Artificial Soiling of Photovoltaic Module Surfaces using Traceable Soil Components

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***Abstract*—Effective evaluation and prediction of photovoltaic performance loss due to soiling requires consistent test methods. Natural grime accumulation is time-consuming and location-specific, and thus does not provide reproducible results across different geographic regions. Therefore, we have demonstrated a technique to apply artificial soiling with NIST-traceable components using an aerosol spray technique. This approach produces consistent soil coatings which were directly correlated to performance loss of multicrystalline Si cells in a laboratory setting. By tailoring the composition of the test blend, termed 'standard grime', the loss due to soiling can be effectively predicted over a range of mass loadings and soil types.**

I. Introduction

Soiling is a significant source of energy loss in photovoltaic (PV) systems [1], [2], but is difficult to quantify globally due to variations in soil type [3], location [4], and weather patterns. Predictive modelling to quantify expected losses and recommended maintenance intervals is currently impractical.

Accelerated soiling has recently been discussed in the literature [3], [5] as an alternative to outdoor studies. These efforts aimed to reduce the time required to determine the severity of loss due to specific soil types and morphology [3] and assist in determining appropriate mitigation methods [5]. However; a standardized, location-independent technique has not been reported. A further complication to developing a repeatable test methodology is the spectral influence of some soil constituents. Reduction in transmittance [6] and spectral response [7] may affect PV performance to a greater extent than the absolute amount of soil on the module surface.

A standard reproducible test would be useful for planning new installations by providing derate factors to incorporate in the modelling and development stage. Additionally, such data could provide manufacturers with anticipated operational ranges and suggested cleaning regimens for their products. Such a technique would be valuable for evaluating cleaning, anti-soiling and cover sheet materials in a controlled environment. In this work, we have demonstrated the use of an artificial soiling coating composed of NIST-traceable test dust (referred to as 'soot') and particulate matter (graded quartz sand, commonly referred to as AZ test dust).

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II. Experimental Methods

A. Grime Formulation

Soils were formulated following the technique developed by Einfeld et al. [8] and used in previous work [9]. Arizona Road Dust (ISO 12103-1, A2 Fine Test Dust nominal 0-80 micron size, Powder Technology Inc.) was mixed with a soot mixture composed of 83.3 % w/w carbon black, (Vulcan XC-723, Cabot Corp, Boston, MA); 8.3 % diesel particulate matter, (NIST Catalog No. 2975); 4.2 % unused 10W30 motor oil, 4.2 % α-pinene, (Catalog No. AC13127-2500, Acros Organics) in a glass jar and tumbled without milling media in a rubber ball mill drum at 150 rpm for 48 to 72 h. Variations in grime composition were produced by mixing major optical components into the grime mixture. Iron oxides, including commercial Fe_2O_3 (Sigma Aldrich, 99.98% trace metals basis) and in-house synthesized göthite (FeO(OH)) were incorporated as the primary spectral components. In keeping with the repeatability emphasis of this study, commercially sourced material was used where possible, and standard synthetic techniques [10] were used when commercial materials were not available. For clarity, the commercial material will be referred to by chemical name (Fe_2O_3) to emphasize that it is a standard product, while the house-synthesized göthite will be referred to by mineral name.

Göthite was produced following the method described by Schwertmann and Cornell [10], which, while not a traceable standard, provided the most reliable source of ochre-colored mineral. Briefly, 0.05 mol (9.9405 g) $FeCl_2{\cdot}4H_2O$ (Fisher, Certified) was dissolved in 1 L of DI H_2O that had been degassed by bubbling N_2 for 30 mi. The solution was buffered with 110 mL of 1 M $NaHCO_3$ (Fisher, enzyme grade) and allowed to stir for up to 48 h. The resulting product was filtered and rinsed in DI H_2O and allowed to dry over night prior to analysis.

Blended soil types were formulated with 40 wt.% iron oxide pigment and 60 wt.% AZ road dust/soot blend. In the notation used, the Fe_2O_3 is listed first, and the göthite second; 30:10 therefore refers to 30 wt.% Fe_2O_3 and 10 wt.% göthite. Soot content in iron-rich soils is typically low, so less than 1 wt.% was incorporated into this test blend. Each mixture

Fig. 1. The spray chamber used to apply grime mixtures.

was matched to Munsell color swatches for quantification and comparison.

Aerosolizable suspensions were prepared by mixing 3.3 g of the dry blend with 275 ml of acetonitrile (Sigma Aldrich). as a carrier solvent. Each suspension was agitated briefly prior to use and remained suspended during the application process.

B. Grime Application

Schott borofloat glass was used as a test substrate after cleaning with a commercial degreaser and rinsing in distilled water followed by ethanol (Sigma Aldrich). After cleaning, a dry coupon was weighed with a Mettler Toledo XP205 balance with 0.00001 g resolution and placed at a 45 °angle inside a filtered spray chamber (Fig. 1). Coupons were prepared by spraying the soil suspension in 25 mL aliquots with a high velocity low pressure (HVLP) automotive detailing gun (Transtar gravity-fed model 6618, 1.0 mm nozzle) held approximately 30 cm from the coupon surface. The detailing gun was aimed a few centimeters past the right edge of the coupon, and was slowly swept to the left until the spray plume had coated the entire coupon. The procedure was repeated until the desired mass loading was reached.

C. Testing

In order to evaluate spectral response, a polycrystalline Si wafer (η = 16%) was used to detect light transmission through soiled slides. The PV response was measured using a Spectrolab XT-10 one sun simulator equipped with a 1 kW Xenon lamp, producing an AM 1.5 spectrum. Calibrated HP 3458A multimeters were used for independent current and voltage measurements. An 81.25 cm^2 cell was centered on a temperature-controlled vacuum chuck, and test coupons were placed directly over the cell. Current-voltage curves were generated by illuminating the test stage and sweeping the voltage from V_{OC} to 0, with 10 repetitions. A calibrated PRC Si reference cell was measured following each sweep of the test cell.

The coupons were then subdivided into 4.5 cm sections to fit into the sample slot of a Varian Cary 5000 equipped with a DRA-250 diffuse reflectance chamber. The spectral response of each sub-coupon was evaluated by UV/vis spectroscopy from 300 to 2500 nm. Quantum efficiency (QE) measurements were collected with three readings per wavelength with a 0.5 sampling interval on a PV Measurements QEX-10. Readings were taken at 10 nm increments over an interval from 300 to 1100 nm. The instrument was operated in AC mode with a beam chopping frequency of 100 Hz. The stage temperature was controlled to 25 °C and the height was adjusted to 20.6 cm in order to focus the sample spot to fit within the cell crossfingers. The spectral response was recorded at a single point for each cell without using a bias light.

III. Results and Discussion

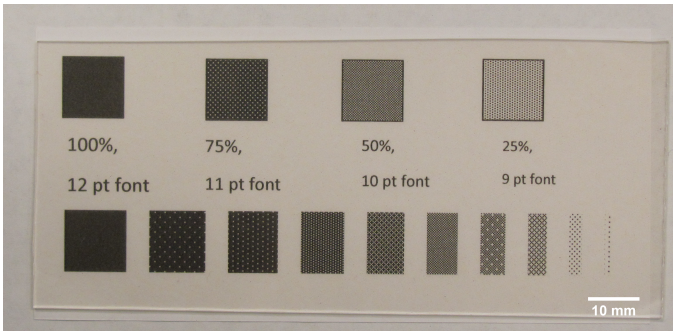
A. Grime Composition

Soil composition is highly location-dependant; however, the key spectral effects under consideration in the present work were replicated with a range of simple mixtures of sand, soot and pigment. As such, the composition was constrained to 40 wt. % of common mineral pigments found in soils throughout the United States roughly following the USDA soil taxonomy [11]. Ensuring a repeatable test formulation was straightforward when using NIST-sourced test sand and soot, and commercially available Fe_2O_3. However, since the göthite was an in-house product, it was necessary to prepare several batches to ensure that the blend (and resulting PV responses) were repeatable. An off-spec sample (Fig. 5) was found to produce a green color well outside the range of desired test colors. The cause was excessive milling and oxidative impurities in the synthesized göthite. Subsequent batches were carefully monitored to ensure a consistent pigment was produced. As this error was correctable, it is believed that this procedure is broadly applicable.

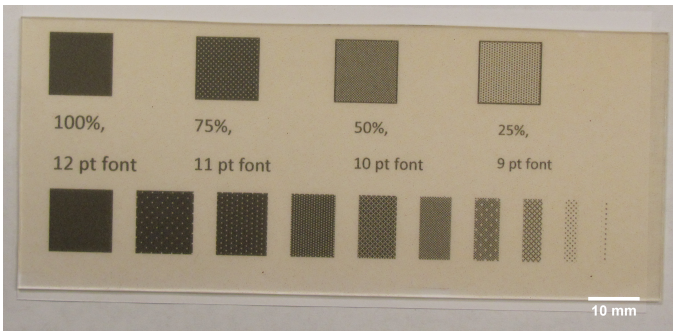
B. Light Transmission through Soiled Glass

Deposited grime films attenuated light transmission in a repeatable manner for each tested blend. The soiling level of each coupon could be visually observed, and was uniform throughout the entire surface (Fig. 2). The color was faintly apparent at low mass loadings (Fig. 2a) and pronounced for loadings greater than 1.0 g/m^2 (Fig. 2b). Instrumental measurements confirmed this trend, indicating a good agreement among several measurement conditions and grime types. Transmission data through each grime blend (Fig. 3) show a strong response in the visible region, up to the UV cutoff caused by the glass substrate. Notably, the most significant decrease in transmission occurs beyond the peak in solar irradiance, as illustrated by the comparison to the ASTM G173 spectrum [12].

The difference between transmission through soiled coupons and a clean reference was integrated over the active (300-1100 nm) wavelength range to compare to the one sun response,



(a) 0.6614 g/m^2 of 0:40 grime



(b) 1.82657 g/m^2 of 0:40 grime

Fig. 2. Soiled coupons overlaid on a printed graphics palette to illustrate the effect of shading caused by increasing mass loading of grime.

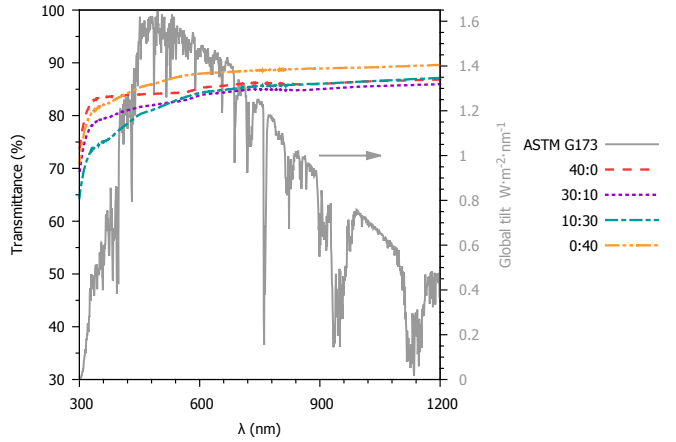
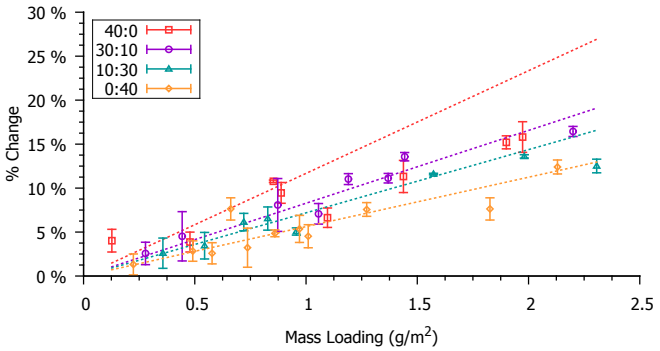


Fig. 3. UV/vis transmission response of coupons soiled with approximately 1.0 g/m^2 of respective grime. Each pigment is responsive in the visible region, although the most significant decrease occurs outside the peak AM1.5 irradiance [12].

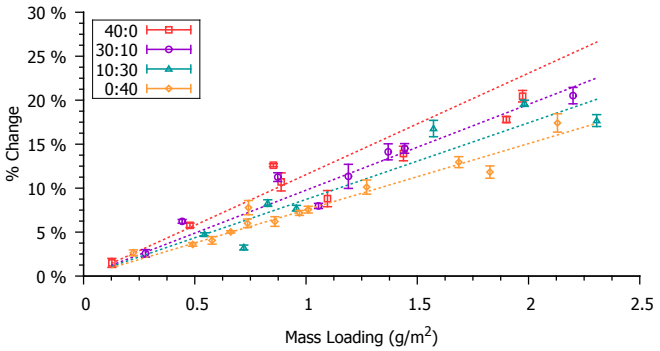
QE measurements, and UV/vis transmission measurements (respectively noted as S in Eq. 1).

$$Loss = \frac{\int_{300}^{1100} S_{clean}(\lambda)\mathrm{d}\lambda - \int_{300}^{1100} S_{soiled}(\lambda)\mathrm{d}\lambda}{\int_{300}^{1100} S_{clean}(\lambda)\mathrm{d}\lambda} \quad (1)$$

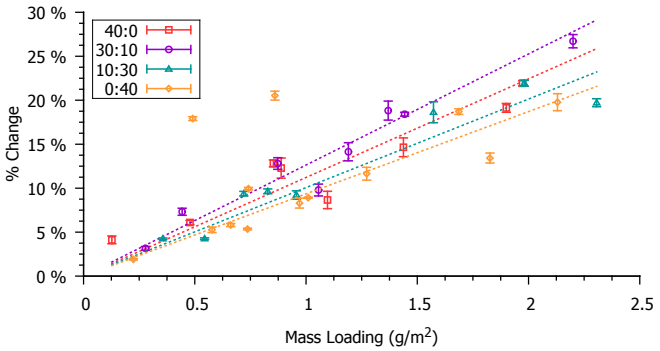
The percent loss, shown in Fig. 4, follows a reasonable linear fit for the 30:10, 10:30 and 0:40 blends. The Fe_2O_3-rich 40:0 soil deviated from the forced linear fit at higher mass loadings. Integral responses of the QE and %T data showed much tighter



(a) One Sun



(b) QE



(c) %T

Fig. 4. Comparison of one sun data (a) to QE (b) and %T data (c).

fits between each soil type. Most significantly, soils progressively richer in Fe_2O_3 tended to cause a greater decrease in measured response (and therefore light transmission) on each instrument.

IV. Conclusion

We have shown that artificial grime application is an effective laboratory analogue to test the response of PV components to various soil colors under repeatable conditions. Application of standardized grime produced consistent decreases in light transmission as measured directly by UV/vis spectroscopy and indirectly by one sun illumination and QE measurements of an underlying multicrystalline wafer. The linear trend noted

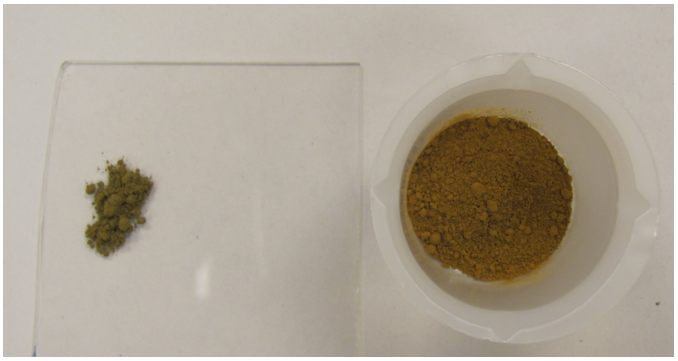


Fig. 5. Comparisons of two blends of 40 wt.% göthite. The powder on the left turned green after excessive milling and was not usable. The powder on the right is the correct shade, matching Munsell swatch 10YR 6/6.

for each mixture suggests that variation in soil color can be repeatably measured by independent techniques. Red-colored soils were more detrimental to light transmission than predominately yellow soils.

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