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Artificial linear brush abrasion of coatings for photovoltaic module first-surfaces

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Short Abstract:

Artificial linear brush abrasion was examined to explore the durability of representative PV first-surfaces. Specimens examined include silane surface functionalized-, roughened (etched)-, porous silica coated-, fluoropolymer coated-, and ceramic (TiO_2 or $\text{ZrO}_2/\text{SiO}_2/\text{ZrO}_2/\text{SiO}_2$) coated-glass, which are compared to monolithic-poly(methyl methacrylate) and -glass coupons. Characterization methods included: optical microscopy, UV-VIS-NIR spectroscopy, sessile drop goniometry, white light interferometry, atomic force microscopy (AFM), and depth profiling X-ray photoelectron spectroscopy (XPS). The corresponding characteristics examined include: surface morphology, transmittance (i.e., optical performance), surface energy (water contact angle), surface roughness, scratch-width and -depth, and chemical composition, respectively. The study here was performed to determine coating failure modes; identify characterization methods that can detect nascent failures; compare the durability of popular contemporary coating materials; and identify their corresponding damage characteristics; and compare between slurry and dry dust abrasion.

- Correlation between transmittance, yellowness index, surface energy, and surface roughness consistent with history of film degradation.
- Abrasion damage primarily resulted from the facets and edges of dust particles and/or brush bristles, i.e., localized abrasion sources.
- A variety of longevities from 100 cycles to 1000 cycles to 10000 cycles was observed for the representative specimens here.
- Details of the test parameters as well as post examination suggest improvement of the linear artificial brush abrasion method.

submitted to Solar Energy Materials & Solar Cells

Artificial linear brush abrasion of coatings for photovoltaic module first-surfaces

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ABSTRACT

Natural soiling and the subsequent requisite cleaning of photovoltaic (PV) modules result in abrasion damage to the cover glass. The durability of the front glass has important economic consequences, including determining the use of anti-reflective and/or anti-soiling coatings as well as the method and frequency of operational maintenance (cleaning). Artificial linear brush abrasion using Nylon 6/12 bristles was therefore examined to explore the durability of representative PV first-surfaces, i.e., the surface of a module incident to direct solar radiation. Specimens examined include silane surface functionalized-, roughened (etched)-, porous silica-coated-, fluoropolymer-coated-, and ceramic (TiO₂ or ZrO₂/SiO₂/ZrO₂/SiO₂)-coated-glass, which are compared to monolithic-poly(methyl methacrylate) and -glass coupons. Characterization methods used in this study include: optical microscopy, ultraviolet–visible–near-infrared (UV-VIS-NIR) spectroscopy, sessile drop goniometry, white-light interferometry, atomic force microscopy (AFM), and depth-profiling X-ray photoelectron spectroscopy (XPS). The corresponding characteristics examined include: surface morphology, transmittance (i.e., optical performance), surface energy (water contact angle), surface roughness, scratch width and depth, and chemical composition, respectively. The study here was performed to determine coating failure modes; identify characterization methods that can detect nascent failures; compare the durability of popular contemporary coating materials; identify their corresponding damage characteristics; and compare slurry and dry-dust abrasion. This study will also aid in developing an abrasion standard for the PV industry.

KEYWORDS

abrasion, anti-reflective coating, anti-soiling coating, erosion, operations maintenance, PMMA

1. INTRODUCTION

Insolation, temperature, and external contamination are the three primary natural factors affecting electricity generation in solar photovoltaic (PV) devices. Regarding the latter, natural soiling (contamination, including inorganic and organic matter) on the surface of PV modules can gradually reduce performance in the order of $1\% \cdot \text{day}^{-1}$ in the insolation-rich Middle East and North Africa (MENA) region, whereas sudden power drops as high as 70% from discrete meteorological events have been recorded worldwide [1,2]. Strategies for improving performance by limiting soiling include cleaning [3,4] and coatings [4,5]. Anti-reflective (AR) and/or anti-soiling (AS) coatings [6] may be added on the front glass to improve the throughput of incident light and/or to limit the rate and amount of contaminant accumulation. In the history of the development of PV technology [7], AR coatings gained popular use in the PV industry starting in ~2005, whereas AS coatings are presently being explored. A variety of manual and automated methods may be applied for the cleaning of PV modules, typically using equipment very similar to or generally based on that used in the building glazing industry. The longevity of AR and AS coatings is presently uncertain because the coatings may be subject to abrasion damage during cleaning, erosion from airborne particulate matter in addition to certain natural processes (e.g., UV degradation, frost, and precipitation). To provide technoeconomic benefit, the cost of a coating must be sufficiently low, and the lifetime sufficiently long, to justify its use. Lastly, there is a growing interest in standardized tests that may be used to compare or further evaluate coatings used in solar panels. The requirements of the PV application, including decades of outdoor life for a device that absorbs the light of the sun, are highly demanding; therefore, they suggest the need to tailor existing normative abrasion test methods developed by the automotive, building glazing, paint, and textile industries for use with PV modules. This work aims to support the development of an abrasion test standard for the PV industry.

Representative coupon specimens are used in this study to examine the abrasion of PV first-surfaces, i.e., the surface of a module incident to direct solar radiation. Artificial linear machine abrasion using a brush has been investigated. A variety of coating materials, along with variations in the abrasive (slurry and dry-dust), and the bristle have been examined. The critical characteristics of optical performance (transmittance), surface roughness, and surface energy were correlated. The goals of this study include the following:

- Determine coating failure modes.
- Identify characterization methods that can detect nascent failures.
- Compare the durability of popular contemporary coating materials subject to artificial linear brush abrasion.
- Compare the damage characteristics for artificial machine abrasion to those observed in a separate field coupon study.
- Compare the rate and subsequent damage characteristics between slurry and dry-dust abrasion.
- Compare the rate and subsequent damage characteristics for factors affecting abrasion, e.g., the use of bristles only with no abrasive or the use of compliant bristles.
- Support the development of an abrasion test standard for the PV industry.

2. BACKGROUND

Table 1 summarizes standardized test methods that could be applied for artificial machine abrasion for accelerated testing for the cleaning of solar PV, concentrating solar power (CSP), and concentrator PV (CPV) technologies. The table is not comprehensive, but seeks to identify the normative methods most likely to be used for solar energy applications. Table 1 provides an update on relevant machine abrasion methods summarized in Ref. [7], including the characteristics of: the name and number of the test method, industry(s) of origin, type of abrasive (including device and/or grit), size of the abrasive (including the geometry of the device and/or diameter of grit), nominal contact pressure (estimated for the total area of the abrasive device, e.g., brush length times the brush width), stroke length, number of cycles (including for device conditioning, incremental testing, or cumulative testing), and the cycle repeat speed. Although not often distinguished elsewhere, the terms “scrub” and “cycle” are often used interchangeably to refer to the complete motion of the apparatus, including both the forward and reverse strokes in a reciprocating apparatus.

The common fields of origin for the methods in Table 1 include the building, paint, or automotive-window industries. The use of BS EN1096-2 in the PV industry is consistent with the use of modules in building-adapted PV or building-integrated PV. The most common abrasives in the table include a solution (of surfactant, cellulose, and/or grit) or grit-embedded-disc products specific to the various Taber abrasion testers.

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2 The present version of several of the standards are not completely defined (“unspecified”), including the details
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4 of size of the abrasive, contact pressure, swipe length, and the **cycle repeat speed**. Regarding the most recent
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6 Taber tester (used in the standard BS EN 1906-2), it applies a greater contact pressure than the brush tests
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8 (ASTM D2486 and DIN 53778). **It remains to be quantified if the contact pressure used in the brush tests more**
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10 closely resembles the equipment and method used to clean PV modules. **For example**, a modest orthogonal
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12 pressure may be applied when using a water-fed, pole-mounted brush to manually clean a PV module because it
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14 may be cantilevered by a pole during cleaning. A swipe length in the order of meters, however, may be expected
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16 for PV based on the typical size of commercial modules. The conditioning of the cleaning device (e.g., soaking
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18 of brush bristles) is required for several of the brush or scrub tests. Device conditioning may occur during PV
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20 cleaning if a PV cleaning device finds use through an entire work shift. The **repeat speed** of 37 cycles per minute
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22 (cpm) remains as a legacy from early mechanically enabled testers, whereas a capability from 6 cpm to 60 cpm
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24 is now commercially available. One variation that is allowed between brush and scrub testers is the use of
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26 constant velocity through the stroke (with all acceleration/deceleration occurring at the start/end of motion) as
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28 opposed to sinusoidal acceleration and deceleration through the stroke (which makes it easier to adjust the stroke
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30 length). Reference [7] summarizes other abrasion methods based on the use of: manual wiping, water drop
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32 impingement, abrasive shaker box, and a grinding wheel. For example, more aggressive versions of the Taber
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34 abrader in ISO 3537, ISO 15082, ASTM D1044, ASTM G195, and ASTM D4060 are typically applied in the
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36 concrete and metals industries.
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42 Table 2 summarizes artificial machine abrasion studies in the literature of the solar PV, CSP, and CPV
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44 industries. In addition to the authors and references from the literature, the characteristics in Table 2 are the
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46 same as those used in Table 1.
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49 The BS EN 1096-2 standard is most commonly used in the solar energy literature; however, applications
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51 to building-adapted PV or building-integrated PV are not specifically identified by the authors. Based on the
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53 present limited use of building-specific PV, the use of BS EN 1096-2 most likely results from the lack of a PV-
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55 industry-specific standard. Like PV, building glazing products also endure prolonged outdoor use. The most
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57 commonly used abrasives in Table 2 include brush bristles, **Arizona (AZ)** test dust, felt, or grit-embedded-disc
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59 products specific to the various Taber abrasion testers. However, the Taber abrasive products do not necessarily
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2 mimic the characteristics of the equipment used to clean PV modules. The experimental details in several of the
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4 studies were not completely defined (“unspecified”), including the details of size of the abrasive, contact
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6 pressure, swipe length, and the cycle repeat speed. Furthermore, the standardized test methods were not always
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8 performed exactly as specified in the normative method, with some studies being just loosely based on the test
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10 standards (“based on”). The swipe length or repeat speed provide examples where the details in Table 2 vary
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12 from the corresponding standardized test methods in Table 1. The nominal contact pressure for the brush tests in
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14 Table 2 is typically an order of magnitude less than the Taber test (BS EN 1906-2). The true area of contact for a
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16 brush may be more difficult to estimate, which suggests that the Taber test has a greater acceleration factor
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18 relative to field cleaning of PV. Most studies were performed for several hundred or a few thousand cycles. In
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20 comparison, over the course of 25 years, one cleaning per month (a complete sweep, in both forward and reverse
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22 directions) corresponds to 300 cycles; one cleaning per week corresponds to 1300 cycles; and one cleaning per
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24 day corresponds to ~9000 cycles.
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29 Other variables from the PV application were not examined or specified in the existing test standards
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31 and literature studies. The experiments summarized in Table 2 were performed at ambient laboratory conditions,
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33 whereas modules in PV installations can experience a wide variety of irradiance, temperature, and humidity
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35 conditions. However, the weather conditions and corresponding field operating conditions for cleaning are not
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37 standardized, e.g., daytime cleaning may be favored in some locations where manual cleaning is most
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39 extensively used, whereas thin-film PV may be cleaned at night to prevent shading damage. The experiments in
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41 previous solar-focused studies were not used with ultraviolet (UV) weathering or artificial soiling (and/or
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43 subsequent cementation) tests. Similarly, the acid/base chemistry at the surface (known to affect the surface
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45 through the process of glass corrosion [38]) was not explored in previous solar-focused studies. The use of a
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47 rotary brush, frequently used in PV cleaning robots [39], was also not examined in previous solar-focused
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49 studies. Many of the aforementioned limitations result from the use of a test method dedicated strictly to
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51 abrasion; the abrasion tests may subsequently be used as part of a standardized accelerated test sequence to
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53 address some of these concerns.
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58 Although not resolving all of the limitations of the literature, certain details were chosen for the study
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60 here based on Table 1 and Table 2. It was intended to simulate PV cleaning equipment while being mindful of
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existing test standards. For this reason, a linear brush test was selected, knowing that the bristle material in several existing standards is presently being revised toward Nylon 6/12 copolymer. A moderate bristle diameter and shorter bristle length may provide accelerated testing relative to representative commercial PV brush products, i.e., diameter of 0.25–0.50 mm and length of 3–8 cm [31]. The results of a review of the surface contamination observed an average particulate diameter of 15 μm for field-soiled PV modules [40]. A4 test dust, as in Ref. [31], is larger in diameter relative to the size of contamination present on PV in most locations. Lastly, ISO 12103-1 test dust does not account for composition, which may vary at locations throughout the world [42], [43], [44], [45], [46].

3. MATERIALS AND METHODS

3.1 SPECIMENS EXAMINED

Table 3 summarizes the coatings and materials examined in this study. The table identifies: a letter index used to refer to each specimen type; the general type of material used in the coatings (additional material added at the surface, if applicable), including fluoropolymers [47] and ceramics [35]; the thickness of coatings present (if applicable); R_a , the average surface roughness {nm}; AR , the presence of an anti-reflective functionality; $\tau_{d,rs,w}$, the direct representative solar-weighted transmittance of photon irradiance (for unaged specimens) { % } [48], [49]; $\Delta\tau_{d,rs,w}$, the change in $\tau_{d,rs,w}$ for coated specimens, relative to the substrate material { % }; AS , the presence of an anti-soiling coating; CA , the water contact angle { $^\circ$ }; and a general classification for the surface energy, based on the CA . The terms “monolithic” and “no coating” are used to identify where no coating was added. Material A was composed of poly(methyl methacrylate), i.e., solar-grade Acrylite 0Z023 (Evonik Industries AG). Porosity was not readily observed using microscopy for coating B and is therefore believed to be sub-micrometer in size; a range of pore sizes was observed for coating E (including pores in the order of micrometers in size at its surface), which would readily affect its surface roughness. The L specimens were roughened (etch depth of 150 nm) at the surface with subsequent chemical processing to affect both optical performance and surface energy. Many of the coatings were applied to the surface of material J, 3.2-mm-thick Diamant low-iron glass (Saint-Gobain S.A.), which has good durability to solarization (change in transmittance based on the redox state of the glass [4],[51]) and glass corrosion [4],[38] relative to other makes of low-iron float glass. The tin-rich surface of the J glass was verified using a UV light (254 nm) and then laser scribed with

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The surface morphology of select samples was analyzed using an atomic force microscope (AFM, Dimension 3100, Bruker Corp.), operated in tapping mode using Nanoscope V electronics. The radius of curvature of the silicon AC160TS (Asylum Research Corp.) tips used was nominally 7 nm, with an included tip cone angle of 40°. Specimens were measured using 100- μ m-wide $\times$ ~33- μ m-long scans with 512 pixels in each direction (i.e., 196-nm and ~64-nm lateral resolution), which were then processed using the flatten (plane fit) and low-pass filter (3×3 pixel averaging) software features. The scratch depth and width were determined manually for up to five separate scratches within each area scan using the Section tool in the instrument's software for separate area scans obtained on five locations on each coupon.

3.4.5 CHEMICAL COMPOSITION

Chemical composition of select samples was examined using X-ray photoelectron spectroscopy (XPS). The XPS spectra were collected in a PHI VersaProbe III system (ϕ ULVAC-PHI, Inc.) with a hemispherical analyzer. The glass specimen was secured on a sample holder with copper clips to provide good electrical contact. The X-ray beam spot size was 200 μ m in diameter and is sensitive to (sub)surface analysis with a penetration depth of 3–7 nm. Glass is an insulating specimen, so the charging effect has been minimized using a neutralizer. Final instrument calibration was done using the adventitious carbon (C 1s) peak calibrated to 284.8 eV. All peaks of individual elements were fitted and the composition was obtained from integrated peak intensities using the CasaXPS software package (Casa Software Ltd.). The elemental depth profiling was performed using a 1-keV Ar ion sputtering gun. The Ar⁺ ion beam was rastered over a small area of 2 mm $\times$ 2 mm, which is sufficiently larger than the X-ray beam spot diameter of 200 μ m used for data acquisition. The etch rate for the glass specimens was estimated relative to a standard SiO₂ reference material. Including a brief pre-sputter, the XPS data on each sample were obtained with a pass energy of 112 eV and energy resolution of 0.4 eV. The data were acquired with 30-s sweeps, and the number of sweeps per sample were chosen to increase signal to noise.

4. RESULTS AND IMPLICATIONS

4.1 OPTICAL TRANSMITTANCE SPECTRA

Figure 2 shows representative direct transmittance spectra for select specimens in Table 3, including specimens B, E, J, L, P, V, and Z. Data are taken as the average of at least three measurements from coupons with no abrasion testing. The range of λ and τ_d in Figure 2 are chosen to emphasize differences between the

specimens. The τ_d for specimens B, E, L, and P is greater than that of J through most wavelengths in Figure 2, consistent with a positive $\Delta\tau_{d,rsw}$ value in Table 3. The τ_d for Z (dashed in Figure 2 to distinguish from E) exceeds that of J from 450–900 nm. The τ_d for V is less than that of J in Figure 2, consistent with a negative $\Delta\tau_{d,rsw}$ value in Table 3. While not shown in the figure to keep the profiles distinguishable, the spectra for specimen R closely resembles that of P; representative spectra for PMMA may be found in Ref. [55].

The improvement in τ_d for specimens B, E, L, P, and Z is consistent with an AR coating, applied to specimen J (glass with no coating). Specimens B, E, L, and P have a spectral bandwidth broader than that of Z, consistent with the use of a graded refractive index (porous silica or etched surface in Table 3) or a refractive index intermediate to that of air and glass (fluoropolymer). The broad spectral bandwidth for specimens B, E, and P is consistent with that observed by the authors for graded-index coatings in previous studies. Multilayer coatings can be designed to provide enhanced transmittance for the broader range of wavelengths typical to Si PV devices (e.g., 300–1250 nm) [56], [57], but specimen Z is optimized for use with CdTe PV (i.e., spectral response from 350–850 nm) [50]. As identified in Table 3, the τ_d of coating V is reduced relative to uncoated glass because the n of TiO_2 is greater than that of glass. Specimen V is coated on a different float glass than specimen J, where the greater Fe content is evident from the absorptance peak (transmittance minima) at 1050 nm for the spectrum of V in Figure 2. The spectral bandwidth for specimens Z and V is limited (relative to the graded-index coatings), consistent with the use of AR coating based on destructive interference [6].

4.2 ABRASION RESULTS (IN GENERAL)

Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, and Figure 10 show the trends in the measured characteristics for specimens subject to artificial linear brush abrasion. Characteristics in the figures include: $\tau_{d,rsw}$ [%] ([48], shown relative to that of uncoated glass, for a specimen with no abrasion); YI {dimensionless} (although no discoloration is expected from abrasion, YI is proportional to the optical scattering); surface energy (CA {°}, the contact angle for water); and surface roughness (where R_a {nm}, the average roughness is the most commonly reported statistic). The same range of variation is examined in the figures, including for $\tau_{d,rsw}$ (range of 15%), YI (12), CA (140°), and R_a (up to 100 nm). For specimen J, values for $\tau_{d,rsw}$ and YI do not change within the variation of measurement. Specimens A, B, E, J, L, P, and R are compared in Figure 3, Figure 4, Figure 5, and Figure 6 for slurry and dry-dust abrasion ($n \leq 5000$), and specimen P is

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2 compared in Figure 7 and Figure 8 for wet and dry abrasion (both with and without test dust) and with the soft-
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4 bristle brush (for slurry only) ($n \leq 20000$). Specimens V and Z are examined for slurry abrasion in Figure 9 and
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6 Figure 10. Specimen J serves as a common reference in all of the aforementioned figures.
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9 To enhance clarity and minimize the number of figures in this manuscript, only the averaged data is
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11 shown in Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, and Figure 10. Additional figures
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13 that identify the variation of the measurements are shown in Figures C-N in the online Supplemental
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15 Information. The $\tau_{d,rsw}$ in Figure 3, Figure 4 Figure 5, Figure 7, and Figure 9 is shown relative to the
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17 transmittance of glass with no coating and no abrasion (sample J at 0 cycles). In the Supplemental Information,
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19 $\tau_{d,rsw}$ is also shown in Figures C, D, G, H, K and M relative to the initial transmittance of each specimen (each
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21 sample type at 0 cycles).
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25 4.3 SLURRY AND DRY-DUST ABRASION FOR SPECIMENS A, B, E, J, L, P, AND R

26 The most overt changes for the slurry experiments in Figure 3 and Figure 4 occur for specimen A
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28 (monolithic PMMA), where τ_d decreases with a corresponding increase in YI and R_a . The final values of τ_d and
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30 R_a for specimen A are -11.1% and 263 nm at 5000 cycles (off the scale of the figures). For specimen E (porous
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32 SiO₂ coating), a local maximum in YI occurs at 25 cycles, preceding a decrease in CA after 50 cycles that occurs
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34 before the maximum in R_a at 100 cycles. For specimen L (roughened surface), simultaneous local maxima in CA
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36 and R_a occur at 50 cycles. For specimen P (polymer coating), a maximum in R_a at 10 cycles occurs while CA
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38 decreases through the experiment. For specimens B (porous SiO₂ coating) and R (silane surface chemistry), the
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40 CA decreases through the experiment with no overt change in the other characteristics examined.
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44 For specimen A in the dry-dust experiments in Figure 5 and Figure 6, τ_d and R_a change outside the range
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46 of values observed for the other materials, finishing at -12.9% and 117 nm, respectively. For dry-dust, the onsets
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48 in changes in τ_d , R_a , and YI for specimen A occur at 10 cycles, which is sooner than with slurry (25 cycles). For
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50 specimen E, a maximum in YI occurs for specimen E at 25 cycles in Figure 5, as in Figure 3. The maximum in
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52 R_a for specimen E occurs at 50 cycles in Figure 6, whereas the maximum occurs at 100 cycles in Figure 4. For
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54 specimen L, a maximum in CA at 25 cycles followed by loss of R_a after 50 cycles is seen in Figure 6. For
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56 specimen R, a more sudden loss of CA is observed in Figure 6 than in Figure 4. More overt changes in R_a and
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variation in the R_a are seen for the dry-dust test than for slurry for specimens B, E, L, and J, Figure 6 and online Supplemental Information. As in Figure 4, the CA for specimen P decreases through the experiment in Figure 6.

Regarding Figure 3, Figure 4, Figure 5, and Figure 6, specimen A is the most affected, including the characteristics of τ_d , YI , CA , and R_a . In the slurry and dry-dust experiments, specimen A is therefore considered an informal working reference material. For specimen A, E, and L, the onset and magnitude of degradation are greater for dry-dust than slurry. The density of dust deposited per abrasion cycle was similar ($13.5 \text{ mg}\cdot\text{cycle}^{-1}$ for slurry, $14.7 \text{ mg}\cdot\text{cycle}^{-1}$ for dry), so this identifies the greater propensity for damage for dry-dust than for slurry. That is, the greater change in R_a in Figure 6 (and the variation in R_a) relative to Figure 4 is not proportional to the 9% greater density of dry-dust used in the experiments. The specimens abraded with slurry may be less affected if water acts as a lubricant and facilitates heat transfer during testing. One key distinction between the experiments is the greater variability of deposition for dry-dust, which may contribute to the variability of the results, e.g., sudden loss of contact angle for specimen R in Figure 6. This variability may result from the propensity of the dry-dust to stick together even at ambient laboratory conditions, as observed in electron microscopy (not shown). A loss in CA was observed at or before an increase in R_a or a decrease in $\tau_{d,rsf}$ for almost all specimens. Only for specimens E (with slurry) and R (with dry-dust) does a decrease of $\tau_{d,rsf}$ precede a decrease in CA . Overall, initial changes in CA and R_a are well-correlated, beginning at the same or adjacent numbers of cycles. Therefore, CA or R_a could be used as early indicators of coating degradation. This correlation between surface energy and roughness follows for materials with a film thickness or surface roughness. A coating thickness (or initial surface roughness) may enable an increase in R_a , as seen in Figure 4 and Figure 6. In comparison, materials with only a surface-chemistry or surface-functionalization (i.e., R) showed only a decrease in contact angle (increased surface energy) through the study. The CA and R_a results suggest that the longevity of the materials examined in Figure 3, Figure 4, Figure 5, and Figure 6 is in the order of 50 to 200 cycles for the test methods used in this study. Specimen J (glass with no coating) shows a gradual decrease in CA and increase in R_a through 20000 cycles in this study, Figure 4, and Figure 6. This behavior contrasts with results from a previous study [4] where CA and R_a exhibited more complex trends, which were attributed to the tribological deposition of a surface layer.

4.4 SPECIMEN P—THE EFFECT OF ABRASIVE AND BRISTLE DIAMETER

The abrasion of specimen P (polymer coating) is shown as a function of the various characteristics in Figure 7 and Figure 8. Experiments in the figure include the abrasive present (dry-dust P_{Dry} , slurry P_{Wet} , dry with no abrasive P_{Dry} (No Abrasive), wet with no abrasive P_{Wet} (No Abrasive) and the bristle type used with slurry (standard brush and soft-bristle brush P_{Soft} Bristle-Slurry). Little change is seen in the τ_d and YI of specimen P in Figure 7, except for dry-dust, where τ_d begins to decrease after 10 cycles. A larger distinction between the experiments is seen for CA and R_a in Figure 8. The characteristics of specimen P in Figure 7 and Figure 8 (including YI , CA , and R_a) asymptotically approach the characteristics of specimen J (the glass substrate with no coating).

Changes in CA and R_a in Figure 8 are summarized in Table 5. For the five experiments in the table, the number of cycles where the onset of a decrease in CA as well as the number of cycles where the occurrence of a local maximum for R_a are identified. No local maximum in R_a was observed for P_{Dry} and P_{Dry} (No Abrasive), indicated as “not observed” in Table 5. A similar analysis is described in the discussion of Figure 4, Figure 6, Figure 8, and Figure 10 but is not formally summarized in a table. A correlation between CA and R_a is seen in Figure 8 and Table 5 for P_{Wet} , P_{Wet} (No Abrasive), and P_{Soft} Bristle, where the onset of the decrease in CA occurs at the maximum for R_a (i.e., 10 cycles for P_{Wet} or 100 cycles for P_{Soft} Bristle, and P_{Wet} (No Abrasive)). It is unclear if the absence of local maximum for P_{Dry} and P_{Dry} (No Abrasive), results from the timing of the measurement read points relative to coating degradation or a different degradation behavior for those experiments.

A finite coating thickness (i.e., coating greater than a few nm) may be necessary to observe a change in R_a when the coating becomes extensively damaged. Regarding the dry-dust and slurry abrasive, these are seen to result in a similar longevity, in the order of 50–200 cycles. The longevity of the coating, however, is increased in the order of 100–1000 cycles if no test dust is used. As in Ref. [26], this suggests the majority of damage results from the test dust, which acts as an abrasive when used in the brush test. The greater longevity of specimen P when a soft-bristle brush is used (P_{Soft} Bristle) suggests that abrasion can be reduced by choice of equipment (including soft bristles). The greater change in τ_d for dry-dust in Figure 7 may result from remaining contamination (where dry dust may have a greater propensity to stick to specimen P), which was qualitatively observed in the microscope images. In Figure 8, the onset of damage occurs at one order of magnitude greater for the soft-bristle brush than for the standard brush. Lastly, the results for CA in Figure 8, which converge toward the CA of specimen J, are consistent with the removal of a surface coating.

4.5 SPECIMENS V AND Z—SLURRY ABRASION RESULTS

Figure 9 and Figure 10 summarize experiments examining the durability of specimens V and Z, where the specimens consist of solid dielectric coatings on glass. All results are shown for slurry testing, including specimens P and J, which are shown for reference. For specimen V (TiO_2 coating), $\tau_{d,rsw}$ decreases during the first 1000 cycles, perhaps due to roughening of and increased optical scattering at the surface. Beyond 1000 cycles, however, $\tau_{d,rsw}$ increases, YI decreases, CA exhibits a maxima, and R_a increases as the coating is removed. For specimen Z (stacked metal-oxide coating), $\tau_{d,rsw}$ and YI decrease and subsequently recover beyond 1000 cycles, whereas R_a increases and subsequently recovers beyond 5000 cycles. The CA for the coated specimens in Figure 10 is seen to converge toward that of specimen J (glass with no coating). Scratches and increased contrast (both brightness and color) were observed in the microscope for specimen Z at 5000 and 10000 cycles, whereas a lighter uniform appearance was observed at 20000 [52].

Evidence of correlation between optical performance, surface energy, and roughness is observed in Figure 9 and Figure 10 for specimens V and Z. These changes are attributed to the localized deterioration (scratching) and destruction of the surface coating. For example, the increase in $\tau_{d,rsw}$ in Figure 9 for specimen V beyond 1000 cycles indicates erosion and removal of the TiO_2 coating. From Figure 2, the YI of ~ 8 in Figure 9 follows from the limited transmittance of specimen V at UV-VIS wavelengths, with the decrease in YI beyond 1000 cycles indicating erosion of the coating. As in Figure 8, the results for CA in Figure 10, which converge toward the CA of specimen J, are consistent with the removal of a surface coating. As in Figure 4, Figure 6, and Figure 8, CA is reduced in Figure 10, indicating a greater hydrophilicity with increasing n for the artificial brush abrasion test. Relative to the surface treatments, surface functionalizations, and coating materials in Figure 3, Figure 4, Figure 5, and Figure 6, a greater durability is observed for the solid dielectric coatings, including specimen V (which deteriorates at 500–1000 cycles) and specimen Z (which deteriorates after 1000–5000 cycles). The change in appearance at 5000 and 10000 cycles with recovery at 20000 cycles suggests the loss in performance for specimen Z results from abrasion damage and/or contamination of the coating, with recovery after the coating is destroyed. Although not verified in this study, the greater durability of the ceramic coatings is presumed to correlate to their greater mechanical hardness relative to the other specimens.

4.6 OPTICAL MICROSCOPY AND SURFACE MORPHOLOGY

Representative micrograph images demonstrating the deterioration and loss of the coating for specimen P are shown in Figure 11. Separate specimens are shown including those abraded for: (a) 0 cycles, (b) 10 cycles, (c) 25 cycles, and (d) 50 cumulative cycles for specimen P in the slurry experiment in Figure 3 and Figure 4 (the same as P_{wet} in Figure 7, Figure 8, Figure 9, and Figure 10). As generally verified using AFM in the related field coupon study [5] and then in this study [52], bright linear features that correspond to scratches are observed in Figure 11 (b). Dark linear features that correspond to remaining coating are observed in Figure 11(c) and Figure 11(d). Although not shown here, a similar morphology was observed (sometimes at very different cycle count) for specimens B, E, L, P, V, and Z (for both slurry and dry-dust, where applicable). A similar damage morphology (with localized scratches at low cycle count) accumulating up to the removal of the coating (as evidenced by the lack of visual features consistent with the coating at high cycle count) was generally observed between the specimens. Individual dark linear features, consistent with localized scratching of the glass substrate, were observed at high cycle count in dry dust and slurry testing, e.g. 100 cycles and 5k cycles. In the case of specimen L, optical microscopy and AFM revealed scratches of the roughened specimen surface through the experiment, even though no surface coating was used.

The morphology in Figure 11 identifies the initiation and subsequent accumulation of surface damage prior to coating failure. Optical microscopy was helpful in this study to qualitatively verify the evolution of the characteristics of τ_d , YI , CA , and R_a . The formation of a network of scratches followed by the loss of the coating is consistent with the correlation between τ_d , CA , and R_a observed in the experiments for specimens B, E, L, P, V, and Z. From Figure 11, τ_d and YI are affected when scratches result in optical scattering. CA is affected by the surface chemistry and surface roughness. R_a is greatly increased as the coating accumulates scratches, e.g., Figure 11(b) and Figure 11(c). The distinct change in τ_d , CA , and R_a in some of the experiments suggests sudden, catastrophic coating failure. Although an increase in R_a is not always observed, the occurrence of a local maximum in R_a in some experiments in this study may indicate fortuitous observation (at an appropriate number of cycles) for specimens with a coating of measurable thickness. In the case of specimen L, presumably the change in performance characteristics corresponds to the smoothing of the surface by the linear abrasion tester.

The scratch morphology of select specimens is summarized in Table 6. In the table, the minimum, average, and maximum values are given for w_s , the scratch width { μm }, and for h_s , the scratch depth (relative to

the specimen surface) $\{\mu\text{m}\}$; in addition, h_n , the nominal coating thickness $\{\mu\text{m}\}$, is repeated from Table 3. Results are given in the table for specimens after 10 cycles of dry-dust or slurry abrasion for specimens B, E, L, P, and J. Additional results are given for specimen P for wet-brush (water with no dust), dry brush (no dust), and the soft-bristle brush (used with slurry). The minimum and average w_s in Table 6 is typically in the order of micrometers, whereas the average and maximum h_s is typically in the order of tens of nanometers. In comparison, the minimum, average, and maximum diameter of 2 μm , 14 μm , and 85 μm were reported by the vendor for the A3 AZ test dust used in this study. The maximum w_s in Table 6 varied between specimen types and test conditions, indicating that a wide range of scratches was observed, particularly for the scratches of greatest width. The maximum h_s approaches or exceeds the nominal coating thickness for specimens B, E, and P in Table 3. The average h_s , however, is typically less than the thickness of the coatings used in this study. Both w_s and h_s are similar for specimen P with dust (slurry and dry-dust) and without dust (wet-brush and dry-brush). The w_s was reduced for the soft-bristle brush on specimen P, whereas the h_s was comparable to the other experiments for specimen P. Representative images from the experiments may be found in Ref. [52]. From side-by-side comparison, the relatively wide scratches for the dry-brush and wet-brush experiments as well as the relatively narrow scratches for the soft-bristle-brush experiments stand out relative to the other experiments. The w_s and h_s in Table 6 may be compared to a recent field coupon study [31], where specimens B, E, and J are examined after 12 cycles of dry-brush cleaning in soiling-prone world locations.

From h_s in Table 6, many of the scratches do not extend through the thickness of the coating (for coated specimens). Furthermore, w_s approaches the minimum size of the A3 test dust used in this study and is significantly less than the 300- μm diameter of the brush bristles. The damage in Table 6, where h_s often does not exceed h_n , is consistent with the initial surface abrasion of the specimens, i.e., $n = 10$. The similar scratch morphology with and without dust for specimen P identifies that facets or edges of the dust and/or bristles facilitate abrasion damage. In addition to Table 6, Figure 5 and Figure 6 show that degradation accumulates more rapidly when dust is present, which may result from the greater hardness, sharpness (i.e., limited contact area), and number of surface features arising from dust particles. Scratch width and depth should depend on the applied force, contact area, and surface hardness. Therefore, the observation of narrow scratches on the hardest surface (specimen J) and when using the softest bristles is qualitatively consistent with tribology theory.

The scratch morphology of specimens B, E, and J was also examined in the field coupon study in Ref. [31], where the average w_s was observed to range from 7.3–12.7 μm for specimens B, E, and J, with a comparable scratch depth observed for both field and artificial abrasion. A significant spacing between scratches was also observed in the field coupons, which identifies that degradation occurs through prolonged localized abrasion, according to the process of initiation, damage accumulation, and then film destruction. Differences between the field and artificial abrasion may result from the different contamination (abrasive) present, brush geometry, bristle material, and different contact pressure applied in the studies. However, the scratch morphology is similar between the brush abrasion in this study and that applied in the field coupon study, as might be expected for the process of initial scratch formation. The similar morphology between specimens gives hope that an acceleration factor might be identified to compare the artificial abrasion in this study relative to the final results of the field coupon study.

4.7 CHEMICAL COMPOSITION OF UNCOATED GLASS

Depth-profiling composition is shown for specimen J samples: unabraded and after 20000 cycles of dry-dust testing in Figure 12 and Figure 13, respectively. Elemental composition is identified for calcium, sodium, magnesium, aluminum, iron, and tin. Silicon and oxygen were quantified, but elemental values (24% atomic concentration for Si and 46% for O in the bulk of the glass) are not shown in the figures. The elements Ca, Na, and Mg (known components of float glass [38]) are observed for specimen J in Figure 12 and Figure 13. From the concentration of Mg, the composition of the glass is seen to be asymptotic in both figures at the subsurface depth of ~ 40 nm. Differences between the specimens include the greater concentration of Sn for the unabraded specimen (seen to peak at the surface in Figure 12) and the greater concentration of Al for the dry-dust abraded specimen (seen to peak at the surface in Figure 13). A lesser increase in Al was observed for specimen J after 20000 cycles of slurry abrasion, Ref. [52], see also online Supplemental Information. Carbon is observed only at the surface of the glass with no abrasion testing in Figure 12, but it extends up to 20 nm into the surface of the dry-dust abraded glass in Figure 13. No increased concentration of Fe is observed for the dry-dust abraded specimen in Figure 13, in contrast to the observations reported in a previous study [31], [59].

The elements Ca, Na, and Mg are known components of float glass [38]; therefore, their presence in the bulk of specimen J is expected. Some variation in the concentration of mobile ion species is seen between Figure 12 and Figure 13, particularly for Ca. In retrospect, more accurate compositional analysis of soda-lime

glass may be achieved using ion milling with C60 (as opposed to the Ar^+ ion beam used in this study), because the penetration depth of milling ions and resulting migration of mobile ions in glass is suppressed by the larger particle size of C60 relative to Ar ions [58]. Sn observed at the surface in Figure 12 is consistent with float glass, where the test surface of the unaged specimen J sample has a Sn-rich surface layer that extends beyond 75 nm. Conversely, the lack of Sn in Figure 13 suggests surface wear of at least 75 nm for the dry-dust abraded sample after 20000 cycles (as separately observed in Ref. [31]). Consider the increase in R_a of more than 10 nm for sample J after 20000 cycles in Figure 4 relative to the outer surface of the glass, where the majority of the Sn in Figure 12 occurs up to 10 nm from the surface. The presence of Al at the surface of wet- and dry-abraded specimen J samples presumably results from Al_2O_3 , a known component of the AZ test dust. A previous study [59] suggested that the presence of Al and Fe at the surface results from the tribological deposition of a layer of surface contamination [60]. The presence of carbon just at the surface in Figure 12 is consistent with carbon surface contamination, typical for specimens in a laboratory environment, that is rapidly removed by sputtering. Removing chemically absorbed carbon from the surface (like that seen in Figure 12) would increase the surface energy and decrease the water contact angle. In Figure 13, however, carbon is seen to penetrate ~10 nm into the glass, which may result from the increased aggressiveness of the abrasion test method (as it was likewise observed for dry-brush testing in Ref. [58], see also online Supplemental Information). The surface is expected to have been cleaned of contamination by abrasion, with subsequent re-accumulation of an outer carbonaceous layer in the ambient during the relatively longer time between CA and XPS measurements. The lack of Fe at the surface of the brush-tested specimens suggests that the tribological deposition of components of the AZ test dust are reduced in this study relative to Refs. [31] and [59], i.e., by the use of longer brush bristles and A3 abrasive. As shown in Ref. [59], the use of water was previously found to reduce the tribological deposition of a surface layer [5]. The use of water with cleaning of PV systems, however, presently depends on the operations and maintenance practices at each PV installation.

5. DISCUSSION

The correlation between the characteristics of transmittance, yellowness index, surface energy, and surface roughness provides insight into the degradation of the coated specimens. The change in characteristics is consistent with the processes of damage initiation, damage accumulation, followed by destruction of the film, with the eventual convergence of τ_d , YI , CA , and R_a to those values observed for the glass substrate. The AFM

results in Table 6 and optical microscopy images in Figure 11 support this mechanism; individual scratches form first from the sharp features and corners of the abrasive (test dust) and/or brush bristles. As observed directly by optical microscopy, localized damage is accumulated with additional abrasion cycles. The cleaning of the surface (removal of an outer carbonaceous layer that is more hydrophobic than clean glass) would likely occur immediately based on local surface contact with bristles and/or dust. For specimens with surface films (i.e., specimens B, E, P, V, and Z in this study, which have a coating thickness of at least tens of nanometers) damage accumulation (as the coating is abraded) leads to a maxima in roughness along with a corresponding reduction in contact angle (increased surface energy) and a simultaneous change in τ_d and YI . Subsequent abrasion results in the destruction of the coating, revealing the smoother glass substrate, with convergence of the characteristics of τ_d , YI , CA , and R_a to those values observed for glass. Additional abrasion would then occur across the surface of the glass. For most specimens, changes in the surface wettability as measured by CA —and to a lesser extent, changes in R_a —precede degradation of optical performance and can be used as early indicators of coating degradation. The characteristics of τ_d , CA , and R_a proved helpful in assessing specimen integrity (particularly for coatings with a thickness), but the evaluation of performance in the field may include other characteristics not examined in this study, e.g., roll-off angle [61,62]. The natural environment contains a greater variety and complexity of chemistries and contaminants than A3 test dust and surfaces may be affected by other factors such as UV degradation of functionalized surface chemistry. Nonetheless, the correlation between the characteristics of interest here, as well as the optical microscopy results, identifies the general process of the degradation of a coating and/or surface functionalization from the linear abrasion test.

The characteristics of YI and λ_{cUV} , which can be acute indicators of damage in UV weathering, are alternate- and not-recommended-characteristics for linear brush abrasion, respectively. YI and λ_{cUV} were examined in this study to assess their usefulness for the characterization of brush abrasion. YI is determined from 300-830 nm [48], where the shorter UV-VIS (“blue”) wavelengths are most prone to being affected by optical scattering, e.g., because the refractive index of the substrate and coatings are greater at these wavelengths. Furthermore, scattered light is not readily recovered in a τ_d measurement, as used in this study. YI could, however, also indicate specimen discoloration if test dust became trapped in pores or embedded in a soft surface coating. The change in YI was in the order of 0 to 2 units for most specimens (not readily perceptible to

a human observer), with the maximum of 4 units for specimen A (PMMA). The limited change in YI in this study may result from the large feature size relative to the wavelengths of light examined (w_s is in the order of micrometers or tens of micrometers in Table 6) as well as the localized nature of the damage (where micrometers or tens of micrometers may exist between scratches in many specimens). In contrast, Rayleigh scattering gives measurable effect with a strong wavelength dependence of the scattering ($\sim \lambda^{-4}$) below the wavelength of ~ 500 nm for features approaching 0.5 nm (i.e., the surface roughness, but not lateral scratches in this study) [63]. The observed changes in $\tau_{d,rs}$ and YI therefore most likely follow from roughening of the surface in this study. While a modest change in YI is observed in this study, YI could be used as an indicator of surface roughness, if R_a measurements were not available. A shift in λ_{cUV} could indicate a change in thickness or even the complete loss of a coating, based on its optical performance relative to that of the underlying substrate. While not shown, the change in λ_{cUV} was in the order of 0 to 1 nm for most specimens, with the maximum of 6 nm for specimen V (TiO₂). The limited change in λ_{cUV} suggests that the reflectance of the coatings cannot be distinguished at the UV cut-off for the specimens examined in this study.

Additional evidence identifies that damage initiation and the eventual destruction of the coatings in this study result from localized damage rather than a generalized thinning of a surface layer. No overt shift in the spectral region of greatest transmittance and no change in λ_{cUV} was observed for specimen Z in the experiments in this study [52]. This is consistent with localized damage of a stacked dielectric film coating (which operates based on destructive interference [6]), rather than a uniform thickness reduction. Similarly, attenuation at all wavelengths with no overt change in λ_{cUV} with the number of cycles was observed for the porous silica coatings B and E [52]. This is consistent with localized damage of graded-index coatings. The increase in R_a with abrasion for specimen E (which had the greatest increase in R_a of the coated specimens examined) may follow from the destruction of individual micrometer scale pores (with corresponding generation of silica debris). In contrast, specimen A (monolithic PMMA) provides an example of the change in characteristics associated with bulk material removal. PMMA is softer than glass (specimen J) and the dielectric coatings, making it generally more vulnerable to cutting and abrasion damage. Importantly, the specimens with a coating are not thick enough to realize a gradual wear (with a net change in thickness), unlike specimen A, because scratches tend to penetrate a substantial portion of thickness of the coating. Therefore, the accumulation of localized damage

dominates the degradation of the specimens with a coating (specimens B, E, P, V, and Z). Damage to the coatings might be analyzed using a machine cutting tool model (to represent localized erosion) rather than an analysis based on the tribological wear of a bulk material (best suited to specimen A in this study).

In a previous abrasion study [31], the accumulation of dust on the glass surface was observed. However, in the present study, modifications made to the test method essentially eliminated the incorporation of test dust into the glass substrate, as verified by XPS depth-profile results (see supplemental information in Ref. [52]). This improvement of the linear artificial brush abrasion method relative to previous study [31] may be attributed to the size of the A3 test dust used in this study [41], which is known to be more similar to the particle-size distribution of contamination observed on fielded PV modules [31], [42], [43] than the A4 dust used in the previous study [31]. Details of the brushes used in this study, including bristle length and diameter, are known to be more similar to commercial PV cleaning equipment [31] than brushes used in existing test standards from other industries [10],[11]. The abrasive and bristles used in this study are believed to reduce the tribological deposition of a surface layer, which is not a necessarily representative result of the cleaning of PV modules.

The linear artificial brush abrasion method in this study, however, still has some limitations. Commercial Nylon bristle brushes are marketed for the cleaning of PV, but other materials and cleaning equipment are presently used to clean PV systems. Some alternate bristle materials including synthetic and natural fibers are explored in Ref. [31], and some alternate cleaning equipment, including water spray and squeegee, are explored in Ref. [5]. Alternate cleaning equipment can include sponge, microfiber fabric, or feathers. Furthermore, the use of rotating cleaning equipment is presently popular in robotic cleaning systems. Although initial abrasion is compared between this study and field coupon specimens in Ref. [31], greater correlation remains to be established. Validation should include a confirmation of the degradation modes (and corresponding damage morphology) as well as the determination of a site- and equipment-specific acceleration factor for the test method. The limitations of equipment-, method-, and site-specific validation need to be addressed through continued study in the PV industry.

6. SUMMARY

The linear artificial brush abrasion of popular types of anti-reflective and anti-soiling coatings used in the PV industry was examined. Coated specimens and substrates with no coating (including float glass and PMMA) were examined after slurry or dry-dust abrasion. Key results include the following.

Overt correlation was observed between the characteristics of transmittance, yellowness index, surface energy, and surface roughness, particularly for specimens with coatings that measure at least tens of nanometers in thickness. The change in these characteristics was consistent with the processes of damage initiation, damage accumulation, followed by destruction of the film, and subsequent abrasion of the substrate—with the eventual convergence of the characteristics of interest to those values observed for the glass substrate. Changes in contact angle (and often, also the surface roughness) were observed to precede degradation of optical properties, indicating that those characteristics may be used for the initial detection of coating degradation **from artificial abrasion**. Furthermore, quantitative change in the characteristics of interest was found to correspond to qualitative observation **with** an optical microscope. The process of abrasion for the coated specimens was consistent with localized damage across the surface, followed by widespread deterioration of surface coating. Damage to the coatings might be analyzed using a machine cutting tool model (to represent localized erosion) rather than an analysis based on **uniform** tribological wear of a bulk material.

Abrasion damage primarily resulted from the facets and edges of dust particles and/or brush bristles, which provide localized abrasion during brush testing. The morphology of the initial damage (scratch width and depth) was similar when dust was or was not present. The smaller-diameter (“soft”) bristles were observed to delay the onset of coating degradation and may offer an approach to extending the lifetime of solar glass coatings should they prove effective for removing dust. A similar initial scratch morphology (except with scratches often narrower in width) was observed when smaller-diameter bristles were used. For the same coating material, the number of cycles to achieve comparable damage was increased from dry-dust, slurry, dry-brush (no abrasive), soft bristle (slurry abrasive), to wet-brush (no abrasive), respectively, distinguishing between the use of water as well as the test dust. The aforementioned comparison also identifies the significance of the equipment (e.g., bristle geometry) used for accelerated abrasion testing.

The similar scratch-width and -depth observed between the artificial abrasion specimens in this study and the separate soiling field coupon study, suggests the same damage mechanisms (local cutting from facets

and edges of dust particles and/or brush bristles). The significant spacing between scratches also observed in the field coupons, identifies that degradation also occurs through prolonged localized abrasion, according to the process of initiation, damage accumulation, and then film destruction. The similar morphology between specimens gives hope that an acceleration factor might be identified to compare the artificial abrasion in this study relative to the final results of the field coupon study.

A variety of longevities from 100 cycles to 1000 cycles to 10000 cycles was observed for the specimens examined here, including: surface-functionalized, surface-roughened, polymer-coated, porous silica-coated, and metal-oxide-coated glass substrates, with the greatest durability to abrasion observed for metal-oxide-coatings. The details related to durability are presumed to depend on characteristics including mechanical hardness, thickness, and abrasion/cleaning method. The durability of some specimens was consistent with use in western locations, i.e., a few cleanings per year—up to 300 cycles—or where the surface properties of the coating (e.g., surface energy) effectively reduce soil accumulation. The durability of some specimens was consistent with use in more challenging locations (e.g., MENA), where daily cleaning may be required—in the order of 9000 cycles. Because the cleaning operations for PV modules can vary greatly with the installation for reasons including the level- and composition- of contamination, longevities of 300 cycles or 9000 cycles may be appropriate in different installations. The best coating material (or even the choice to use a coating material) may therefore depend on a technoeconomic analysis that is location specific (for challenging locations), material specific (if a module manufacturer chooses between a limited set of coating materials) and/or maintenance specific (including the cleaning equipment and frequency).

Details of the test parameters as well as post examination suggest improvement of the linear artificial brush abrasion method relative to previous study [31]. The size of the A3 test dust used in this study is known to be more similar to the particle size distribution of contamination observed on fielded PV modules. Details of the brushes used in this study are known to be more similar to commercial PV cleaning equipment than brushes used in existing test standards from other industries. Furthermore, composition analysis suggests that the tribological deposition of a surface layer has been greatly reduced for the method in this study. However, equipment-, method-, and site-specific-validation as well as the corresponding site-specific acceleration factor for the test method remain to be established.

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8. CONFLICT OF INTEREST

The authors declare no conflicts of interest. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. government. Instruments and materials are identified in this paper to describe the experiments. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology or NREL. The U.S. government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. government purposes.

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Figures:

Figure 1: Representative images of the experimental configurations, including: (a) isometric view of the slurry tester, (b) isometric view of the dry-dust tester, and (c) top-down view of an abraded specimen. Key components are labeled in the figure.

Figure 2: Representative direct transmittance spectra (obtained with no integrating sphere) for select specimens with no abrasion. A subset of the transmittance (measured from 0%–100%) and wavelengths examined (measured from 200–2500 nm) are shown.

Figure 3: Slurry test – optical measurements: comparison of the change in transmittance (i.e., coating optical performance) and yellowness index (which may vary with optical scattering) with the cumulative brush-cycle count ($n \leq 5000$) for select coatings for artificial linear brush abrasion. The experiments in Figure 3 and Figure 4 compare specimens with a variety of surface treatments, surface functionalizations, and coating materials.

Figure 4: Slurry test – surface measurements: comparison of the change in surface energy (contact angle for water) and average surface roughness with the cumulative brush-cycle count ($n \leq 5000$) for select coatings for linear abrasion.

Figure 5: Dry dust test – optical measurements: comparison of the change in transmittance and yellowness index with the brush-cycle count ($n \leq 5000$) for select coatings for linear abrasion. The experiments in Figure 5 and Figure 6 compare specimens with a variety of surface treatments, surface functionalizations, and coating materials.

Figure 6: Dry dust test – surface measurements: comparison of the change in surface energy and surface roughness with the brush-cycle count ($n \leq 5000$) for select coatings for linear abrasion.

Figure 7: Effect of abrasion test type on coating P: comparison of the change in transmittance and yellowness index with the brush-cycle count ($n \leq 20000$) for select linear abrasion experiments. The experiments in Figure 7 and Figure 8 compare a variety of methods that may be used to affect the rate of linear abrasion of the same coating.

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Tables:

Table 1: Summary of the standardized test methods for artificial machine abrasion from the building, paint, and automotive-window industries that could be applied for solar applications.

TEST METHOD	INDUSTRY OF ORIGIN	ABRASIVE MATERIAL	SIZE ABRASIVE (GEOMETRY) {mm}	NOMINAL CONTACT PRESSURE {kPa}	STROKE LENGTH {mm}	<i>n</i> , NUMBER OF CYCLES {dimensionless}	CYCLE REPEAT SPEED {cpm}
BS EN 1096-2 (Annex E) [9]	bulding glazings	felt or grit embedded rubber tip	14.5 or 7 (diameter)	24.2 or 103.9	120	500	60
ASTM D2486 [10]	paints	wet Nylon 6 bristles plus silica, surfactant slurry	35 x 85 (area); 19 (length) & 0.30 (Æ)	1.5	270	pre-condition brush 400 cycles; test 400 cycle increments to failure	37
DIN 53778-2 [11]	paints	wet hogs bristle plus sodium-n-dodecylbenzenesulphonate in water	38 x 89 (area); 10.5 (length)	0.7	270	pre-condition brush 1000 cycles; test # cycles to failure	not specified
ISO 11998 [12]	paints	wet steel wool pad plus sodium-n-dodecylbenzenesulphonate in water	39 x 90 (area); 38 (thick)	not specified	300	pre-soak; 200 cycles	37
ASTM D4213 [13]	paints	wet steel wool pad plus cellulose, surfactant slurry	77 x 97 (area); 6 (thick)	not specified	255	pre-soak; 200 cycle increment test up to 800 cycles	not specified
ASTM D3450 [14]	architectural coatings	damp cellulose sponge with silica, surfactant slurry	76 x 95 (area); 38 (thick)	2.0	not specified	0, 25, 50, 75, 100	37
ASTM D4828 [15]	paints	unspecified sponge	not specified	not specified	255	100	37
UN/ECE Regulation 43 [16]	automotive glazings	chloroprene rubber wiper blade plus ISO 12103 A4 dust	11 (length)	not specified	130	10k plus 10k cycles	37
ISO 15082 [17] ISO 20566 [18] UN/ECE Regulation 43 [16]	automotive glazings	polyethylene brush plus 24 mm Ø silica slurry	440 (long) & 0.8 (Æ) bristles	not specified	>300	10 cycles	30 cpm (linear) 127 rpm (rotation)
ISO 3537 [19]	automotive glazings	abrasive or grit embedded wheel	12.7 (wheel width) 44.4 - 52.5 (wheel Æ)	not specified	N/A	100, 500, or 1000	rotate at 60 rpm or 72 rpm
ISO 15082 [17]	automotive glazings	Al ₂ O ₃ or SiC grit embedded in matrix	12.7 (wheel width) 44.4 - 52.5 (wheel Æ)	not specified	N/A	100, 500, or 1000	rotate at 60 rpm or 72 rpm
ASTM D1044 [20] ASTM G195 [21]	transparent plastics general use	abrasive or grit embedded rubber wheel	12.7 (wheel width) 44.4 - 52.5 (wheel Æ)	not specified	N/A	10, 25, 50, 100; user defined	rotate at 60 rpm or 72 rpm
ASTM D4060 [22]	paints	abrasive or grit embedded rubber wheel	12.7 (wheel width) 44.4 - 52.5 (wheel Æ)	not specified	N/A	50 cycle increment test up to 500 cycles	rotate at 60 rpm or 72 rpm

Table 2: Summary of abrasion studies in the solar energy research literature.

AUTHORS, REFERENCE	TEST METHOD	ABRASIVE MATERIAL	SIZE TEST FIXTURE (GEOMETRY) {mm}	NOMINAL CONTACT PRESSURE {kPa}	STROKE LENGTH {mm}	<i>n</i> , NUMBER OF CYCLES {dimensionless}	CYCLE REPEAT SPEED {cpm}
Bengoechea et. al. [23]	based on BS EN 1096-2	Nylon 6/6 bristles with SiO ₂ sand, Aramco test dust, or silica	20 x 40 (area) 0.060ÆÆ0.200	2.5	70	200	120
Cauchois et. al. [24]	based on BS EN 1096-2	felt or grit embedded rubber tip	not specified	not specified	not specified	10, 20, 50, 100, 150, 200, 250 500, 1k, 2k, 4k, 6k, 10k	not specified
Ferretti et. al. [25] Ferretti et. al. [26]	BS EN 1096-2	grit embedded rubber	7 (diameter)	90.9	100	0, 25, 50, 250, 500, 1k	60
Ferretti et. al. [27]	custom rotary brush	CTP-300-3 Method 313 sand [28]; PA 6 bristle	0.16 or 0.42 (Æ); 40 (length) & 0.3 (Æ)	not specified	module length	1k	not specified
Klimm et. al., [29]	BS EN 1096-2	felt	14.5 (diameter)	24.2	120	0, 500, 1k, 1.5k	60
Lange et. al. [30]	ISO 11998	PA bristle; ISO 12103 A2 test dust [xxx]	35 x 85 (area) 19 mm (length);	1.5	100	0, 10 , 50, 100	72
Miller et. al. [31]	based on ASTM D2486	bristles: PA, hog bristle, PE, horsehair; ISO 12103 A4 test dust [xxx]	35 x 85 (area) 19, 38 (length) 0.30, 0.64, 0.22, 0.25 (Æ);	1.5	270	0, 100, 500, 1k, 5k, 10k, 20k	37
Pan et. al., [32]	BS EN 1096-2	felt	not specified	not specified	not specified	0, 500, 1k, 2k, 5k	not specified
Pop et. al., [33]	BS EN 1096-2	felt	14.5 (diameter)	24.2	100	0, 200, 400, 600, 800, 1k	30
Weber et. al., [34]	BS EN 1096-2	felt grit embedded rubber	7 (diameter)	103.9	100	0, 50, 100, 250, 1k	60
Womack et. al. [35] Isbilir et. al. [36] Womack et. al. [37]	BS EN 1096-2	felt grit embedded rubber	7 14.5 (diameter)	259.8 30.3 & 60.6	30	100	60

Table 3: Summary of the coatings and materials examined in this study, including their physical, anti-reflective (AR), and anti-soiling (AS, shown for water) characteristics.

SPECIMEN INDEX	COATING OR MATERIAL	COATING THICKNESS {nm}	R_a , COATING ROUGHNESS {nm}	AR	$\tau_{d,rsw}$ { % }	$\Delta\tau_{d,rsw}$ { % }	AS SURFACE FUNCTIONALIZATION	CA, CONTACT ANGLE {°}	WETTING CHARACTERISTIC
A	monolithic PMMA	no coating	3.6	no	89.2	N/A	no	70	least-hydrophilic
B	porous silica*	125	4.6	yes	91.8	1.7	yes	88	least-hydrophilic
E	porous silica*	130	25.3	yes	93.0	2.3	no	49	moderately-hydrophilic
J	monolithic glass substrate	no coating	3.4	no	90.1	N/A	no	43	moderately-hydrophilic
L	etched glass	no coating	5.5	yes	90.8	0.7	yes	50	moderately-hydrophilic
P	polymer	40	5.0	yes	90.8	0.6	yes	118	hydrophobic
R	silane chemistry	no coating	3.4	no	90.2	0.1	yes	102	hydrophobic
V	TiO ₂ ⁺	50	2.2	no	79.3	-7.5	yes	45	moderately-hydrophilic
Z	ZrO ₂ /SiO ₂ /ZrO ₂ /SiO ₂	20/30/135/95	7.4	yes	90.2	0.1	no	9	most-hydrophilic

Table 4: Summary of the artificial linear machine abrasion experiments performed in this study, including the “material,” brush, wet and/or dry test conditions, use of abrasive, and cycle count.

SPECIMEN INDEX	BRUSH	WET TEST	DRY TEST	ABRASIVE PRESENT	n , NUMBER OF CYCLES {dimensionless}
A	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k
B	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k
E	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k
J	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k, 10k, 20k
L	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k
P	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k
P	default	Y	Y	none	0, 10, 100, 500, 1k, 5k, 10k
P	soft bristle	Y	N	ISO 12103 A3	0, 10, 100, 500, 1k, 5k, 10k
R	default	Y	Y	ISO 12103 A3	0, 10, 25, 50, 75, 100, 5k
V	default	Y	N	ISO 12103 A3	0, 10, 100, 500, 1k, 5k, 10k, 20k
Z	default	Y	N	ISO 12103 A3	0, 10, 100, 500, 1k, 5k, 10k, 20k

Table 5: Summary of the observed changes in contact angle and roughness for the experiments in Figure 8.

SPECIMEN INDEX	ONSET ΔCA {number of cycles, dimensionless}	OCCURENCE LOCAL MAX[R_a] {number of cycles, dimensionless}
P_{Dry}	1	not observed
P_{Wet}	10	10
$P_{Dry (No Abrasive)}$	10	not observed
$P_{Wet (No Abrasive)}$	100	100
$P_{Soft Bristle}$	100	100

Table 6: Measured scratch geometry for select specimens after 10 cycles in the linear abrasion experiments. Minimum, average, and maximum values are given as well as the nominal coating thickness.

COATING	TEST CONDITION	w_s , SCRATCH WIDTH { μm }			h_s , SCRATCH DEPTH {nm}			h_n , NOMINAL COATING THICKNESS {nm}
		MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	
B	SLURRY	1.2	2.0	4.0	128	136	142	125
	DRY DUST	0.6	1.7	4.8	1.5	76	136	125
E	SLURRY	0.6	1.8	7.1	3.3	42	121	130
	DRY DUST	0.6	1.2	2.2	8.8	43	121	130
L	SLURRY	0.6	1.0	3.7	8.8	34	84	0
	DRY DUST	0.6	2.7	22	19	46	88	0
P	SLURRY	1.0	3.3	17	28	38	50	40
	DRY DUST	1.0	4.3	13	17	24	33	40
	WET BRUSH	0.6	2.9	8.5	12	25	62	40
	DRY BRUSH	0.6	4.2	11.9	20	36	58	40
	SOFT BRUSH (SLURRY)	0.6	1.7	3.7	13	30	55	40
J	SLURRY	0.8	0.9	1.2	5.1	13	24	0
	DRY	0.4	0.8	1.2	5.2	20	69	0

Figure

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RDM Data Profile XML

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Supplementary material

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