"The IEC 62788-7-3 abrasion methods standard and supporting experiments at NREL on PV surfaces and coatings"

NREL
Transforming ENERGY

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[*]Presenter (David.Miller@nrel.gov)

Indo-UK PV Soiling Workshop (https://drive.google.com/file/d/1WugU5Q3BTh9hMIexzktAbs1usOK-Y9ce/view)
Tuesday, 2022/1/25, 04:20-04:50 am MT
Virtual event (MS Teams)

“The IEC 62788-7-3 abrasion methods standard and supporting experiments at NREL on PV surfaces and coatings”

NREL Transforming ENERGY

-Slides originally presented at Indo-UK PV Soiling workshop have been updated for PV Robot Cleaning workshop-

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PV Robot Cleaning Workshop
Monday, 2022/3/28, 12:25-12:50 UTC (06:25-6:50 am MT)
Virtual event (webex)

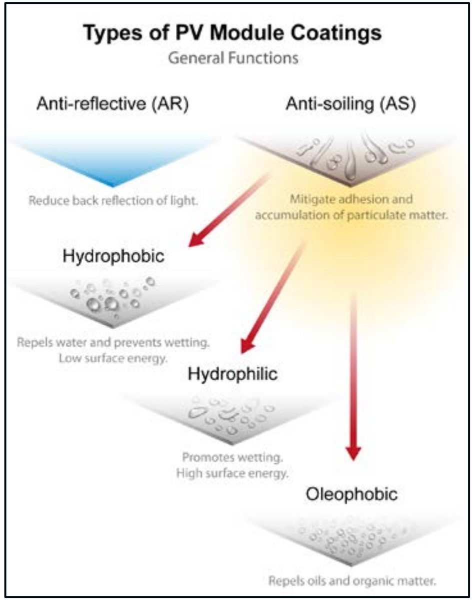
Motivation

- PV now uses AR and/or AS coatings to increase electricity generation and reduce effects of soiling.
- ~1%·day^{-1} performance loss in MENA $\Rightarrow$ clean PV modules daily.

Vendor cleaning building glazings (at NREL campus).

Concerns related to the IEC 62788-7-3 (PV abrasion methods) standard:

- Much of the damage to coatings results from cleaning.
- The applicability of damage from airborne particulate matter remains to be established.
- The durability of coatings may be compared between methods.



Coatings used on PV front surfaces.
Einhorn et. al., J PV, 9, 2018, 233-239.

Look for in This Presentation

IEC 62788-7-3 was published 2022/2/22.
I hope to give an understanding of how & why the methods became prescribed and to get your feedback on:

- Abrasives.
- Characterization used with abrasion tests.

- Linear brush test.
- Rotary brush test
- Falling sand test.
- Forced sand impingement test.

IEC TC82 WG2 accelerated tests: PV abrasion (methods)

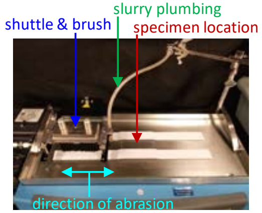
•Upon review, no existing standard from other industries was found readily suited for PV.

-Example: frosted –glass– specimens from Taber test. See: Newkirk et. al., https://doi.org/10.1016/j.solmat.2020.110757.

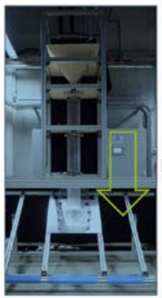
⇒Accelerated abrasion standard for PV surfaces was developed in IEC WG2.

Methods

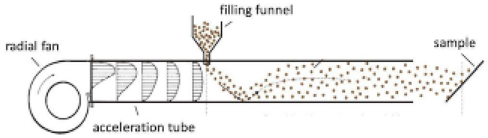
- Artificial machine abrasion.
  - -**Cleaning** of PV (front surface coatings & VIPV).
  - -Includes slurry or dry dust abrasive.
  - -Linear translating or rotating brush.
- Falling sand test.
  - -Natural abrasion (wear from typical meteorological conditions).
  - -Front surface coatings & backsheets.
- Forced sand impingement test.
  - -Covers severe storms (infrequent, but high velocity wind).
  - -Front surface coatings & backsheets & vehicle integrated PV.



Fixture for (slurry) linear machine abrasion test. From Miller et. al., J PV, 2019.



Fixture for falling sand test. From Mathiak et. al., Proc. EU PVSEC 2018.



Schematic of forced sand impingement test. From Klimm et. al., Proc. Euro. Weathering Symp. 2015.

Topics

- Abrasives.
- Characterization used with abrasion tests.

- Linear brush test.
- Rotary brush test
- Falling sand test.
- Forced sand impingement test.

Details of the Linear Artificial Brush Abrasion Test

<u>Linear brush:</u>

- Design based on ASTM D2486 (20^{th} century legacy).
- Bristle ∅ 0.23 mm (in range of PV equipment).
- Round bristle, no taper:
  easy to manufacture, certify, and analyze (hopefully).
- Bristle length 35-<u>38</u> mm (<u>maximum</u> for existing testers).
- *Net* mass 455 g → contact force 4.46 N.
  (dry brush + added weight + fasteners).

<u>Abrasives for Surface Abrasion Test 01 (SAT01):</u>

- Abrasive: ISO 12103-1 A3 ("medium") AZ test dust.
- Dry dust: 0.7 mg·cm^{-2}·$cycle^{-1}$. ☞Condition brush & dust!
- Slurry: 5.0 g·l^{-1} in deionized water, at 5.0 l·h^{-1}.
  Slurry more consistent than dry dust.

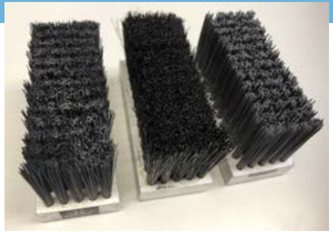
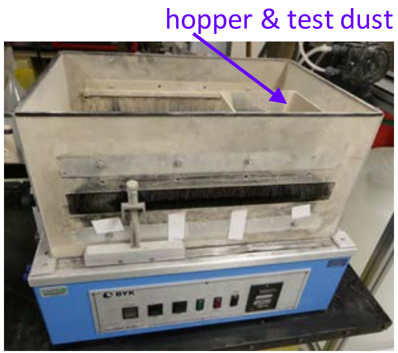
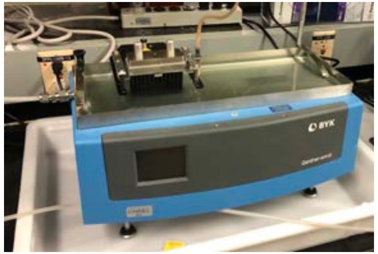
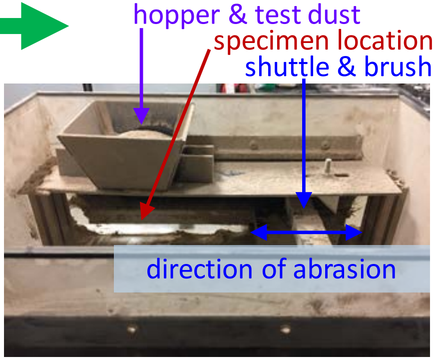


Photo of linear brush.



front view (lid removed)

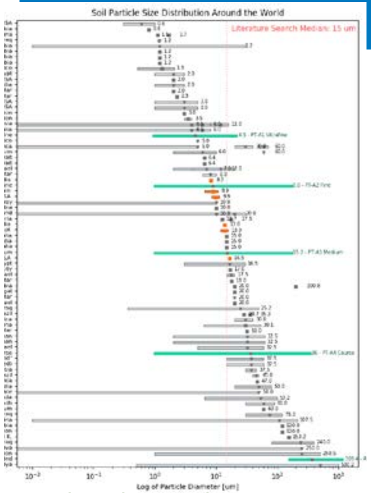




back view

Photos of linear abrasion testers at NREL: Slurry (left) and dry dust (right).

Example: Abrasive Size Relative to Field Contamination



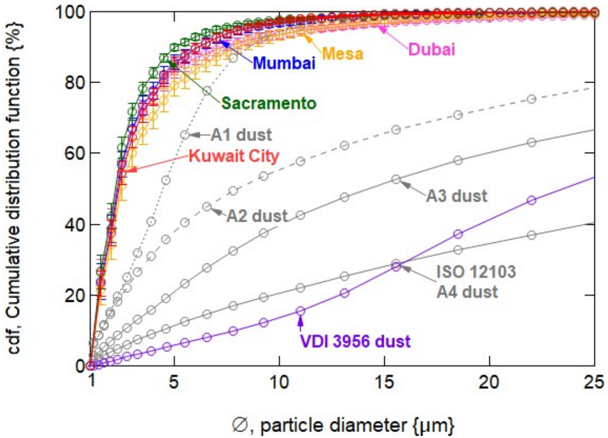
Nayshevsky et. al.,
Proc. Intl. Soiling Work., 2018.

- 16 µm ∅ (median) in PV literature.

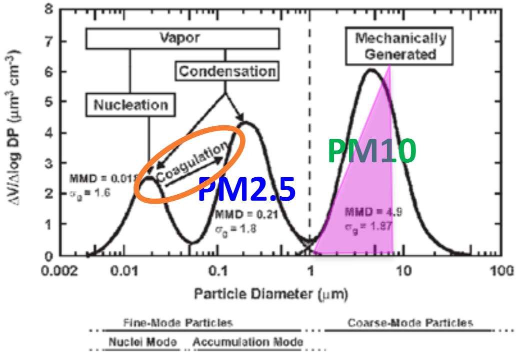
- 2.5 µm ∅ (50^{th} percentile) in field study.

???

-Cementation observed (e.g., Dubai & Kuwait).
-Size limited by natural cleaning (timing of wind & rain) and international return shipping.
-Measurement methods: laser vs SEM.

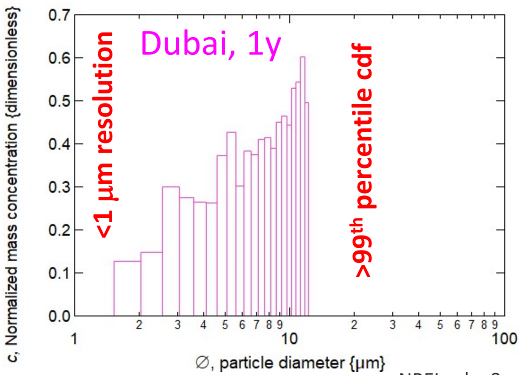


Miller et. al., NREL/PR-5K00-74183, 2020.



Mass concentration of airborne PM.
Wilson & Suh, J. Air & Waste Manage. Assoc., 1997.

- PM2.5: from combustion, chemical processes.
- Airborne fine PM evolves to PM2.5.
- PM10: from mechanical origins.
- Mass concentration distribution of field sites resembles airborne PM10 contamination.

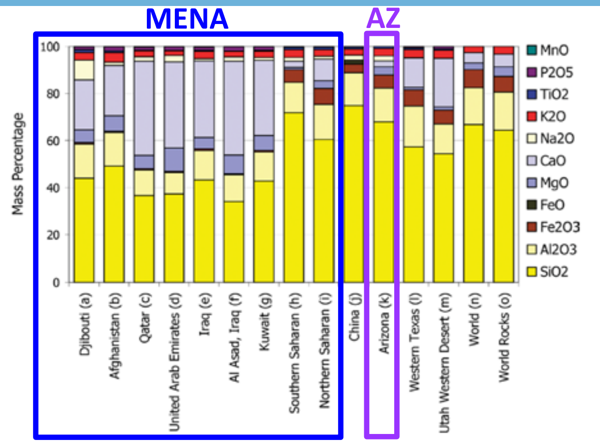


Measured mass concentration (“Q_3”) for the Dubai No Clean field coupon.

Composition Analysis Suggests Additional Dust Varieties May Ultimately Be Required

- Local composition of soil (therefore PM10) varies between world locations.

- "Compared with the Sahara, China, US, and world dusts, Middle East samples had lower proportions of SiO_2 and higher proportions of CaO and MgO", Engelbrecht et. al.
- Palygorskite [$(Mg,Al)_2Si_4O_{10}(OH)\cdot 4(H_2O)$] is a mineral commonly found in MENA locations, but not in AZ (ISO 12103-1 test dust).
- Clays and salts affected considerably by water (including dew cycles), contributing to cementation.



Comparison of dust from various locations. Engelbrecht et. al., Inhalation Toxicology, 21, 2009.

- Location specific differences also exist within MENA.
- What location might be a benchmark for MENA?
- A MENA test dust product presently exists from VDI 3956.
- Quartz free AZ dust products exist (respiration safety).
- AZ test dust chosen from existing literature base.

  Please help support other options in future IEC revisions!

Chemical composition for ISO 12103-1 AZ test dust. PTI Inc, Safety Data Sheet.

MINERAL COMPONENT	C, CONCENTRATION {%}	H>soda-lime glass?	H_V	H_{Mohs}
SiO_2, silica (fine dust)	69-77	>	≤1200	6-7
Al_2O_3, alumina	8-14	>>	1400-1800	9
CaO, calcium oxide	2.5-5.5	N		3-4
K_2O, potassium oxide	2-5	N		low
Na_2O, sodim oxide	1-4	N		low
Fe_2O_3, hematite (Iron III)	4-7	~	1000-1100	5.5-6.5
MgO, magnesia	1-2	>	1500-1650	6.0-6.5
TiO_2, titania (anatase/rutile)	0-1	~	800	5.5/6.5
soda-lime glass	FOR REFERENCE	~	550	5.5-6.5

Details of Specimens in Abrasion Experiments

- Monolithic materials (no coating): Diamant glass (typical substrate) or PMMA.
- "Coatings": surface chemistry, etching, porous SiO_2, polymer, TiO_2, oxide stack
- Coatings include commercial products and academic research materials.

Summary of specimens examined.

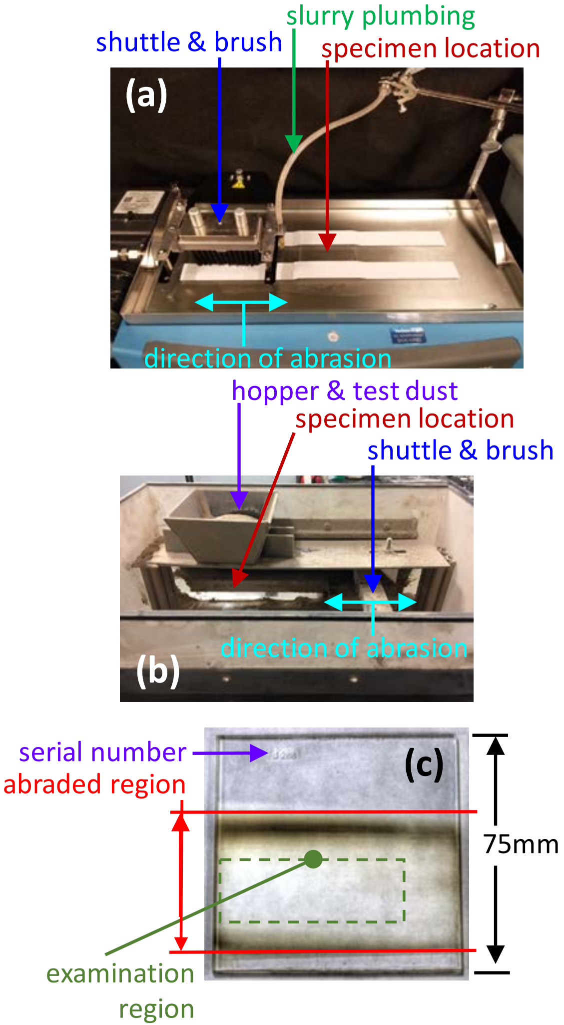
SPECIMEN INDEX	COATING OR MATERIAL	COATING THICKNESS {nm}	R_a, COATING ROUGHNESS {nm}	AR	$\tau_{d,rsw}$ {%}	$\Delta\tau_{d,rsw}$ {%}	AS SURFACE FUNCTIONALIZATION	*CA*, CONTACT ANGLE {°}	WETTING CHARACTERISTIC
A	monolithic PMMA	no coating	3.6	no	89.2	N/A	no	70	least-hydrophilic
B	porous silica*	125	4.6	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	least-hydrophobic
R	silane chemistry	no coating	3.4	no	90.2	0.1	yes	102	least-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

Summary of surface energy classification scheme.

greatest surface energy	
$0<\theta\leq10$	most-philic
$10<\theta\leq50$	moderately-philic
$50<\theta\leq90$	least-philic
$90<\theta\leq120$	least-phobic
$120<\theta\leq150$	moderately-phobic (Wenzel state)
$150<\theta\leq180$	most-phobic (Cassie-Baxter state)
least surface energy	

- I don't know of a standardized surface energy taxonomy. ☹
- Glass is inherently hydrophilic.
- Most PV industry coatings modestly affect surface energy (research grade coatings are expensive!)

Details of the Linear Artificial Brush Abrasion Tester



Experiments:

- Custom **slurry** or **dry dust**.
- Brush bristles: polyamide (Nylon 612), 3.8 cm length.
- A3 "medium" AZ test dust abrasive (ISO 12103-1).
- Slurry (5 g·L^{-1}) dispensed continuously at 100 mL·min^{-1}
- 20 mg dry dust dispensed with each cycle.

Specimen test region:

- Characterizations performed only within examination region.
- Image (c) is from a previous study.

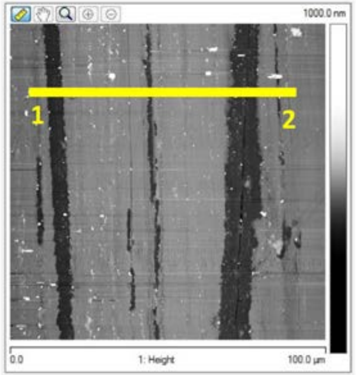
Miller et. al., IEEE J PV, 2020, 10.1109/JPHOTOV.2019.2947029.

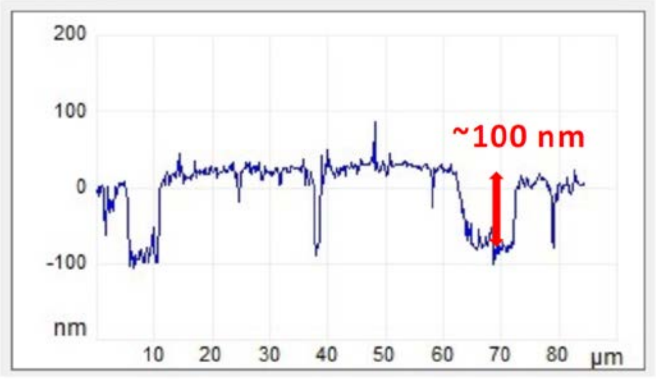
-Reduced residual surface contamination observed this study (longer bristles, finer abrasive, lower cycle count).

Typical Characteristics Examined

- (Initial) coating thickness (ellipsometer and cross-sectional SEM).
- Visual appearance (optical microscope).
- Surface energy (H_2O [polar], static contact angle from goniometer).
  Diiodomethane [dispersion]? Formamide [acid/base]? Roll-off angle [hysteresis]?
- Surface roughness (white light interferometer, mechanical profilometer).
- Optical transmittance (spectrophotometer, option: integrating sphere).
- (Select) surface morphology (AFM for scratch-width and –depth).
- (Select) chemical composition (XPS).

IEC 62788-7-3 only defines abrasion methods!!!

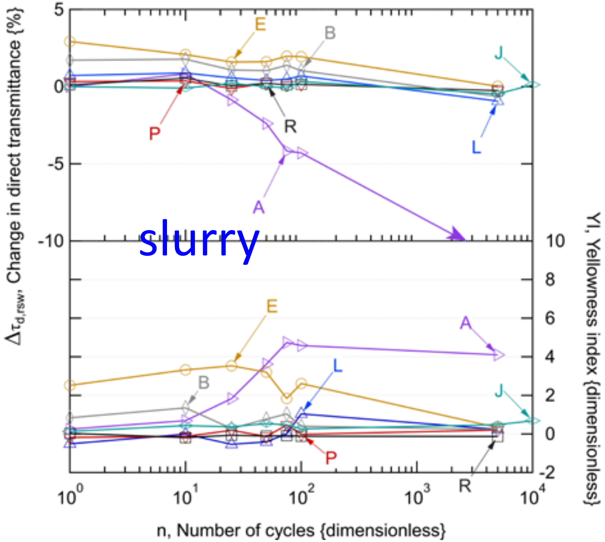


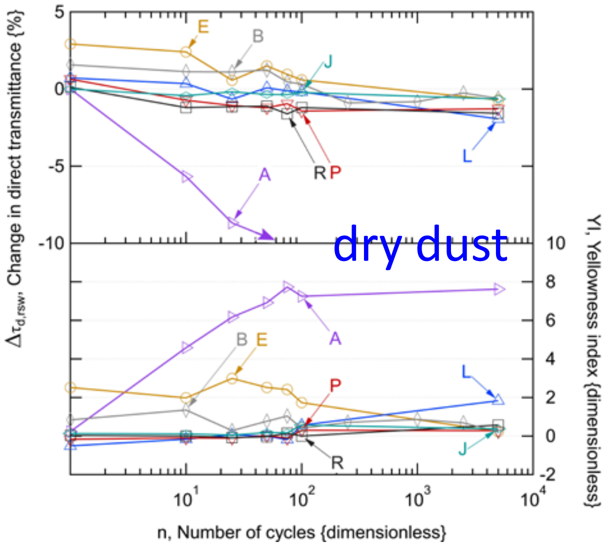


Representative profile of AFM scan for scratch size assessment (specimen B), after 1y of monthly Dry Brush cleaning in Dubai.
Einhorn et.al., IEEE J PV, 2019, https://ieeexplore.ieee.org/document/8529245.

Comparing Slurry and Dry Dust Abrasion (Transmittance and YI)

- Working reference specimen A most affected, including τ_d, *CA*, and R_a.
- IEC 62788-7-3 references: PMMA, B 270 "Superwite" crown glass, "Borofloat" glass (Schott AG).
- Onset quicker, magnitude of degradation greater for dry dust than slurry.
  Similar dust deposition rate $\Rightarrow$ greater damage propensity for dry dust.

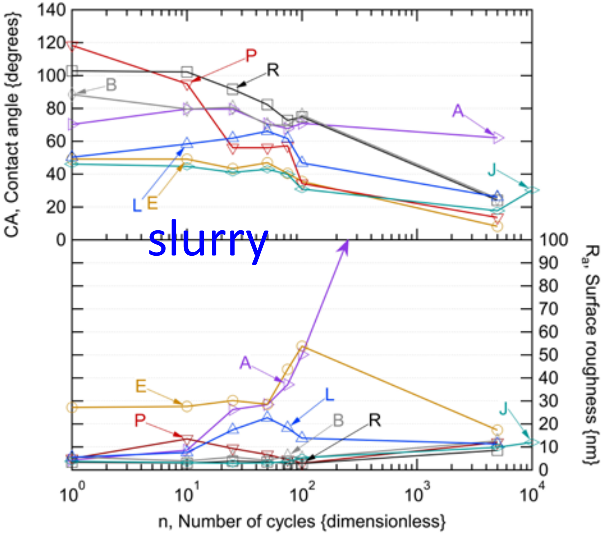




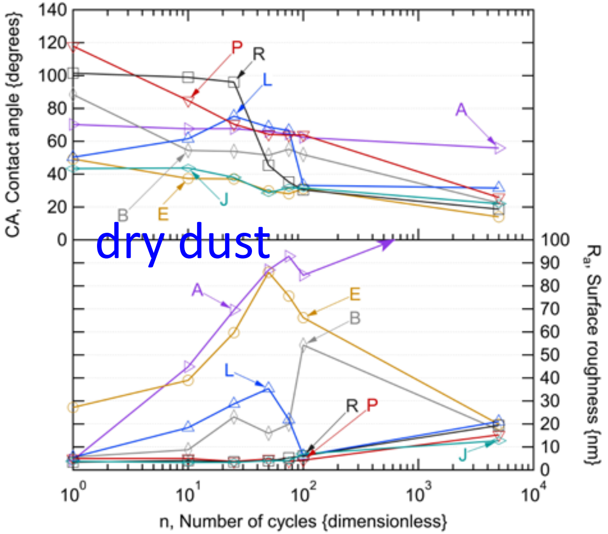
Comparison of the change in transmittance (i.e., coating optical performance) and yellowness index (which may vary with optical scattering) with the cumulative brush cycle count (n ≤ 5000) for select coatings for linear abrasion with slurry (left) and dry dust (right).

Comparing slurry and dry dust abrasion (surface energy and roughness)

- *CA* & R_a suggest longevity of the coatings examined is ~ 50 < n < 200 cycles.
- Loss in *CA* and/or R_a often observed before $\Delta\tau_d$ for B, E, L, and P.
- Changes in *CA* & R_a occur for coatings with a film thickness.



- *Greater Δ's* for dry dust → water acts as a lubricant and facilitates heat transfer.



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 with slurry.

Optical Microscopy Corroborates Degradation & Coating Failure

- AFM confirms bright linear features (scratches) in (b); dark features (remaining coating) in (c) and (d).

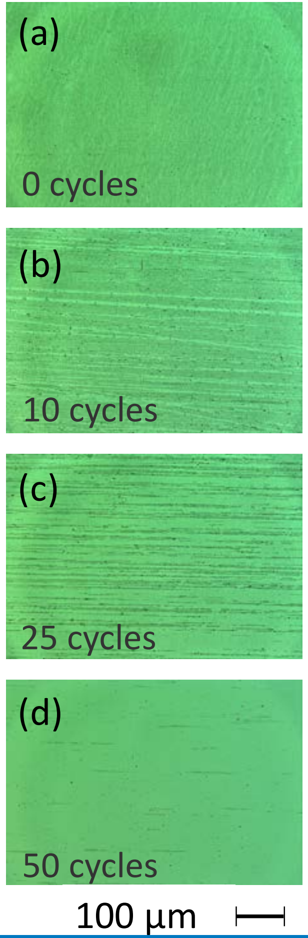
- Formation of a network of scratches followed by loss of coating is consistent with the correlation between *CA*, R_a, and τ_d, observed for specimens B, E, L, P, V, and Z.

- Distinct change in τ_d, *CA*, and R_a in some experiments suggests complete coating failure.

- Occurrence of a local maximum in R_a in some experiments may indicate fortuitous observation (appropriate # of cycles at destruction).

- Coating degradation from scratch accumulation also observed in Dry Brush cleaned field soiling coupons.

Toth et. al., SOLMAT 2018, https://doi.org/10.1016/j.solmat.2018.05.039

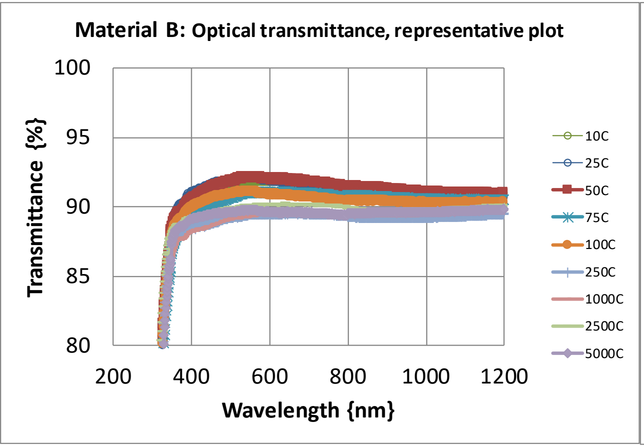


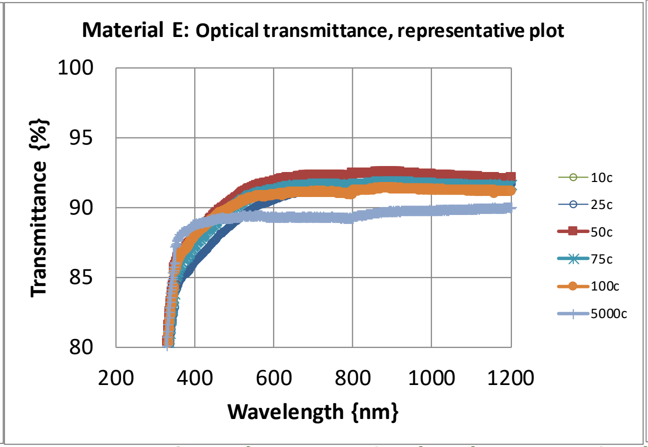
Select optical microscopy images of the P coating for linear abrasion with slurry.

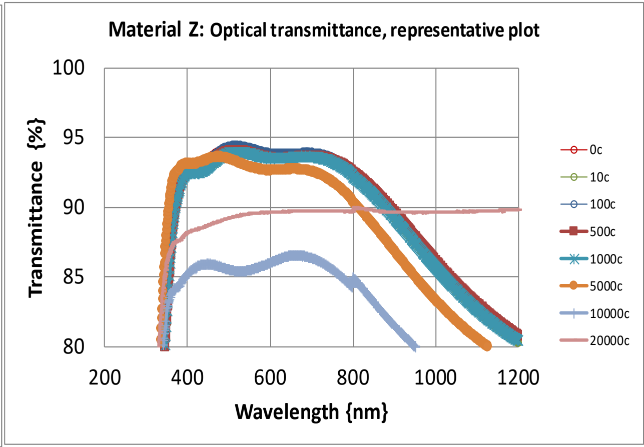
Coating Degradation Results From Localized Damage Accumulation

- No shift in λ_{cUV} observed for PS specimens B & E.
- No shift in spectral region of greatest τ_d & no $\Delta\lambda_{cUV}$ observed for multilayer specimen Z.

- Consistent with localized damage to film coating rather than uniform thickness reduction.
- All coatings not thick enough to realize a gradual wear (with a net change in thickness), unlike specimen A (monolithic PMMA).







Direct transmittance through the abrasion experiments for B (porous silica), E (porous silica), and Z (stacked dielectric) coatings.

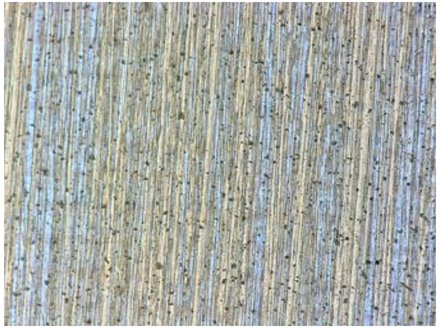
Estimating Coating Life for the Dry Brush Cleaned (Abraded) Coupons

- Goal: compare field Dry Brush cleaned coupons relative to machine abrasion (linear & rotary brush).

- With study → 5 years, we evaluated the coating life based on appearance (≤10% area remains).

-Sometimes obvious, comparing read points.

-Or apply oblique visualization method,
like Karin et. al., IEEE J PV, 2021, https://doi.org/10.1109/JPHOTOV.2021.3053482.
Works good for PS AR's (present PV industry),
not polymer AS coatings (U here, from research).



Oblique imaging to visualize coating integrity:
(left) microscope configuration, (right) representative image.

- Typical field lifetime: 12 < n < 730 cycles.
Linear brush: 50 < n < 200 common.
- Variety of lifetimes might be expected based on the variability of contamination and the (manual) cleaning.

	COATING: END OF LIFETIME (years/cycles)			
LOCATION	B	D	G	U (approximate)
Dubai	t > 4y/48c	t < 2y/24c	t < 1y/12c	t < 1y/12c
Kuwait	t < 2y/730c	t < 1y/365c	t < 1y/365c	t < 1y/365c
Mesa	t > 5y/60c	t < 4y/48c	t > 5y/60c	t < 2y/24c
Mumbai	t > 5y/60c	t < 3y/36c	t < 2y/24c	t < 3y/36c
Sacramento	t > 4y/48c	t > 4y/48c	t < 3y/36c	t < 2y/24c

Summary of preliminary results for the field coupon study.

Toth et. al., SOLMAT 2018, https://doi.org/10.1016/j.solmat.2018.05.039

Topics

- Abrasives.
- Characterization used with abrasion tests.

- Linear brush test.
- Rotary brush test
- Falling sand test.
- Forced sand impingement test.

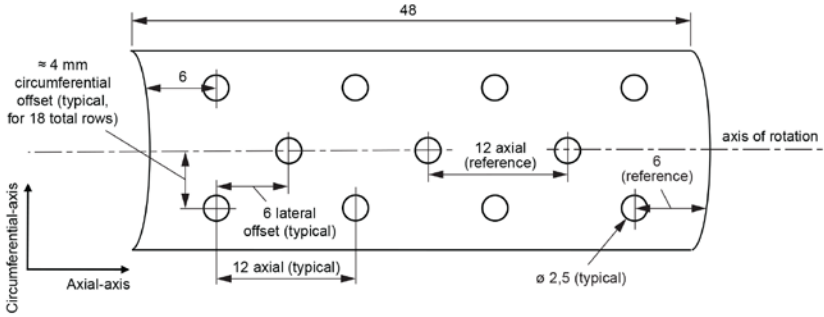
Details of the Rotary Artificial Brush Abrasion Test

<u>Rotary brush:</u>

- Design based on ASTM D2486, i.e. linear brush.
- PA 612 bristles →

  accelerated test, durable, facilitate cleaning.

  Miller et. al., IEEE J PV, 2020, 10.1109/JPHOTOV.2019.2947029.
- Brush outer ∅ 48 mm (range of PV industry designs).
- 120 rpm selected from wide variety of rotation speeds.
- Anticipate effects of bristle scratch (⊥) and dragging (//).

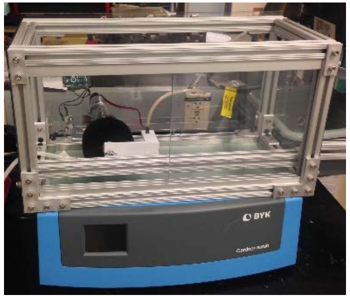


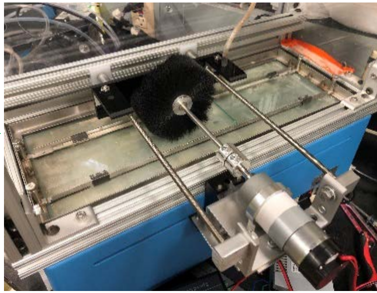
Schematic for the rotary brush.

<u>Surface Abrasion Test 02 (SAT02, as in SAT01):</u>

- Same slurry and dry abrasives & dispensing rates.
- Translation speed 30 cm·s^{-1} →

  37 cpm in traditional equipment (14.5 cm stroke).
- Method A: 0-100; B: 0-500; C 0-10k cycles (5 reads).

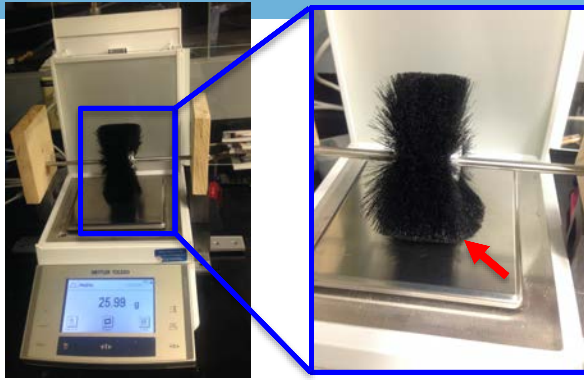




Photos of rotary abrasion tester at NREL.
Supporting experiments presently underway.

Bristle Deflection Characterization Identifies Buckling Behavior for Rotary Brushes

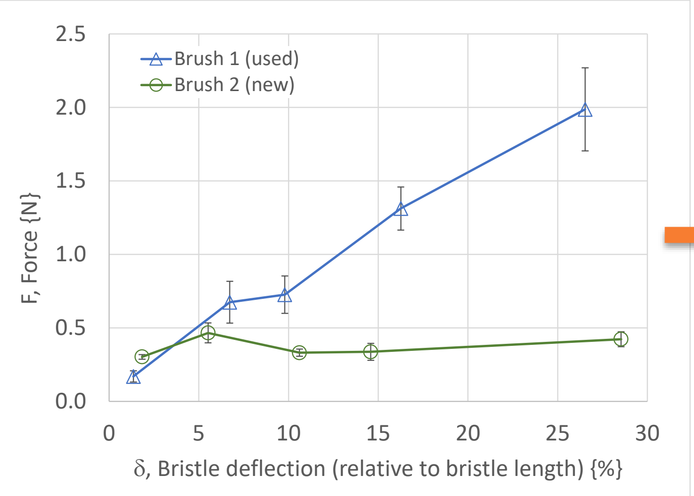
- Estimated area of contact more readily distinguishes brush force-deflection and pressure-deflection response.
- Bristle buckling observed during characterization.
- Compare brushes using Euler buckling based model.
- Separate brushes readily distinguished… contamination- or aging-stiffening of bristles?

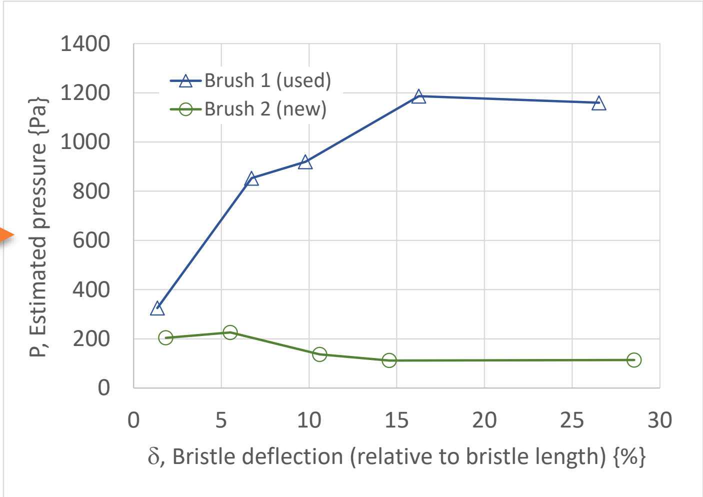


Experimental setup for characterizing the brush deflection characteristics. The buckling of bristles is indicated with an arrow in the inset.

$$F_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

Euler equation for critical buckling load.



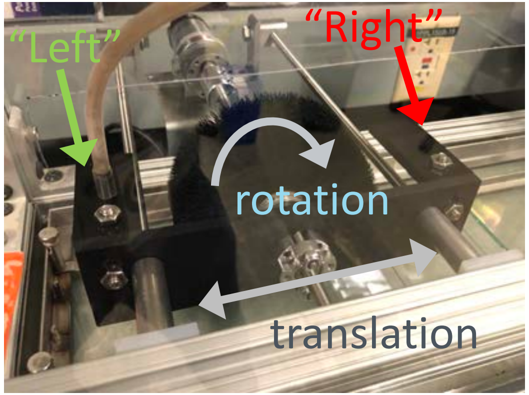


Comparison between measured force-deflection and estimated pressure-deflection characteristics for a new and previously used brush.

Optimizing the Configuration for Dispensing Slurry

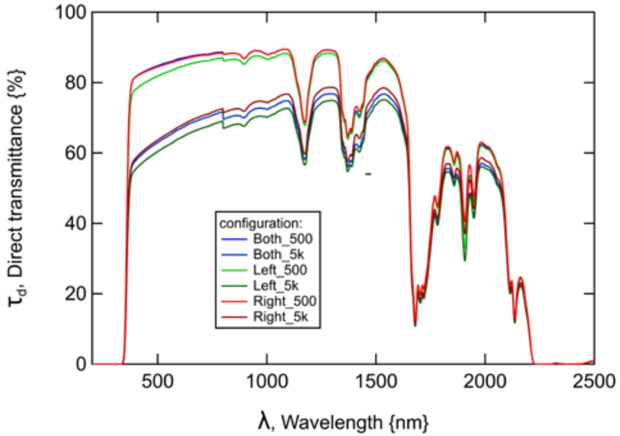
Question: Is there a more damaging dispensing configuration – "Left", "Right", or "Both"?

- The brush rotates in one direction (CW to operator).
- The brush translates in two directions during operation.
- Verify using abrasion prone PMMA at modest (500) and advanced (5000) cycle count.



Photograph of NREL rotary brush abrasion tester (operator's perspective).

- Greatest loss of transmittance observed for Left configuration.
  - -Observed at both 500 and 5000 cycles.
  - -Translational- and tangential-velocities are additive.
- Industry feedback suggests the same most damaging configuration
  - -Many cleaning robots use a rotary brush, cleaning using Right configuration.
- Specified *accelerated* Left configuration in 62788-7-3.



Comparison of transmittance at 500, 5000 cycles.

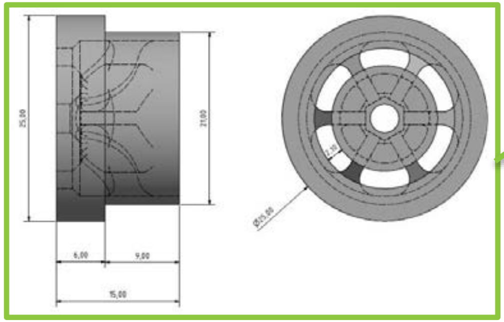
Topics

- Abrasives.
- Characterization used with abrasion tests.

- Linear brush test.
- Rotary brush test
- Falling sand test.
- Forced sand impingement test.

Details of the Falling Sand Test (SAT03)

- Apparatus: DIN 52348
  - -Build it yourself (probably).
  - \- Orifice diameter: 3.5 mm (now 3D printable).
  - -Guide tube inner diameter: 120 mm.
  - -Number of mesh sieves: 2.
  - -Fall length 1.65 m (impact velocity 5.7 $m \cdot s^{-1}$).
  - -Specimen angle: 45°.

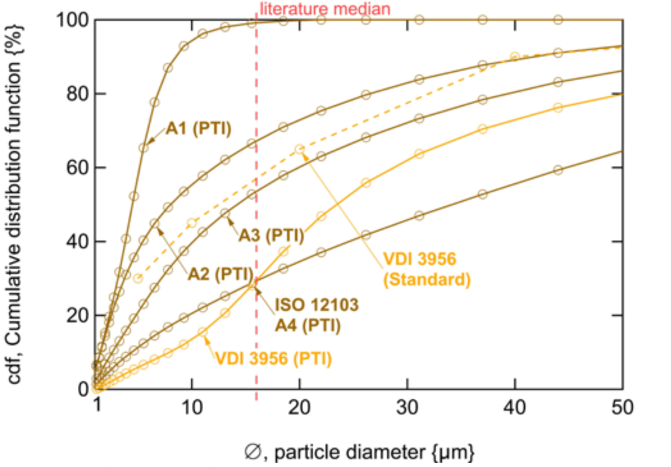


DIN 52348 orifice design.
Thanks Gerhard Mathiak!!!

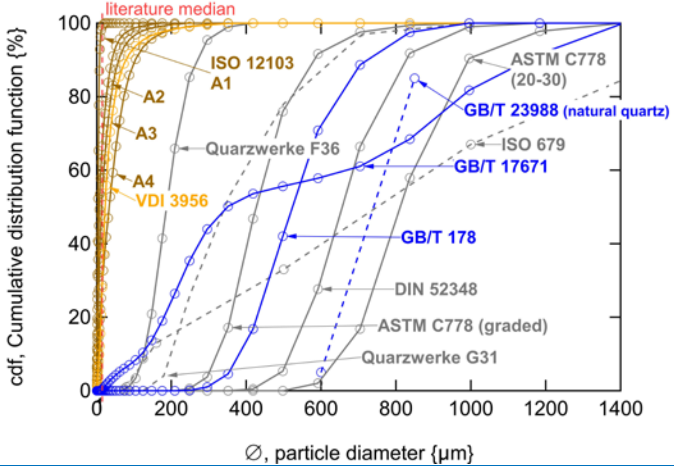
- Abrasive: DIN 52348 (silica sand, ISO 3310-1 mesh of 30-22).
  - -1.5, 3.0, 6.0, 9.0, and 12.0 kg.
  - -Condition (23°C, 50% RH) prior to testing.
  - -Do not re-use sand (rounding of grains).

NREL DIN 52348 test fixture.

Comparing Test Dusts and Test Sands



- Remember: PV module contamination, median diameter of 16 μm. *Nayshevsky et. al., Proc. Intl. Soiling Work., 2018.*
- Popular test dusts are shown (solid lines: verified at PTI using Microtrac S3500).



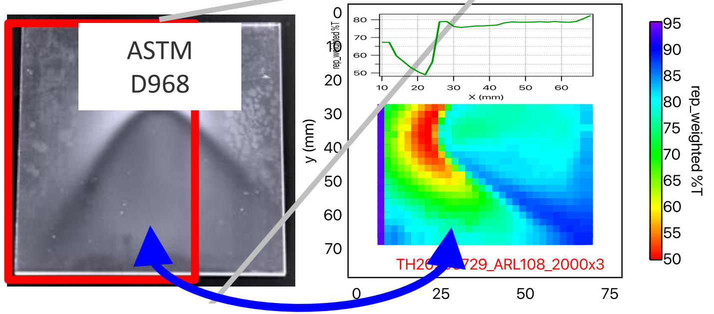
- Test dusts and test sands shown from the PV-literature and –industry.
- GB test sands are subject to export control (limited amount of sand).
- There is a notable difference in size between dust and sand.
- Larger particulate ∅ possible for blowing sand (e.g., from saltation with limited adhesion).

Optical Mapping Readily Distinguishes Falling Sand Abrasion Fixtures

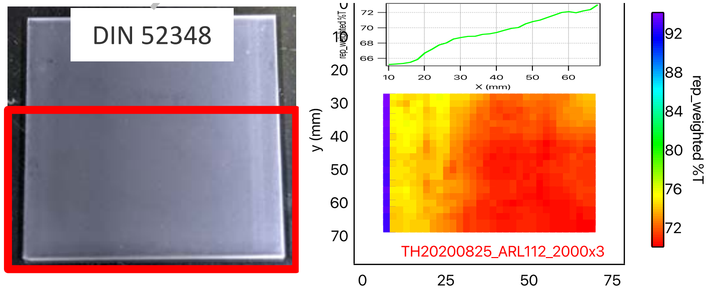
Comparison of sand drop fixtures: ASTM (left) and DIN (right) for 16 kg ASTM C778 graded sand on solar grade PMMA coupon.

Question: use ASTM or DIN fixture?

- Custom Optical Mapping Instrument developed for quantitative mapping. Khan et. al, IEEE J PV 2022, https://doi.org/10.1109/JPHOTOV.2021.3122925.
- ASTM fixture gives comet shaped wear pattern, for DIN 52348 test sand!
- $\Delta\tau_h$ of 42% identified for ASTM fixture!
- Large guide tube, mixing sieves moderate the DIN fixture.



Appearance (left) and measured τ_h (right) for PMMA specimen (ASTM D968 fixture).



Appearance (left) and measured τ_h (right) for PMMA specimen (DIN 52348 fixture).

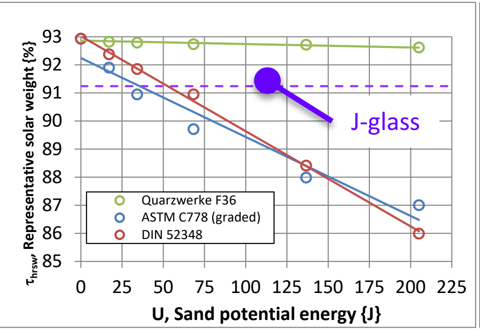
- $\Delta\tau_h$ of ~8% observed across DIN specimen.

Apply 250 rpm rotation?

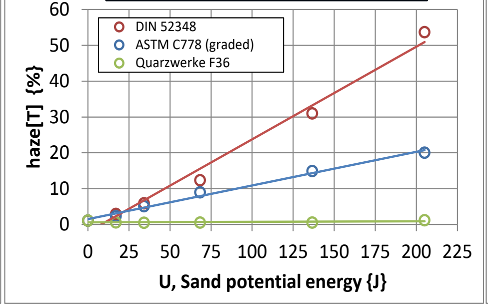
B (PS Coating) Specimens Distinguish Test Sands (1)

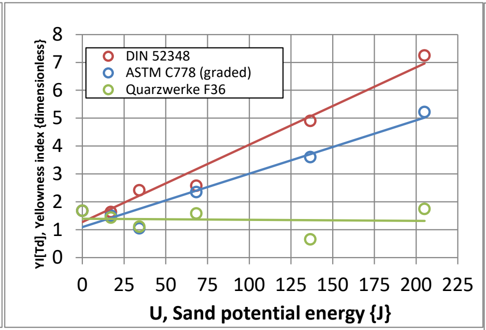
- Statistically significant $\Delta\tau_{hrsw}$ observed for ASTM C778, DIN52348 sands.
- Appearance and $\Delta\tau_{hrsw}$ B specimens (and J glass with no coating): not frosted substrate, even for 16 kg of sand!
- τ_{hrsw} for B specimens matches J glass at 2.7 – 5.3 kg of sand.
  $\Rightarrow$ Some coating may still be present but is rendered ineffective.
- Haze readily distinguishes sands; YI too (alternative measurand, > machine abrasion).
- λ_{cUV} gives limited ability to diagnose $\rightarrow$ not suggested (change similar to λ_{cUV} measurement precision).

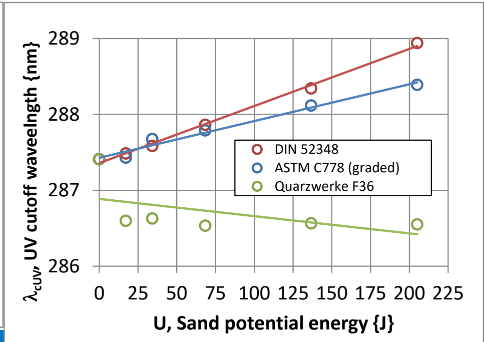
Comparison of different test sands (up to 16 Kg, for fall height of 1.315 m) on the DIN 52348 falling sand fixture for specimen type B (glass with PS coating).



$$haze = (\tau_h - \tau_d) \cdot \tau_h^{-1}$$







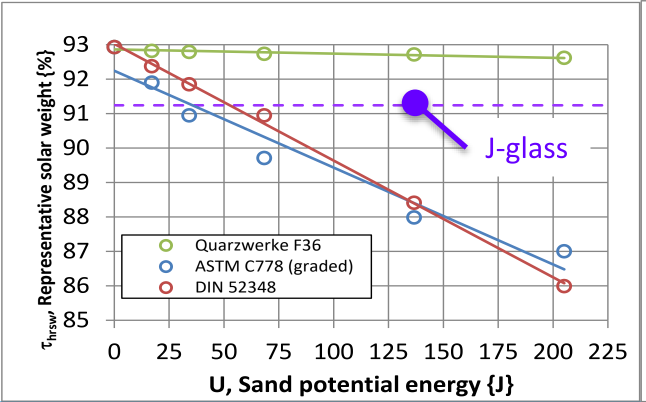
B (PS Coating) Specimens Distinguish Test Sands (2)

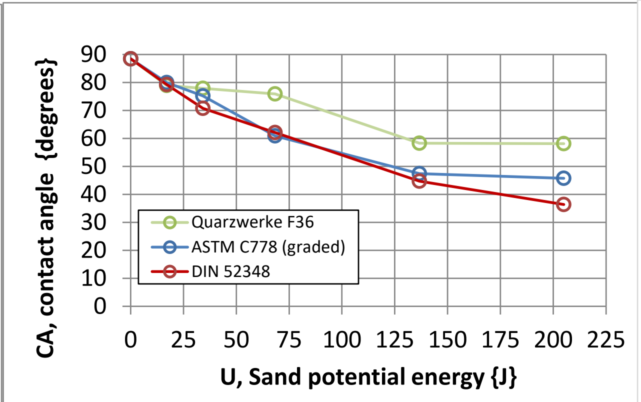
- General correlation between $\Delta\tau_{hrsw}$ & R_a (also *CA*) is consistent with accumulated wear of surface coating.
- *CA* more gradually decreased than J glass, does not reach 20°<θ<30°. Some coating remains.
- Greater magnitude of $\Delta\tau_{hrsw}$ & ΔR_a observed for B coating than J glass. Consistent with damage to a coating more delicate than substrate.
- R_a is comparable to 110 nm coating thickness for ASTM sand: severe localized damage.

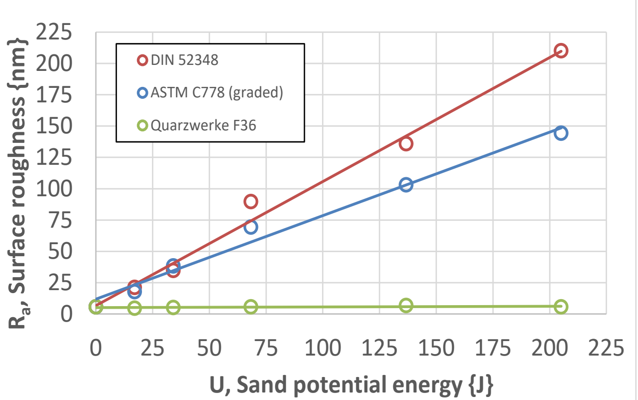
Summary of surface energy classification scheme.

greatest surface energy	
0<θ≤10	most-philic
10<θ≤50	moderately-philic
50<θ≤90	least-philic
90<θ≤120	least-phobic
120<θ≤150	moderately-phobic (Wenzel state)
150<θ≤180	most-phobic (Cassie-Baxter state)
least surface energy	

Comparison of different test sands (up to 16 Kg, for fall height of 1.315 m) on the DIN 52348 falling sand fixture for specimen type B (glass with PS coating).

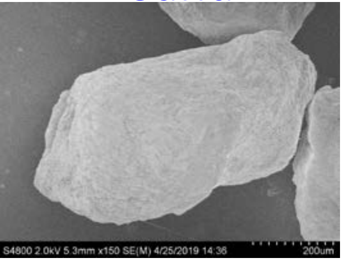




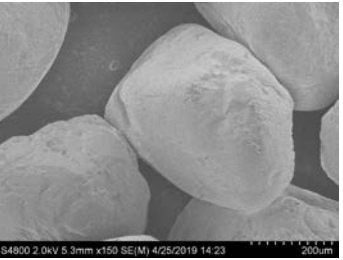


Surface Spalling Damage Mechanism Observed for PS and Glass

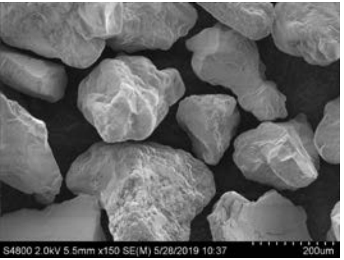
Sand



DIN 52348



ASTM C778



F36

200 μm

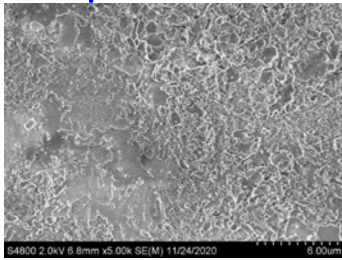
- SEM confirms a surface spalling damage mechanism for B coating and uncoated J glass. (Flakes of glasses, no individual scratches).

- SEM confirms ΔR_a includes adhered glass. (Smaller particles more readily adhere to the surface).

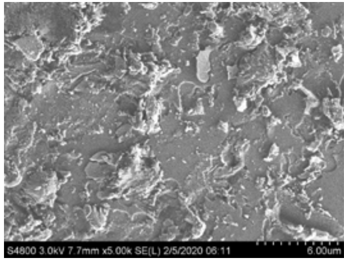
- F36 sand (smallest sand) is still orders of magnitude larger than much of the surface damage & contamination found on PV surfaces (fielded modules), but causes limited surface damage.

Specimen

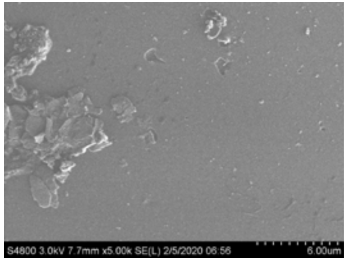
DIN 52348



ASTM C778



F36



6 μm

Morphology: of the falling sand (left); to the resulting damage morphology on specimen B (right, porous silica coating) after 16 kg of falling sand.
Note the different size scale between (left) and (right)

Topics

- Abrasives.
- Characterization used with abrasion tests.

- Linear brush test.
- Rotary brush test
- Falling sand test.
- Forced sand impingement test.

Details of the Forced Sand Impingement Test (SAT04)

- Apparatus: injection system + temperature, %RH, and carrier velocity control.
  - -Test labs with room-sized chamber (limited # international locations) or smaller custom system.
  - -Test at 63°C, 25 %RH (legacy, other standards).
  - -Carrier velocity: 18 or 30 $m{\cdot}s^{-1}$ (PV/meteorological literature, wind storm or extreme location).

- Specimens:
  - -Mount at 90° or 45° (standardize).
  - -Option to rotate specimens.
  - -3 replicates (as in other SAT methods).

- Abrasive: DIN 52348 (same as in falling sand).
  - -Concentration: 2.2 $g{\cdot}m^{-2}$ (literature).
  - -Condition sand (80°C) prior to testing.
  - -2 hour test (legacy, practical $).

Mathiak et. al, Proc. PV Module Forum, 2019.

Damage mechanism: surface spalling (assumed, TBD).

Remember From This Presentation

- Abrasives:
  - -Presently ISO 12103-1 A3 (“medium”) dust or DIN 52348 (falling & forced) sand.
  - -Future: maybe also MENA VDI 3956 and/or Al_2O_3-based.
- Characterizations:
  - -Optical performance, surface energy, roughness/morphology often used.
  - -Use of characterizations in SAT’s specified elsewhere.
- Linear & rotary brush tests:
  - -Intended to simulate cleaning of PV.
  - -Damage mode: accumulation of discrete scratches.
  - -May include bristle -scratch (⊥) and -dragging (//).
- Falling & forced impingement tests:
  - -Damage mode: localized, microscopic spalling of surface.
  - -Correlation between tests & occurrence/locations of field applicability unknown.

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☺ If interested in the PVQAT TG12-3 (soiling & coatings) activities or IEC 62788-7-3 PV abrasion standard, please contact: David.Miller@nrel.gov Participants wanted. ☺

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