figure 3b is from a remote location showing “normal” soiling compositions (with some content associated with indigenous soil and fertilizer components). Figure 3c is from a module mounted close to a road—and the particles have compositions that include high degrees of diesel fuel contamination. These layers, like those with other organics, also bind together to form cement-like films that are bound to the module surface (especially near the edges and frames where accumulation occurs). This is commonly observed for modules in these “urban” field areas, and the hydrocarbon tends to bind the particles together and adhere to the glass itself and the metal frame. This is very difficult to remove (requiring scraping)—and the build-up can cause shading (leading to other reliability issues), as well as loss in power output. The adhesion is illustrated in the 3 characteristics in Fig. 10. The particle from the rural area (Fig. 10a (green)) has typical “dry” adhesion properties. Figure 10b (magenta) shows a particle from near the highway, with some enhanced adhesive force associated with that diesel fuels contaminated surface. The evidence for the presence of the hydrocarbon Fuel is presented in Fig. 11, a Raman spectrum of the sample from which the particle in Fig. 10b is taken. The spectrum shows the presence of several salts (Na, Mg, and Cl based) with

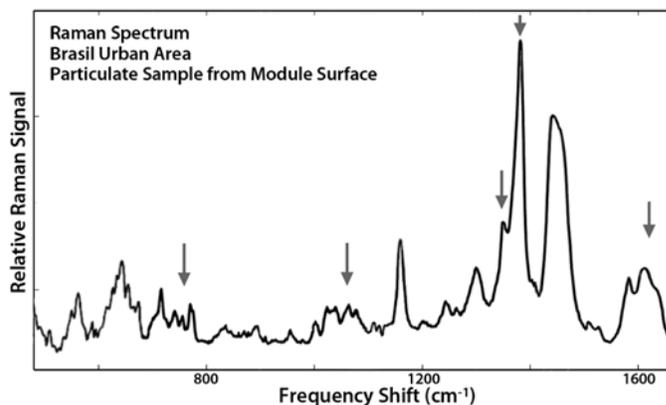


Fig. 11. Raman spectrum for sample of particles collected from module surface in urban area (near vehicular traffic highway) in Brazil. The particles form a cement-like film. The spectrum represents a number of organic species, including diesel hydrocarbon origin indicated by the arrows.

the signature of the diesel fuel components specified by the arrows. This Raman evidence is typical in samples collected from the arrays located in the urban areas in the vicinity of highways heavily trafficked by trucks especially. In order to try to mimic the case in which the particle is exposed to the fuel while is on the surface or before it is deposited on the module surface, we exposed particles to diesel fuel (soaking) on the glass and letting them dry. However, because this processing had to be accomplished outside the AFM chamber, it was very difficult to isolate a suitable single particle. We were able to make one measurement (listed in Table 1)—though the adhesion was so strong that the limit of bowing of the cantilever was reached (i.e., about 400 nN) before the exact force could be measured. (The particle was loosened—actually propelled—from the surface, but beyond the measurement range of the technique.) One interesting case is shown in Fig. 10b (blue). We were able to re-measure the exact particle from Fig. 10b (magenta), showing some degree of reproducibility (about the same characteristic and the same release force).

C. Limitations and Investigation Directions

These first-time studies of the fundamental mechanisms involving the adhesion of dust/soiling particles to the surfaces of PV module materials are preliminary. They are intended to provide qualitative comparisons currently, rather than precise and independent determinations of the adhesive forces. The intent is to provide some insights and confirmations on the forces holding real dust/soiling particles to the surfaces of the solar PV collectors, especially the mechanisms that might be associated with the physical and chemical properties of the particles. The studies provide a proof-of-concept for using this AFM methodology for these fundamental studies. Because these are preliminary evaluations, we also want to investigate the reproducibility, sources of inaccuracies, strengths, and future development needs of these techniques. A particular concern is the potential and usefulness of linking these fundamental, nanoscale studies to furthering understanding of the soiling mechanisms and providing guidance for future solutions to the macroscale soiling problems with these solar technologies.

Reproducibility. There are many factors that can affect or control the adhesive force measured using this technique. The first is the particle surface-glass surface contact area. Most of the particles in this study had (visually) about the same area of contact with the surface of the module glass. We did some preliminary investigations of these potential effects and are presented in Fig. 12. The three particles shown for surfaces having surface concentrations of organics and soluble minerals have relatively small differences in the measured forces. Those for the particles moisture treated before the measurement have a typically much larger spread. However, these results are not sufficient to make conclusions—because we really do not know the exact morphology of the particle surface intersecting the glass—and the determination of the *force-per-unit contact area* might be a better measure. The contact area is more than just simple geometry, but also depends upon the complex morphology and particle surface chemistry uniformity. These determinations are currently underway, with the first estimations relating the mass of the dry particles to the velocity as the particle is pulled across the surface (the downward portion of the characteristic) to indicate the force

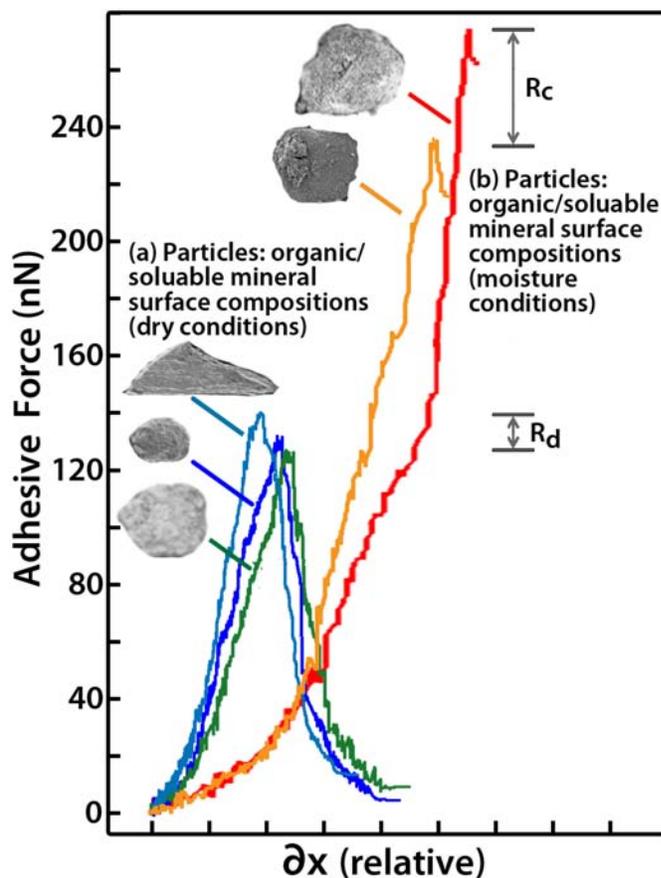


Fig. 12. Comparison of adhesive forces of various single dust particles to examine the potential effects of geometry and morphology on the measurement. Particles in these sets are high organic surface compositions. Cases are for dry (set on left) and for moisture-treated particles (as in Fig. 9b,a).

per unit area of contact. However, there are some initial indications of the reproducibility of the measurement in comparing at least the similar surface chemistries (see Table 1). As indicated, this study presents some *proof-of-concept*—but the results are encouraging for extending these correlations and further developing the methodology.

Probe Location and Geometry. The studies reported here all tried to position the probe at least 1/4-1/3 below the top of the particle. This was decided after some experimental investigation. Because of the length of the AFM tip (Δz in Fig. 1), there was a constraint on how low the tip could engage the particle before coming close to the cantilever. The distance Δz was 20 μm to 100 μm (depending on the particle size), and the particle size with vertical distances to about 150 μm maximum could be investigated for the approximately spherical particles. Otherwise, the side of the tip element would contact the particle, and this would require a more complex analysis of the lateral force than if the particle were driven by the tip alone. We did conduct some investigation of the probe placement. The tip Δz was chosen so that for larger particles, Δz was in the higher length range—and in the lower length range for smaller diameter particles. It seemed that choosing Δz to be about 40% of the particle length avoided possible effects of the mass of the tip for the tips we utilized. *These geometrical parameters, the probe geometry, and the positioning of the tip require additional evaluation for effects on the forces observed*

TABLE I
SUMMARY OF INVESTIGATIONS/EXPERIMENTS SHOWING THE RANGE OF PARAMETERS, INDICATIONS OF THE
REPRODUCIBILITY OF THE TECHNIQUE, AND THE EXPERIMENTAL CONDITIONS

Number of particles investigated	Range of particle size (μm)	Dominant particle surface chemistry	Residing surface (substrate)	Adhesion force range (nN)	Conditions and Comments
22	30-90 μm	Quartzite/Silicates	Glass	60-95 nN	Dry conditions; Morphologies mostly smooth
12	30-120 μm	Organics, secondary salts	Glass	100-160 nN	Dry conditions, Morphologies smooth
14	40-160 μm	Organics, secondary salts	Glass	240-480 nN	Moist conditions; morphologies mostly smooth
4	40-50 μm	Secondary silicates, hydrocarbons (fuels), organics, agricultural residues	Glass	150-220 nN	Dry conditions, uneven morphologies (Brazil)
1	50 μm	Secondary silicates, fuels, organics, agricultural residues	Glass	>400 nN (beyond range of cantilever)	Exposed to alcohol and dried (<i>collected sample exposed to diesel and other fuels/fumes</i>) (Brazil)
4	30-50 μm	Organics, secondary salts	SHB coating	2-8 nN	Dry conditions; morphologies mostly smooth
2	45 μm	Organics, secondary salts	SHP coating	6.5, 12 nN	Dry conditions; smooth morphology

and the validity of the measurement. However, there are some initial indications of the reproducibility of the measurement in comparing at least the similar surface chemistries (see Table 1). As indicated, this study presents some proof-of-concept—but the results are encouraging for extending these correlations and further developing the methodology.

Cantilever Properties. The major critical parameter for the cantilever is that of its “spring constant,” k . This parameter dictates the bowing of the cantilever during the measurement and the force translation. If k were too large (e.g., to about 40 N/m), insufficient bending of the cantilever occurs before the particle was moved—if the adhesive force was small holding the particle in place. If too small (e.g., to 0.15 N/m), the cantilever would bend very much for particles held with high adhesive force (cementitious, for example)—and would not overcome the force holding the particle in place. The cantilever could bend sufficiently to actually intercept or touch the particle—disrupting the measurement. *The k -values of the cantilevers for ascertaining the accuracy of the force measurement need further investigation and definition.* Higher k -values will also provide a path to determine the adhesion force for particles that are highly-bonded to the surface, such as those we encountered with hydrocarbon-rich surfaces (Sec. 3.2). One last measurement concern is the fastening of the AFM tip to the cantilever. This is commonly done with a special adhesive that is sufficient for normal AFM applications. In one case of high adhesive force holding the particle in place, the tip actually detached from the cantilever during the measurement.

Calibration and Anisotropy. It would be valuable to establish a mechanism to calibrate the force measurement. This would help in establishing the effects of the physical parameters just discussed. Several groups have measured lateral forces using mica [34]. The forces are in the range of those determined here. We attempted to use this as a benchmark, but the measurement is anisotropic—and

using this or graphite as a calibration standard needs accurate directional (AFM tip movement) positioning that we did not have. This issue raised concerns on the anisotropic nature of the forces holding particles—something that has some evidence in the insert in Fig.10, with the adhesion for measured 4 times for the same particle (the one from rural Brazil). The measurement for Fig 10a (green) is repeated—showing good reproducibility. Then the sample was rotated about 90 degrees, and measurement was repeated. The particle was separated at a lower force than it has previously experienced—perhaps indicating there is a directional nature to the adhesive force. (The particle was scanned again—with a good reproduction of the initial 90° characteristic.) However, many parameters could influence this difference between the directional scans. It is not known, for example, if the first measurement could have partially altered some of the surface features of the particle before the second measurement was made. The sample geometry could also influence this. Also, the “replacing” of the tip on the particle may invoke the effects of exact tip location, etc. on the particular measurement—and this observation may just be within the experimental uncertainty. At this point, the “anisotropy” investigation is inconclusive—though it did provide some “repeatability” information. *The production of reproducible calibration standards would be extremely important for improving the precision and reducing the measurement uncertainties [18].*

Other issues for consideration. The interest in electrostatic- and electrodynamic-systems for dust mitigation [35,36] provide a noteworthy area of investigation—that of the effects of *particle and surface charge* on the adhesion. The dust particles encountered in the field are charged, but no evaluation of this was attempted in this paper. This is possible for this system, but requires some hardware additions to be able to control, determine, and measure the charge on the particle and control of the surface charge. The surfaces used in this study were all module glass (flat,

un-textured). *Other surfaces* (optical plastics used for CPV lenses, various coated and metal surfaces used in CSP heliostats, organics used in flexible PV, etc.) can also be evaluated. However, the instrumentation has limitations for surface flatness in order to scan the AFM tip.

IV. SUMMARY AND CONCLUSIONS

This paper reports on the first measurements and technique proof-of-concept of the adhesion of individual dust/soiling particles to the surface of module glass at the micro- and nanoscale. The measurement focused on the direct determination of the adhesive force of various particles collected from modules from various geographical regions having different surface chemistries. Some specific contributions and results include:

- A novel configuration AFM adapted as an optical-lever microscope has provided the particle adhesion force through the bowing of the cantilever as the tip pulled on particle (Fig. 1). Laser deflection from top of cantilever with other AFM parameters is translated into the force holding the particle in place through the consideration of the instrument, tip, and cantilever physical properties.
- First determinations of the adhesion of individual dust/soiling particles to module glass surfaces are reported. These adhesive forces were correlated with aspects of the specific surface chemistry of the individual particles evaluated. These measurements correlate with the expectations from the “Cuddihy principles” involving the physical and chemical nature of the substrate surface and the particle [26,27]. The relative adhesive properties were explained in terms of the chemistry and physical nature of the particles. The paper also provided some microscale evaluations of the chemistry and composition, including the mapping and identification of impurities on individual particle surfaces and in the regions binding particles or grains together.
- The “cementation” mechanism observed for dust on module surfaces in the desert regions that experience moisture conditions (e.g., heavy morning dews, high humidity, etc.) was recreated in single-particle experiments. The individual particle were exposed to water vapor and allowed to dry before the adhesive force was measured. Significantly higher adhesion forces were measured due to the bonding of the particles to the glass due to the surface organic/mineral concentrations that chemically bind the particle to the surface under the influence of the water.
- The first observation and report of the “cementation” process involving hydrocarbon fuels (e.g., diesel) from vehicle emissions for arrays installed in urban areas near heavily-trafficked roadways are discussed. The direct confirmation of the hydrocarbon-source bonding of the particles to the module surface are reported using the AFM techniques, with significantly higher observed adhesive forces. The effect is analogous to that moisture (water) has in interacting with particles having organic or other soluble salt surface chemistries [1,5,8,9, 20, 21].
- The positioning of the tip and the possible anisotropy of the adhesion force (the anisotropy of the adhesion of the particle to the surface of the module) has been initially investigated. Some initial observational rules have been noted on the

positioning of the tip. The anisotropy has to be further investigated; the preliminary data was not strong enough to confirm these mechanisms.

- Several limitations, areas of technique development, and future research requirements were indicated and discussed relating to reproducibility of the adhesion measurement technique applied to these dust/soiling particles. The purpose of this initial work has been to demonstrate the viability of determining the fundamental forces holding the particles to module surfaces. These have validated experimental observations of dust issues at the macroscale (on real modules in the field). The critical conditions involving moisture/hydrocarbons and the dust were recreated at the microscale—demonstrating the importance of the particle and surface chemistry on the adhesion mechanisms.

These investigations have provided a proof-of-concept for the evaluation and determination of the forces between dust particles and the surface on which they reside. The preliminary results of these fundamental studies provided direct evidence for importance of chemistry and environmental conditions for the adhesion of dust particles to the solar module surfaces. Certainly, the chemistry of the particles (and surface) have been shown to be critical parameters for the adhesion. It is planned to continue these proof-of-concept investigations to in order to possibly find pathways toward more effective *restorative* cleaning methodologies or the development of *preventative* dust mitigation coatings.

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