"Soiling, Cleaning, and Abrasion: The Results of the Five-Year Photovoltaic Glass Coating Field Study"

Joanna Bomber[1] , Asher Einhorn[1], Chaiwat Engtrakul[1], Clare Lanaghan[1], Jeffrey Linger[1], Leonardo Micheli[1], David C. Miller[1]*, Joshua Morse[1], Helio Moutinho[1], Matthew Muller[1], Jimmy M. Newkirk[1], Lin Simpson[1], Bobby To[1], Sarah Toth[1] of NREL;
Telia Curtis[2], Fang Li[2], Govindasamy Tamizhmani[2], Sai Tatapudi[2] of ASU;
Vivian Alberts[3], Aaesha Al Nuaimi[3], Pedro Banda[3], Jim J. John[3], Gerhard Mathiak[3], Ahmad O.M. Safieh[3], Marco Stefancich[3] of DEWA;
Bader Alabdulrazzaq[4], Ayman Al-Qattan[4] of KISR;
Sonali Bhaduri[5], Anil Kottantharayil[5] of IIT-Bombay;
Ben Bourne[6], Zoe deFreitas[6], Fabrizio Farina[6], Greg Kimball[6] of SunPower; Adam Hoffman[7] of Maxeon;

[1]National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), Golden, CO 80401-3214
[2]Photovoltaioc Test Laboratory (PTL), Arizona State University (ASU), 7349 E Innovation Way South, Mesa, AZ, 85212
[3]Dubai Electricity & Water Authority (DEWA) Research and Development Center, Mohammed Bin Rashid Solar Park, Al Qudra - Saih Al Dahal, Dubai, UAE, 564
[4]Kuwait Institute for Scientific Research (KISR), Al-Jaheth Street, Shuwaikh, 13109, Kuwait
[5]Department of Electrical Engineering, India Institute of Technology (IIT) at Bombay, Powai, Mumbai 400076, India
[6]SunPowerTechnologies, 880 Harbour Way South Suite 600, Richmond, CA 94804
[7]Maxeon Solar Technologies, 51 Rio Robles, San Jose, CA 95134 USA

*Presenter (David.Miller@nrel.gov)

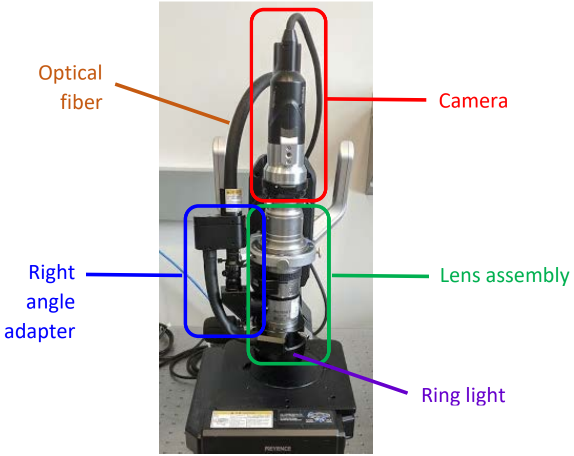
Supplementary Information

NREL/PR-5K00-90174

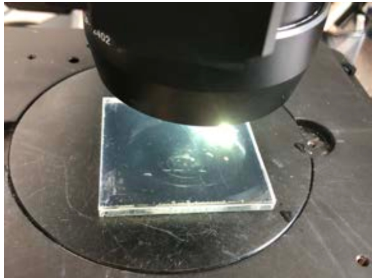
Microscopy for Determination of Particle Area Coverage (PAC) and Particle Size Distribution (PSD)

•Preparation: clean specimen back with DI water/Liquinox soap solution using TWILIX 1622 cleanroom wipes (Berkshire Corp.).

•Instrument: VHX-5000 (Keyence Corp.)
- Transmission mode lighting (tradeoff of detection vs. resolution).
-No polarizers for PAC & PSD
 (facilitate subsequent image thresholding).
-Polarizers used for representative .jpg imaging
 (maximize detection & color saturation… green background).
-Image at 200x (1 pixel is 1.07 μm x 1.07 μm). Consider ISO 13322-1.
-High Resolution High Dynamic Range (HRHDR) imaging
 1.92 MPix (tradeoff of detection vs. resolution).
-HRHDR settings:
 Use default Brightness and Contrast settings from Keyence software.
 Set Color to 0 (facilitate subsequent image thresholding).
 15<Texture<25 (keep small particles; avoid image pixel grid).
-.tiff file format (lossless, for subsequent image analysis in ImageJ).



Keyence VHX-5000 microscope (shown for components & default configuration).



Keyence VHX-5000 microscope (shown for PAC & PSD imaging).

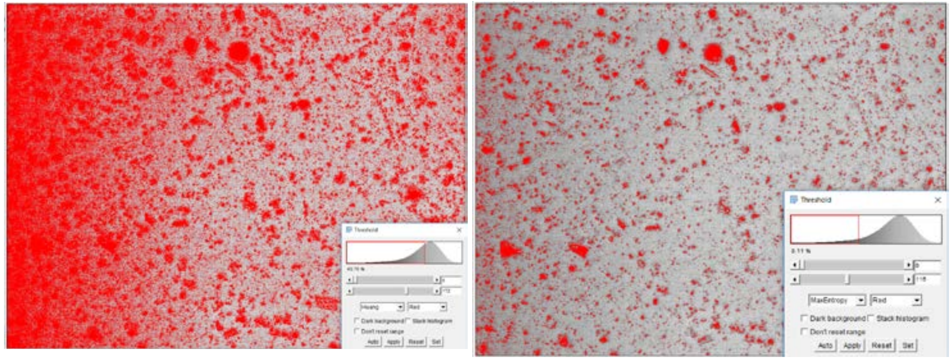
Microscopy for Determination of Particle Area Coverage (PAC) and Particle Size Distribution (PSD)

- Goal: automated image thresholding and analysis to limit subjectivity and operator bias.

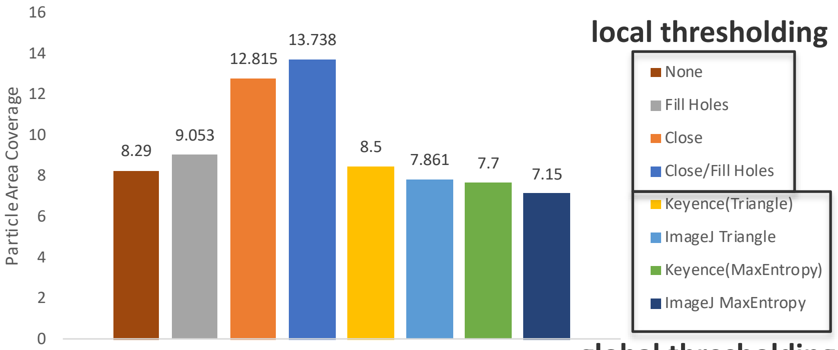
ImageJ macro code (Java based) to automate thresholding & analysis:

- Use local thresholding (Phansalkar method) to reduce effects of specimen misalignment & curvature, maximizing identification including smallest particles.
- P=0.5 coefficient setting for Phansalkar method for consistent identification of pixel-scale particles.
- Use Fill operation to aid thresholding of large particles.
- Default to Fill up to 500 μm^2. If max[perimeter]>1000, then Fill to 50 μm^2 (limit effect of scratches or fungus).
- Automated scratch and fungus detection with separate binning of the results.
- Do not use Close operation to avoid excess merging of adjacent pixel-scale particles into I, L, T, etc geometries.
- Subsequent PSD analysis from Area (more like an ideal) not Feret size (including I, L, T, etc geometries).

Phansalkar et. al., Int. Conf. Commun. Signal Process., 2011, 218-220.



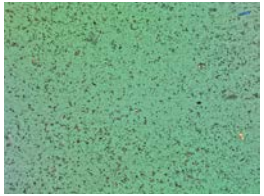
Examples of global (above left) and local (above right) thresholding in ImageJ.



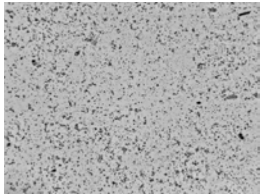
Comparison of PAC for local & global thresholding to develop an analysis algorithm.

Imaging, Thresholding, and Analysis Procedure @ NREL (1)

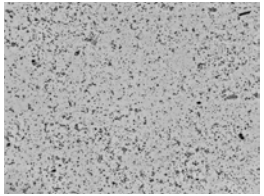
Microscope imaging (Keyence)
-Light transmitted through specimens.
-Representative image using polarizers.
-HRHDR. With
-200x, 1.92 Mpix image (1.1 μm·pixel^{-1})



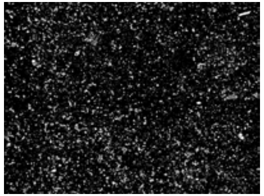
Microscope imaging (Keyence)
-Remove polarizers for analysis image.
-Post processing (brightness, contrast, texture, color).



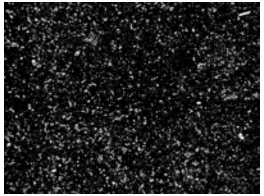
Scale Image (ImageJ)
-1.07 μm·pix^{-1}



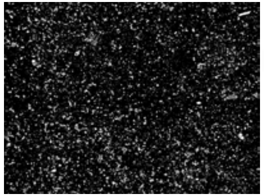
Local thresholding (ImageJ)
-Phansalkar method (radius=1000, P_1=0.4, P_2=0.3).



Analyze Objects (ImageJ)
Calculate an average circularity for the image, excluding objects smaller than 200 μm^2.



Characterize Image (ImageJ)
Coupon location and cleaning method are considered to determine if fungi are expected

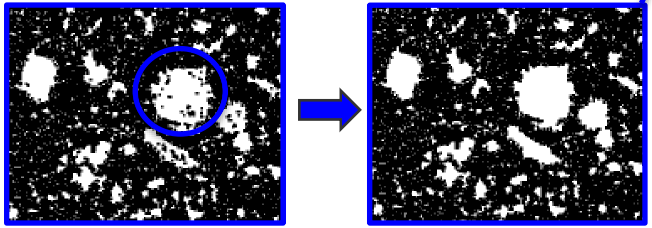


Full-Fill Holes (up to 750 pixels) (ImageJ)
-If fungi are not expected AND avg[circularity] is normal (i.e. >5 for Dubai, Kuwait, Mesa).

Conservative-Fill Holes (up to 10 pixels) (ImageJ)
-If fungi are expected AND avg[circularity] is normal (i.e. <25 for a Mumbai, <35 Sacramento

User-Fill Holes (up to 10 or 750 pixels) (ImageJ)
-If avg[circularity] is abnormal, the user chooses between full and conservative filling options.

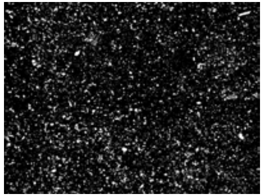
Example: Fill Holes



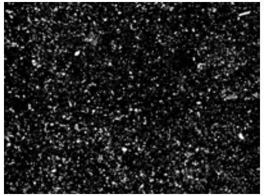
Circularity:

$$c = \frac{4\pi A}{P^2}$$

Imaging, Thresholding, and Analysis Procedure @ NREL (2)

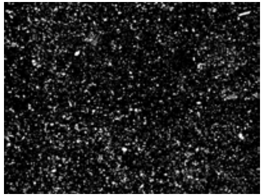


Analyze Objects
(ImageJ)
-Analyze PAC, STDEV[PAC] from pixels.
-Save area data.

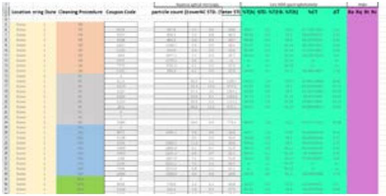


Watershed All Objects
(ImageJ)
-Watershed all objects (where applicable) for DUB, KUW, AZ, SAC.

Watershed Select Objects
(ImageJ)
-Watershed objects with circularity > 5 for MUM.

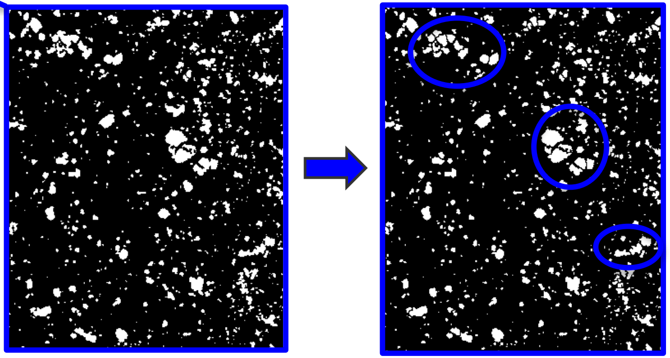


Analyze Objects
(ImageJ)
-Calculate #Particles and STDEV[perimeter].
-Save shape data.
(Python)
-Calculate C {g·m^{-2}}.

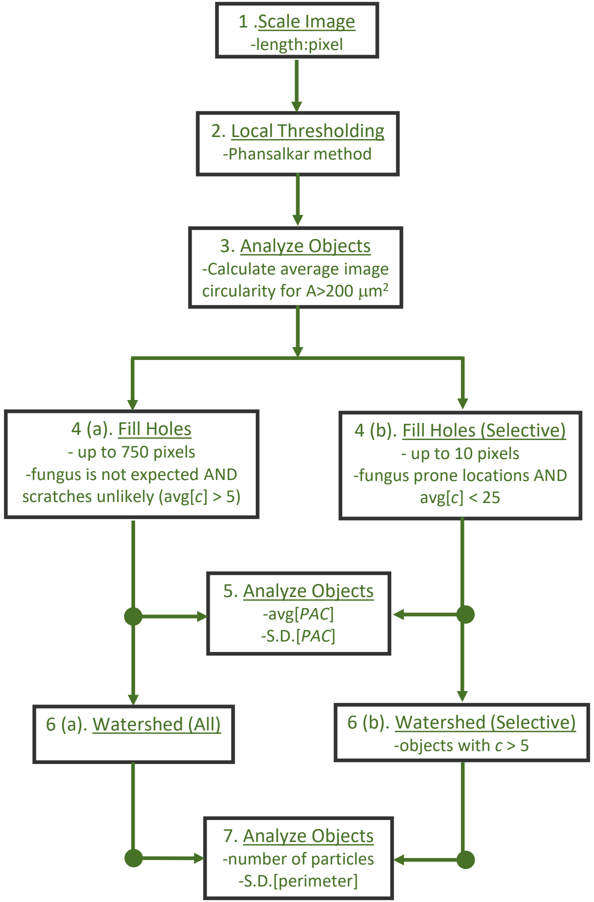


Compile data
(Python/XLWings/Excel)
-Avg. key statistics from (5) images taken for each coupon.

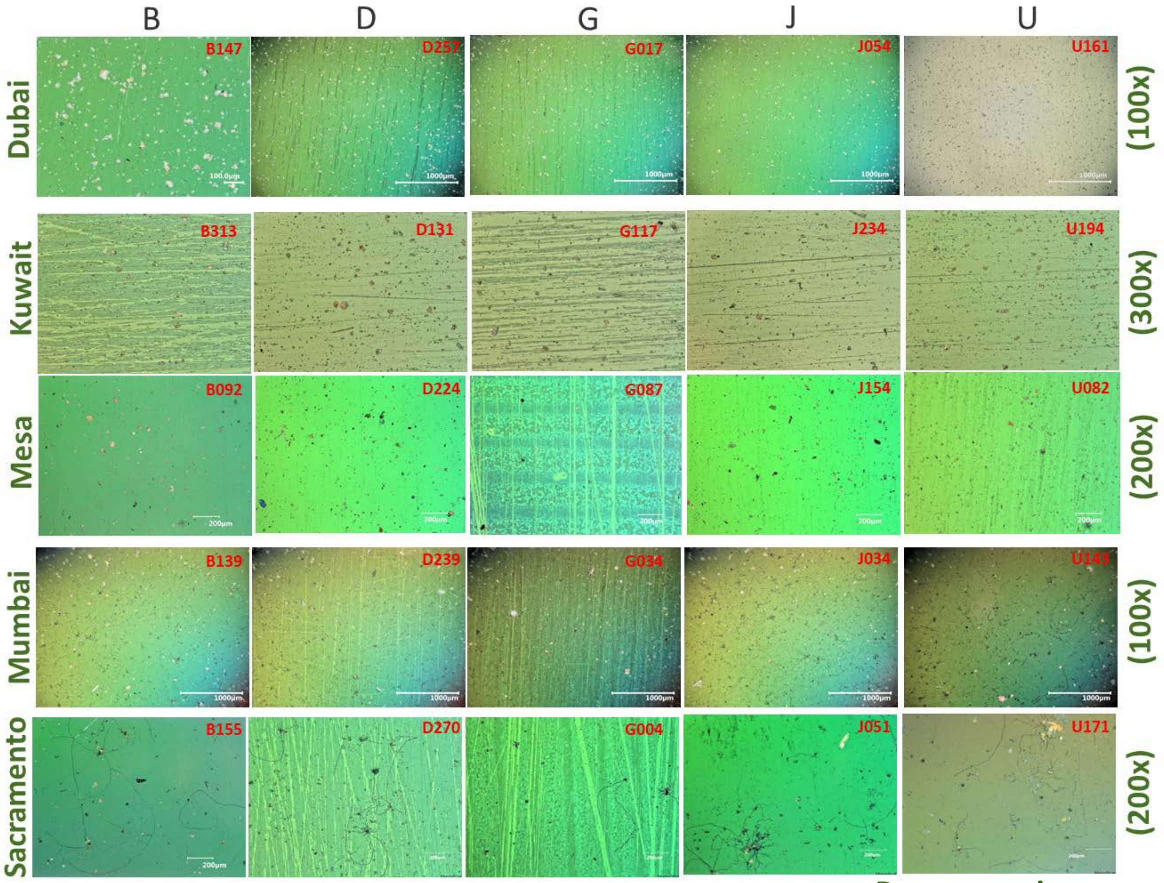
Example: Watershed



Imaging, Thresholding, and Analysis Procedure @ NREL (3)

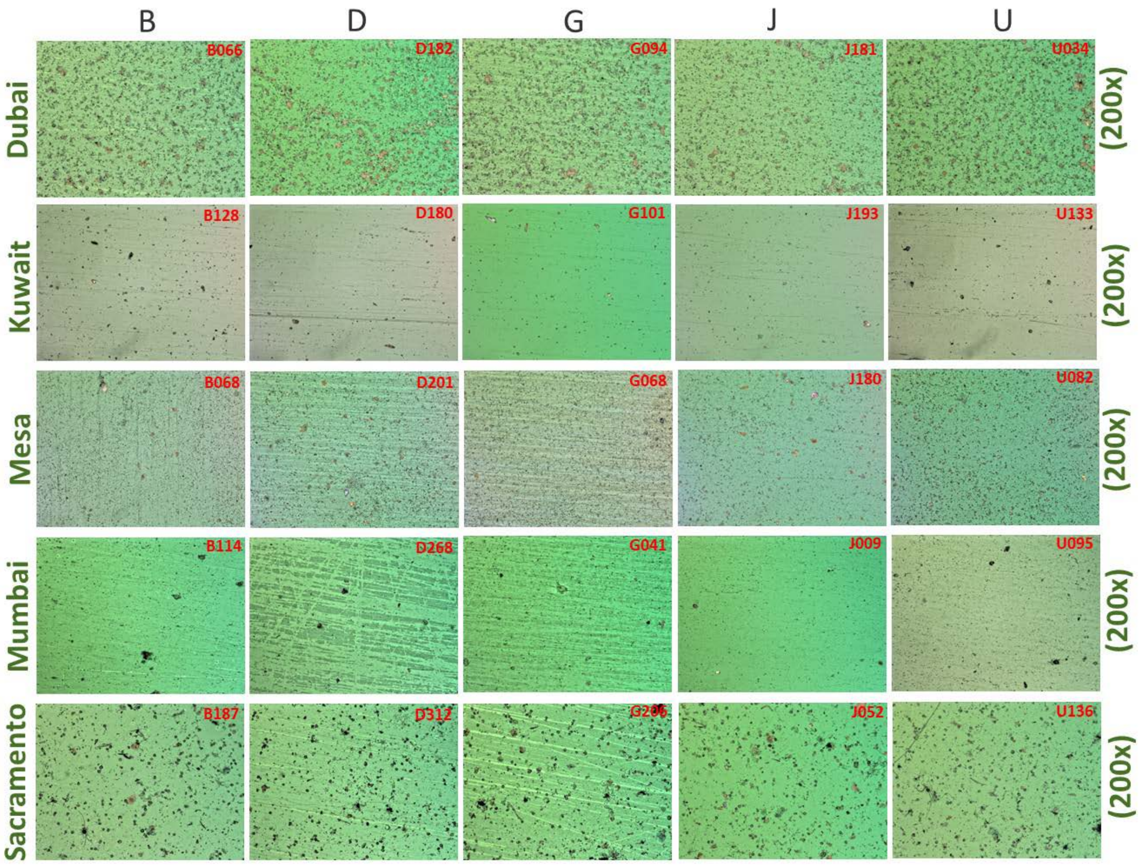


Microscopy of 1y DB Samples (Magnifications Including 100x, 200x, 300x)



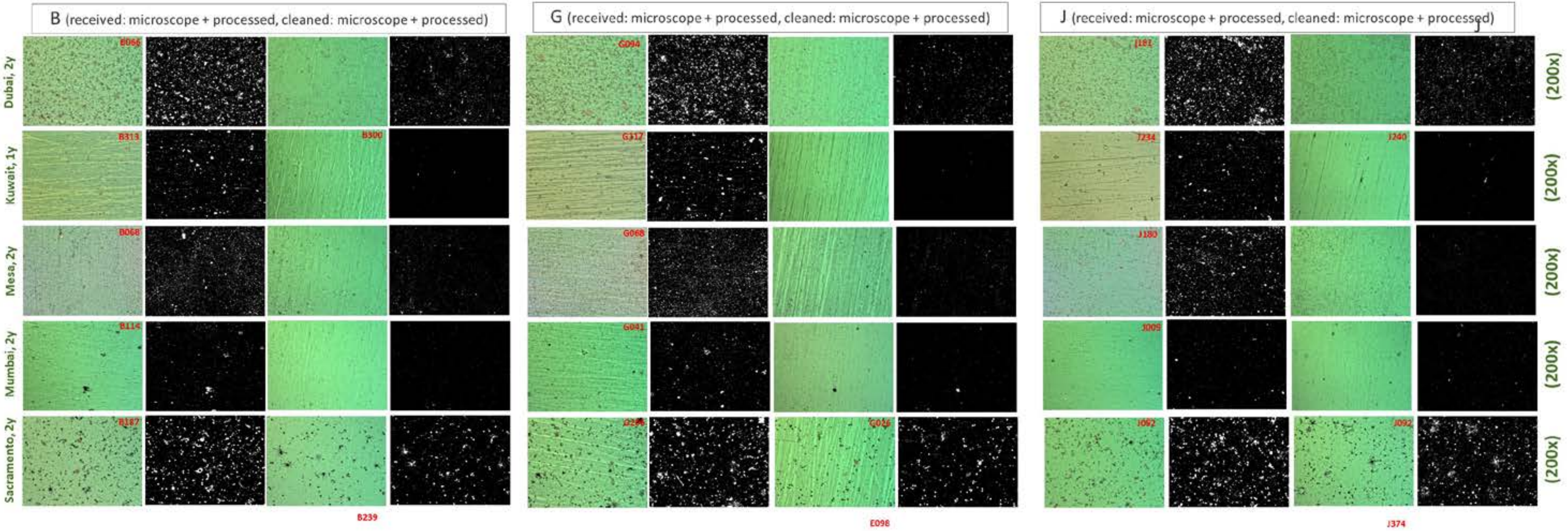
Representative examples shown for five indices of interest, for all five sites.

Microscopy of 2y DB (Magnification 200x)



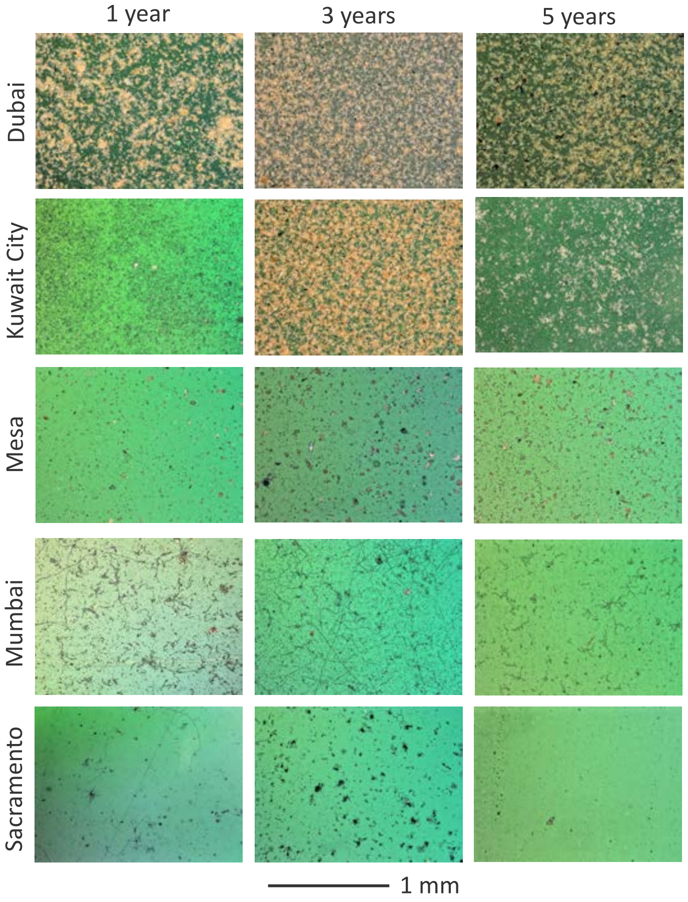
Representative examples shown for five indices of interest, for all five sites.

Comparison of DB Microscopy and Corresponding Image Thresholding



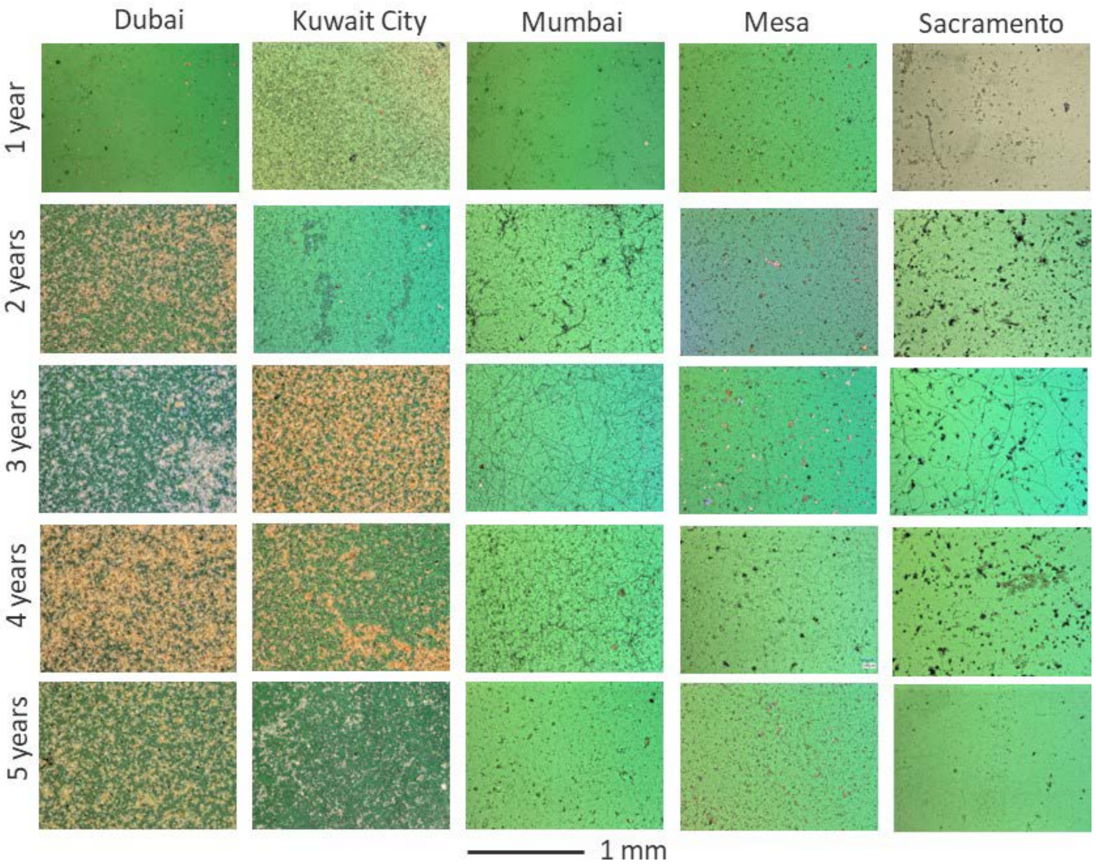
Representative examples shown for PS coatings, uncoated glass for early in the study, for all five sites.

Index J (uncoated glass) NC Samples 1y vs. 3y vs. 5y (200x)



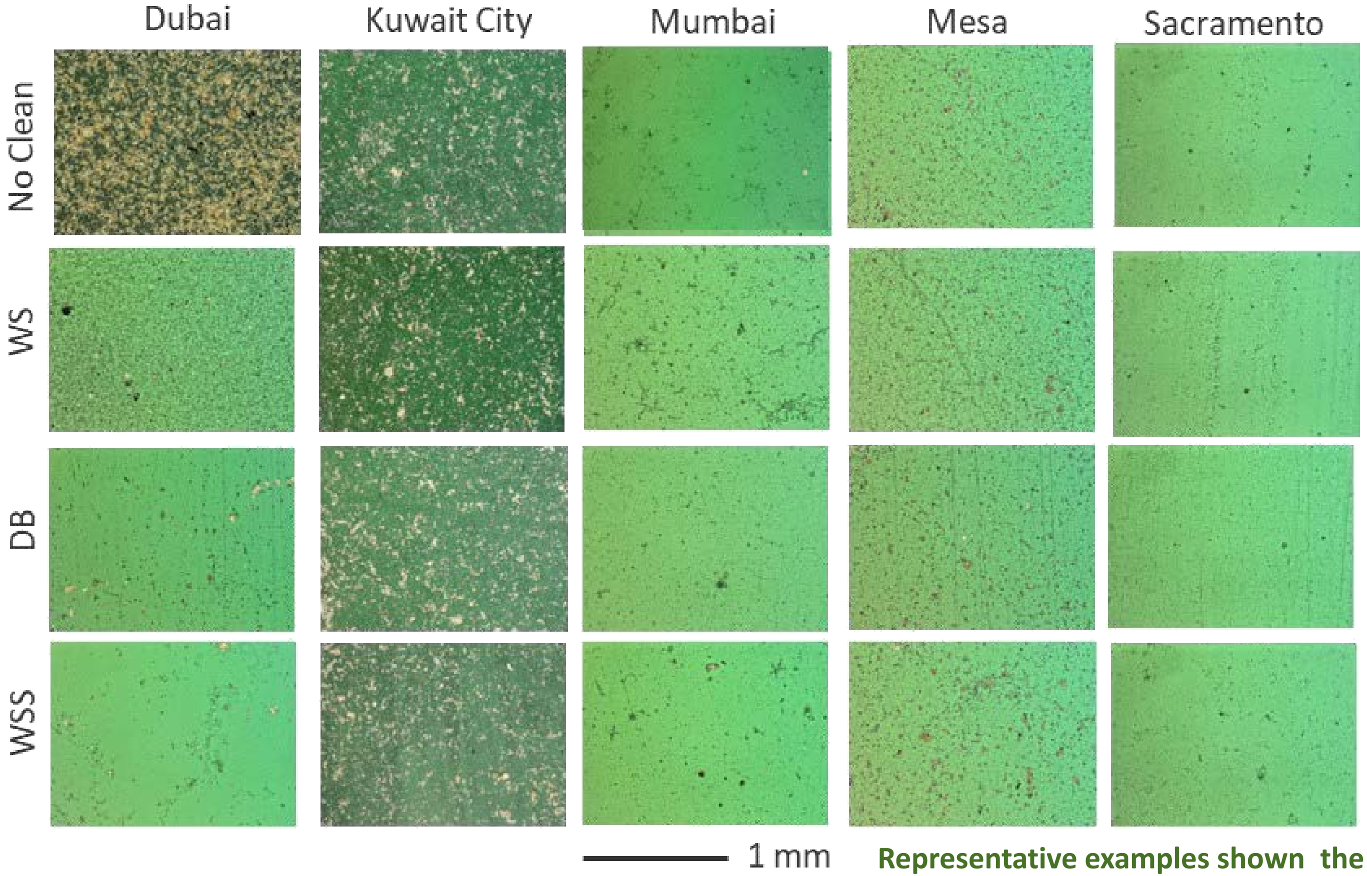
Representative examples shown for all five sites.

Index J (uncoated glass) NC Samples Through Five Years(200x)



Representative examples shown through five years.

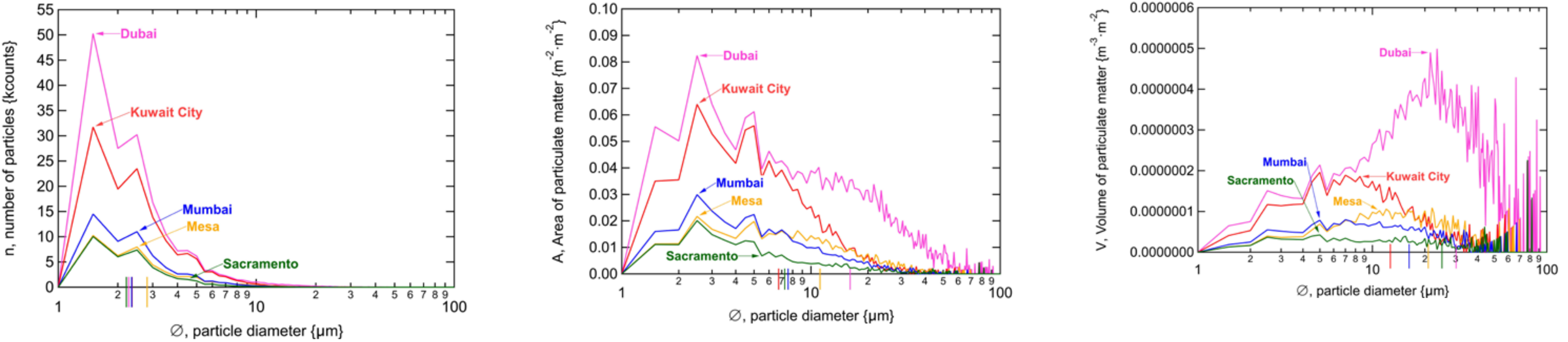
Index J (uncoated glass) Samples At Five Years(200x)



Representative examples shown the five year read point.

- While the NC coupons were not affected, the specimen cleaning was interrupted at some sites by the CoViD pandemic.

Distribution of Particle Size (@ 1y)



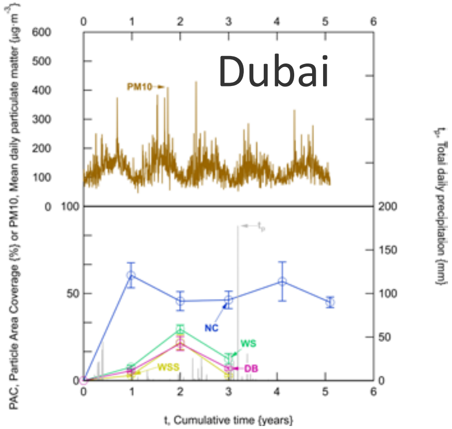
•Median size (p_{50}) varies between 2 µm and 3 µm (*n*); 6 µm to 20 µm (*A*) and from 10 µm to 30 µm (*V*).

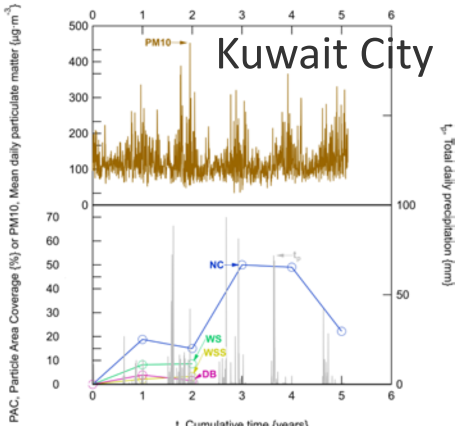
•*n* directly identifies size of contamination; *V* may be compared to atmospheric sciences.

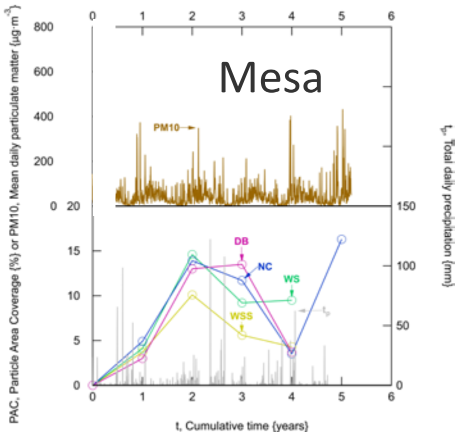
•With a 1.07 µm resolution, optical microscope can only assess PM10, which often varies from 0.5 µm to 30 µm

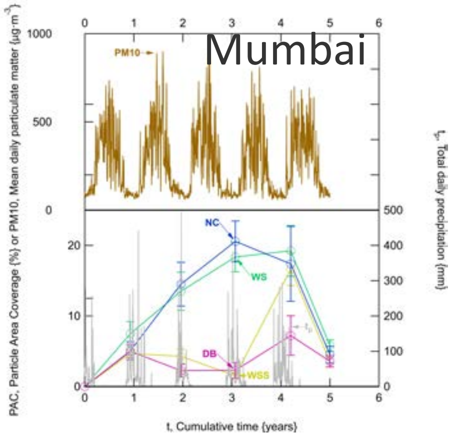
•p_{50} size greater than 30 µm (for Dubai) suggests that cementation has occurred.

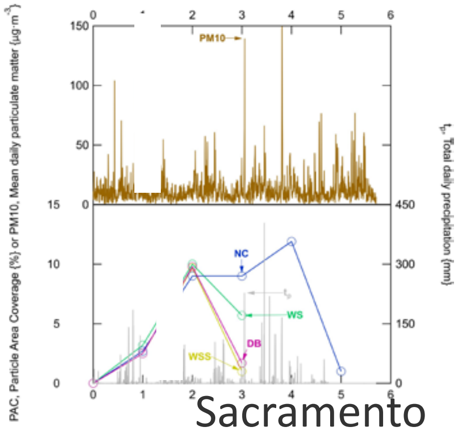
PAC: Comparison Cleaning Methods AVG[B, D, G, J, U] Coupons







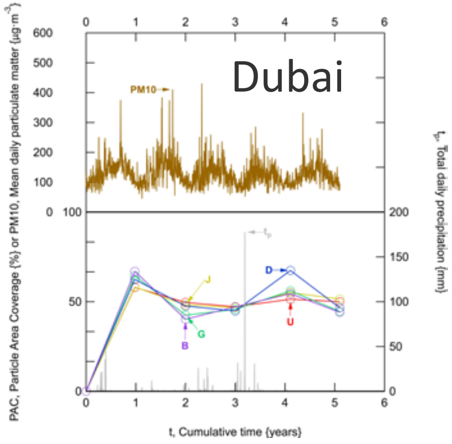


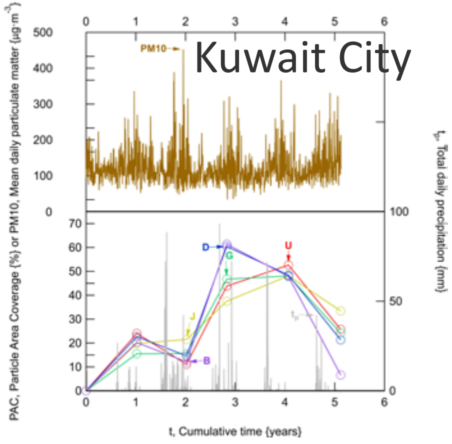


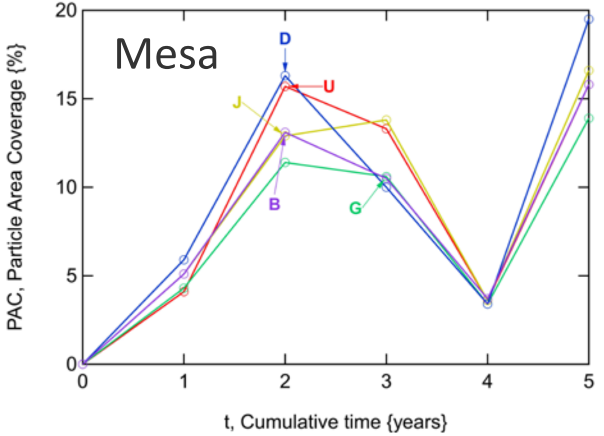
- Cleaning can improve efficiency by 10's of percent!
- Efficacy of contact cleaning (WSS and DB) is greatest, when it can be allowed.
- Erratic PAC with time in may reflect fortuitous timing of sample collection (natural cleaning.)

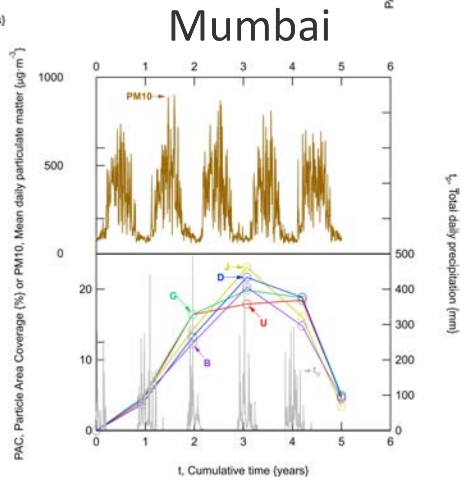
Data shown for all 4 cleaning methods for all 5 sites, where the history of cleaning was not affected by the CoViD pandemic.

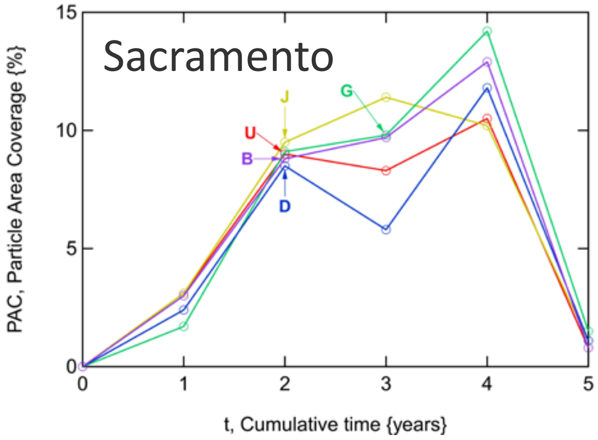
PAC: Contamination Comparison, by Coating (No Clean)





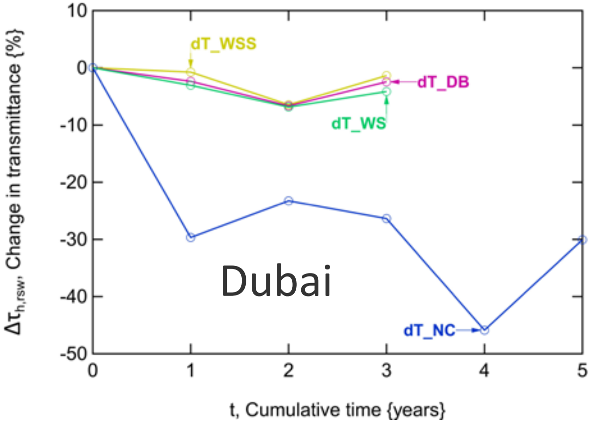


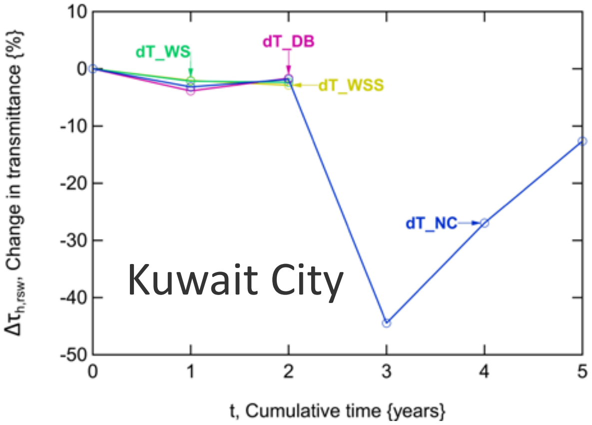


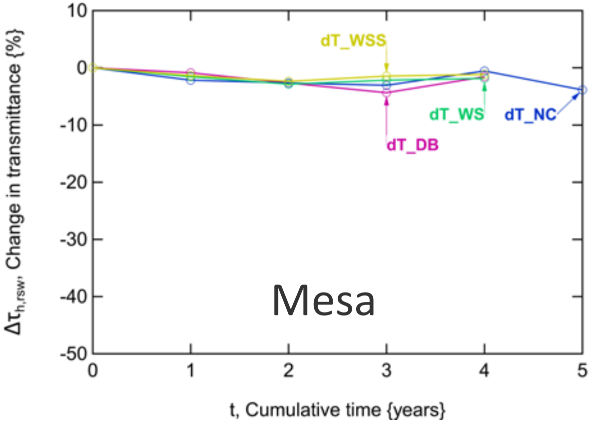


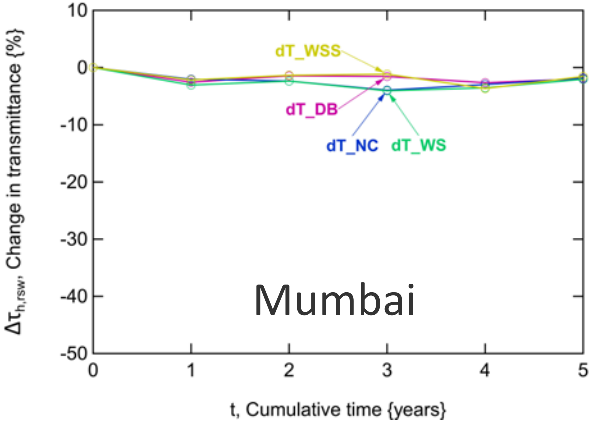
Data shown for 5 indices of interest for all 5 sites.

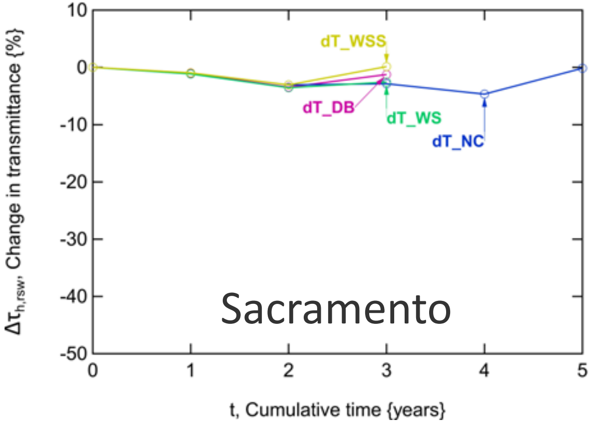
T_h: Comparison Cleaning Methods AVG[B, D, G, J, U] Coupons





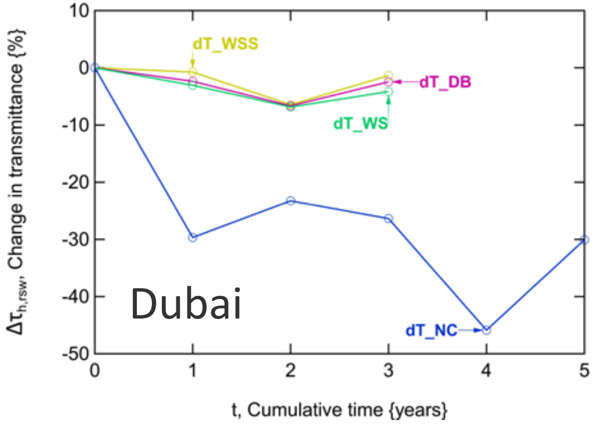


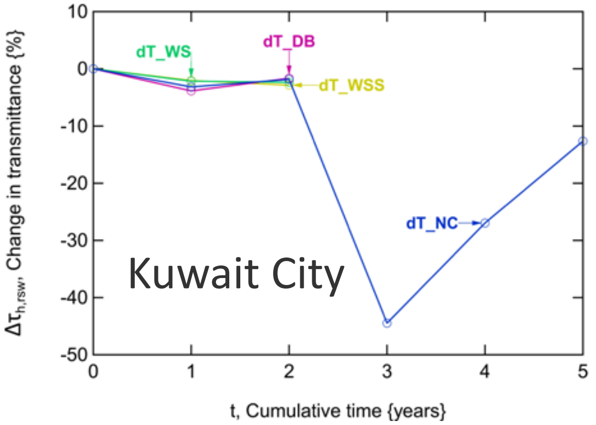


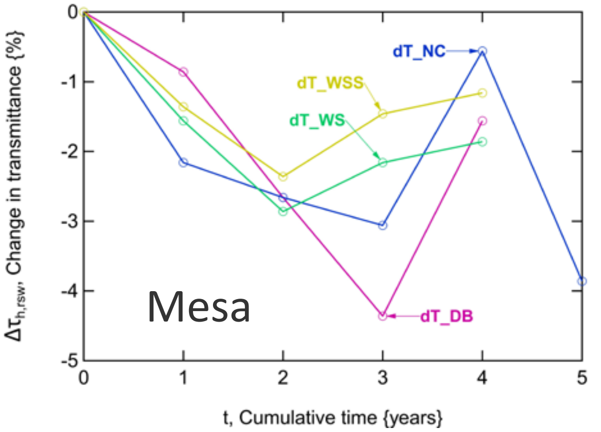


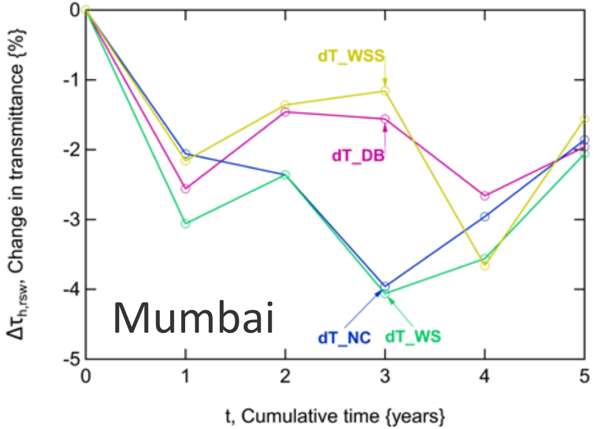
Data shown for all 4 cleaning methods for all 5 sites, where the history of cleaning was not affected by the CoViD pandemic.

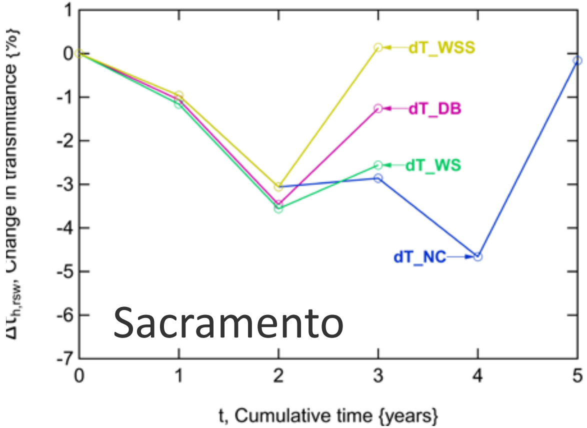
T_h: Comparison Cleaning Methods AVG[B, D, G, J, U] Coupons





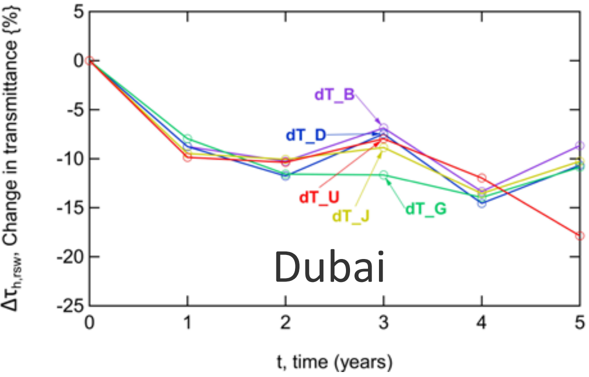


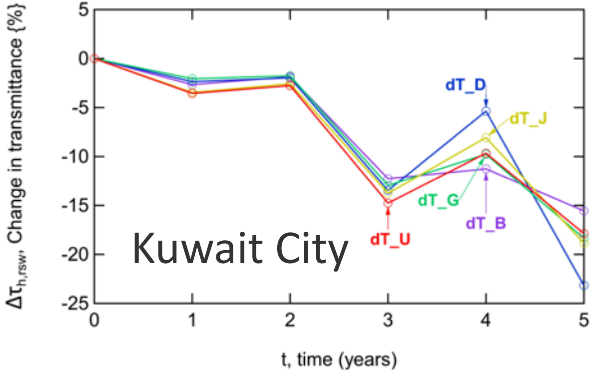


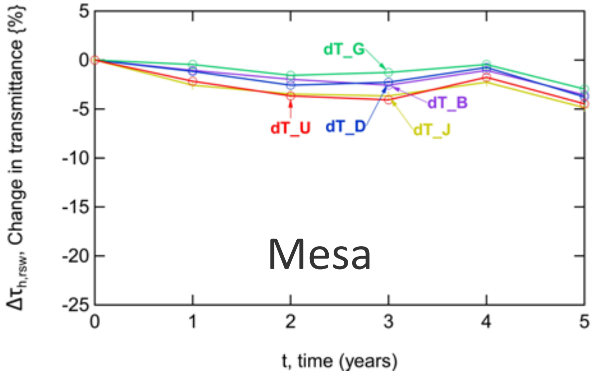


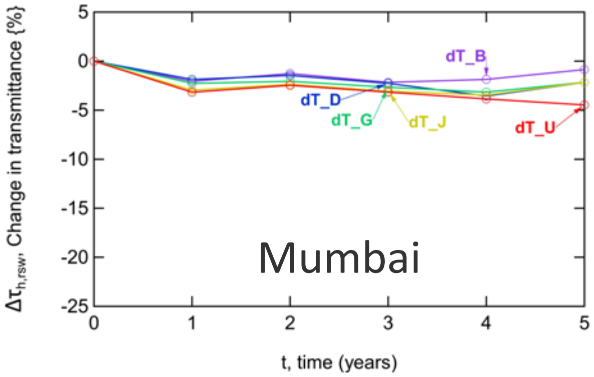
Data shown for all 4 cleaning methods for all 5 sites, where the history of cleaning was not affected by the CoViD pandemic.

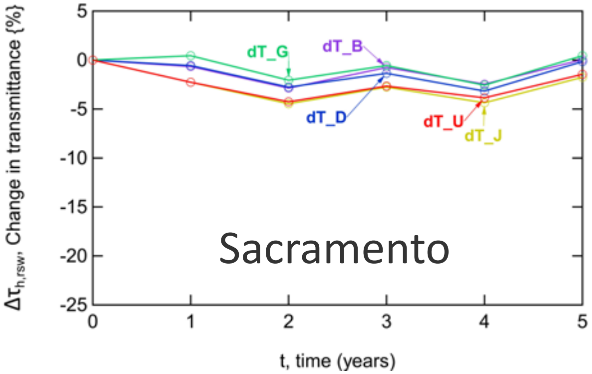
T_h: Contamination Comparison, by Coating (No Clean)





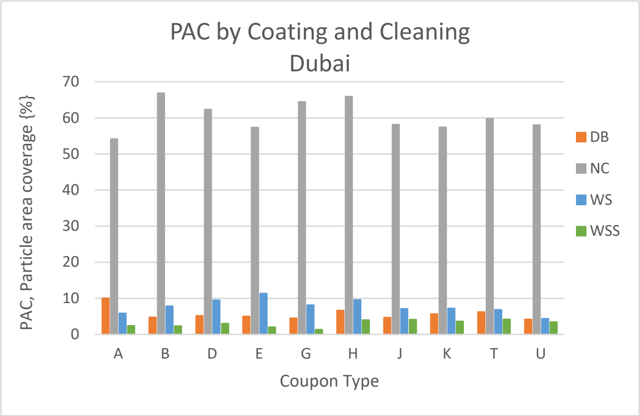


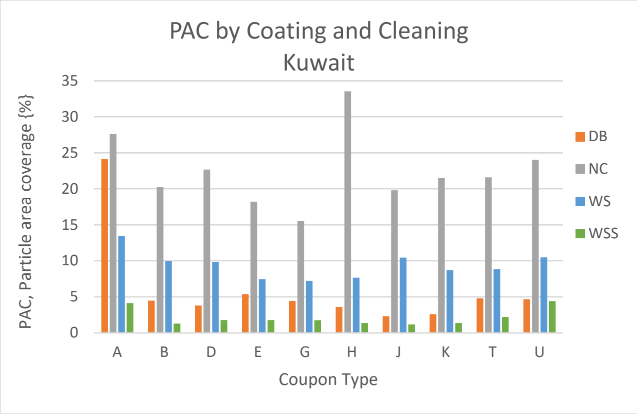


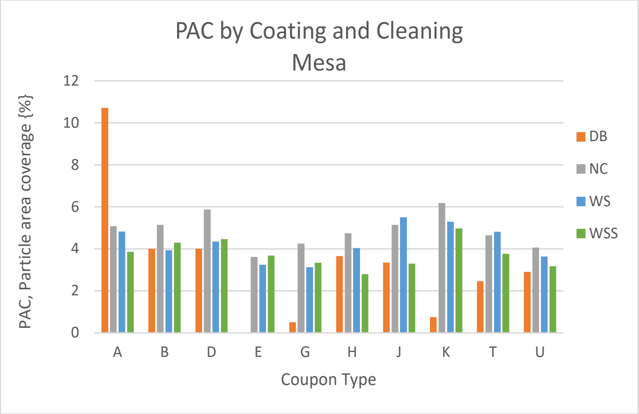


Data shown for 5 indices of interest for all 5 sites.

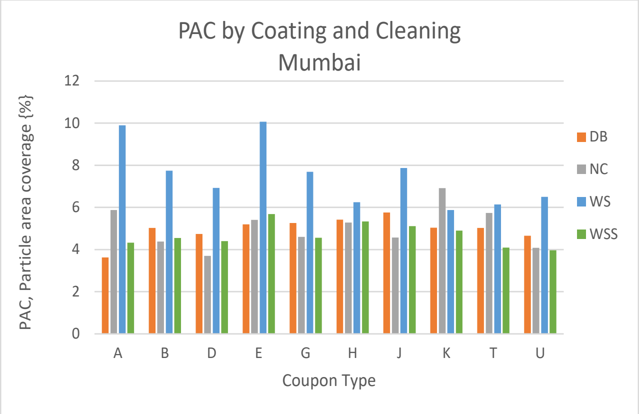
The Cleaning Methods Are Distinguished Between the Field Sites (1y)

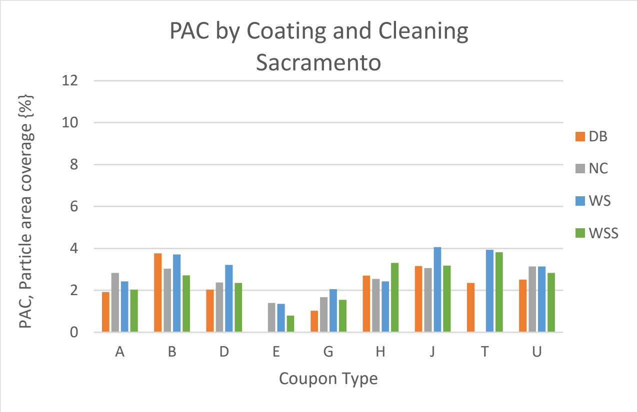






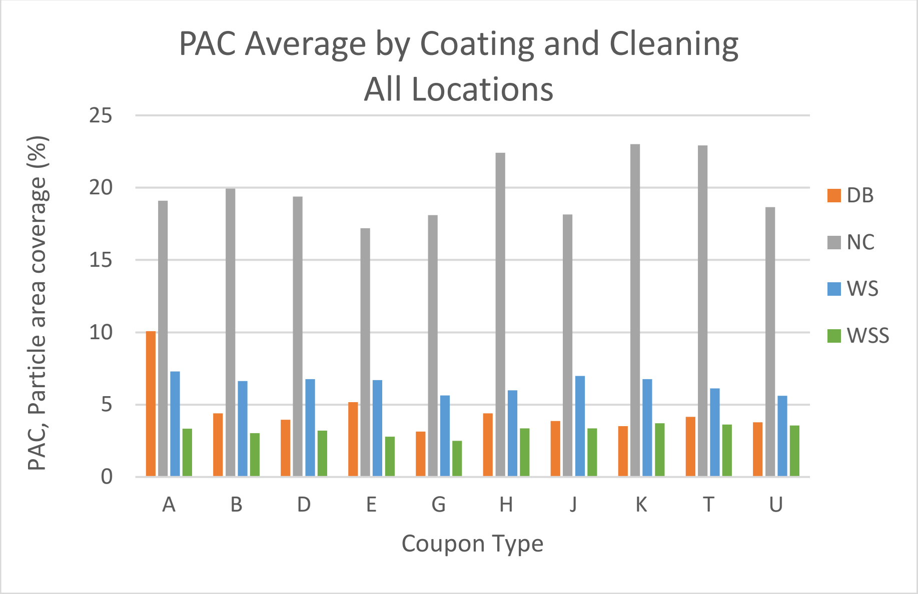
Data shown for 1 y read point.





- MENA locations significantly more contaminated than other sites, i.e., NC>>WS>DB>WSS.
- There is a notable distinction between No Clean (NC) in MENA and other cleaning methods (DB, WS, and WSS).
- WS uniquely most contaminated in Mumbai (most fungus).
- A (PMMA) distinguished for DB (scratches from cleaning).

Cleaning Methods and Coatings Are Distinguished in the Field Study (1y)



SPECIMEN INDEX	AVERAGE RANK {dimensionless}	STDEV RANK {dimensionless}	FINAL RANK {dimensionless}
G	12.5	11.3	1
U	15.8	8.1	2
E	18.8	14.7	3
D	19.0	12.7	4
H	20.5	10.2	5
B	20.8	13.0	6
J	21.0	13.1	7
T	24.5	12.0	8
A	24.8	13.8	9
K	27.5	13.9	10

The (10) specimens were ranked (1-40) by cleaning method according to PAC. The average and S.D. (1σ) are given by specimen, with a final (overall) rank.

- In the average[PAC], the effect of cleaning is readily distinguished for all specimen types.
- In average[PAC], cleaning methods were more subtly distinguished, i.e. WS>DB>WSS.
- In average[PAC], the coatings are not as readily distinguished, but can be sorted by rank order.
- Monolithic (no coating) specimens (A, J, K, T) ranked behind coated specimens, suggesting added value (antireflective and/or antisoiling capability).

Comparison of Coating Performance by Coating or Location

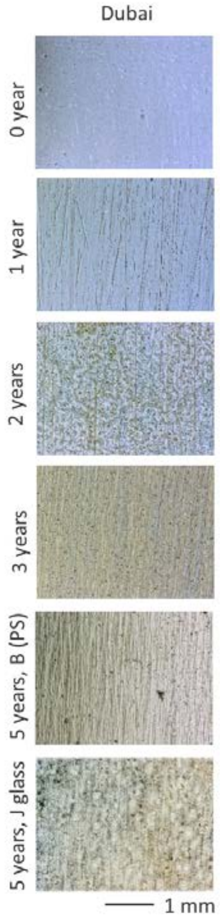
	SPECIMEN INDEX	RAW DATA: AVERAGE LEVEL SOILED (UNAGED) {%}	RAW DATA: VARIATION IN LEVEL, 1 S.D. {%}	RANK ANALYSIS: AVERAGE RANK {dimensionless}	RANK ANALYSIS: VARIATION IN RANK, 1 S.D. {dimensionless}	RANK ANALYSIS: OVERALL RANK {dimensionless}
$\tau_{h,rsw}$, hemispherical representative solar weighted transmittance	B	87.9 (92.9)	5.9	2.2	1.1	1 (cleanest)
	G	87.5 (94.1)	6.6	2.2	1.0	2
	D	87.4 (93.2)	6.1	2.8	1.2	3
	U	86.8 (91.3)	22.0	3.7	1.1	4
	J	86.7 (91.2)	6.7	4.0	1.0	5 (dirtiest)
PAC, particle area coverage	unaged	0	N/A	N/A	N/A	unaged
	G	12.0	11.0	2.6	1.3	1 (cleanest)
	J	12.4	10.3	3.0	1.4	2
	U	12.4	10.1	3.0	1.4	3
	B	12.4	10.4	3.1	1.3	4
	D	12.6	10.4	3.1	1.3	5 (dirtiest)

Comparison of the effectiveness of the select coatings and substrate materials for all sites and cleaning methods through the five-year study. The optical performance (average $\tau_{h,rsw}$ through the study), obscuration (average PAC), and cumulative rank order is given for the five select coatings of interest based on the transmittance or quantitative microscopy from each read point and at each location.

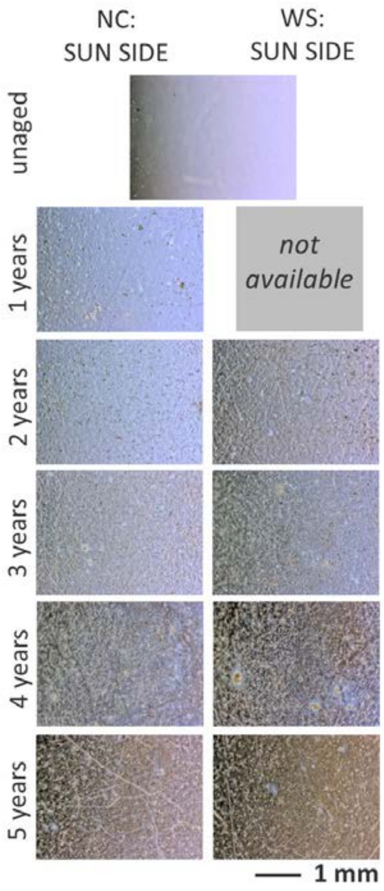
	LOCATION	RAW DATA: AVERAGE LEVEL {%}	RAW DATA: VARIATION IN LEVEL, 1 S.D. {%}	RANK ANALYSIS: AVERAGE RANK {dimensionless}	RANK ANALYSIS: VARIATION IN RANK, 1 S.D. {dimensionless}	RANK ANALYSIS: OVERALL RANK {dimensionless}
$\tau_{h,rsw}$, hemispherical representative solar weighted transmittance	unaged	91.2	N/A	N/A	N/A	unaged
	Sacramento	89.4	1.7	2.4	1.4	1 (cleanest)
	Mumbai	89.7	0.9	2.6	1.3	2
	Mesa	89.2	1.0	2.8	1.2	3
	Kuwait City	83.2	11.6	3.6	1.5	4
	Dubai	82.1	13.0	3.5	1.4	5 (dirtiest)
PAC, particle area coverage	unaged	0	N/A	N/A	N/A	unaged
	Sacramento	5.4	4.2	1.7	0.9	1 (cleanest)
	Mesa	9.8	5.5	2.9	1.0	2
	Mumbai	8.5	6.4	3.0	1.4	3
	Kuwait City	16.7	13.6	3.5	1.6	4
	Dubai	21.7	20.2	3.8	1.2	5 (dirtiest)

Comparison of the effectiveness of the uncoated glass substrate (index J) for all cleaning methods through the five-year study. The optical performance (average $\tau_{h,rsw}$ through the study), obscuration (average PAC), cumulative rank order is given based on the transmittance or quantitative microscopy from each read point and at each location.

Evolution of Coating Abrasion From DB vs. NC and WS in Mumbai

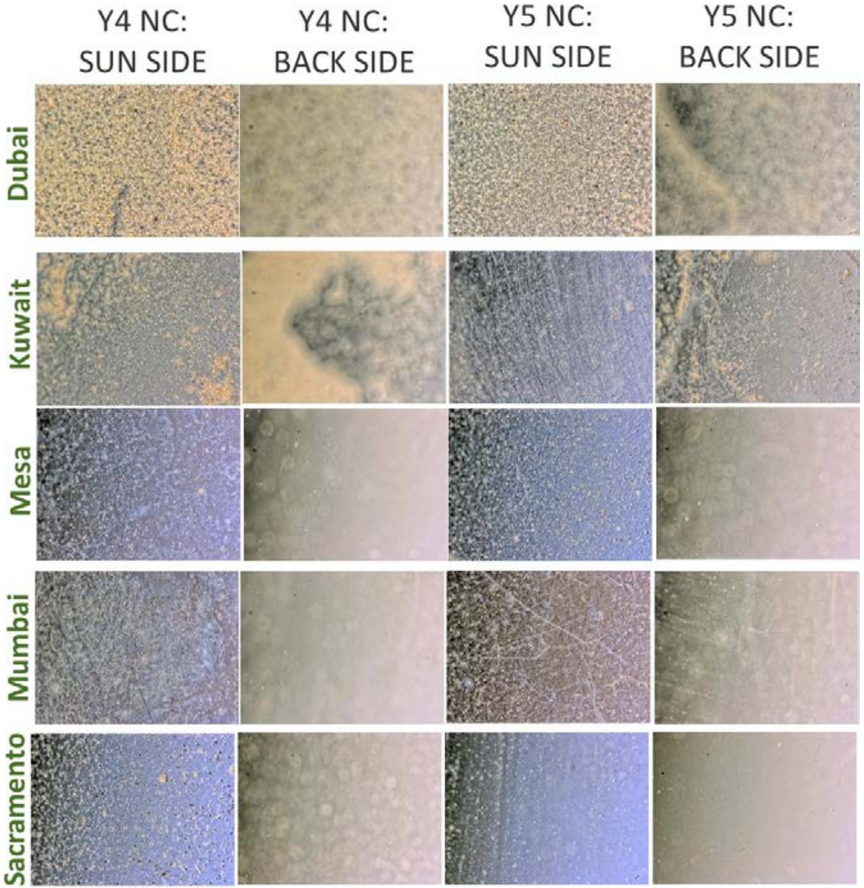


Visualization of the presence and integrity of the B (porous silica) coating through dry brush (DB) cleaning in Dubai. From its thickness, the coating appears blue in oblique imaging (years 0, 1, and 2). In contrast, the bare glass substrate appears brown in oblique imaging (years 3 and 5). Because it was not cleaned through the CoViD pandemic year 4 is omitted. Index J (uncoated glass substrate, after five years of DB cleaning in Dubai) is shown for comparison.



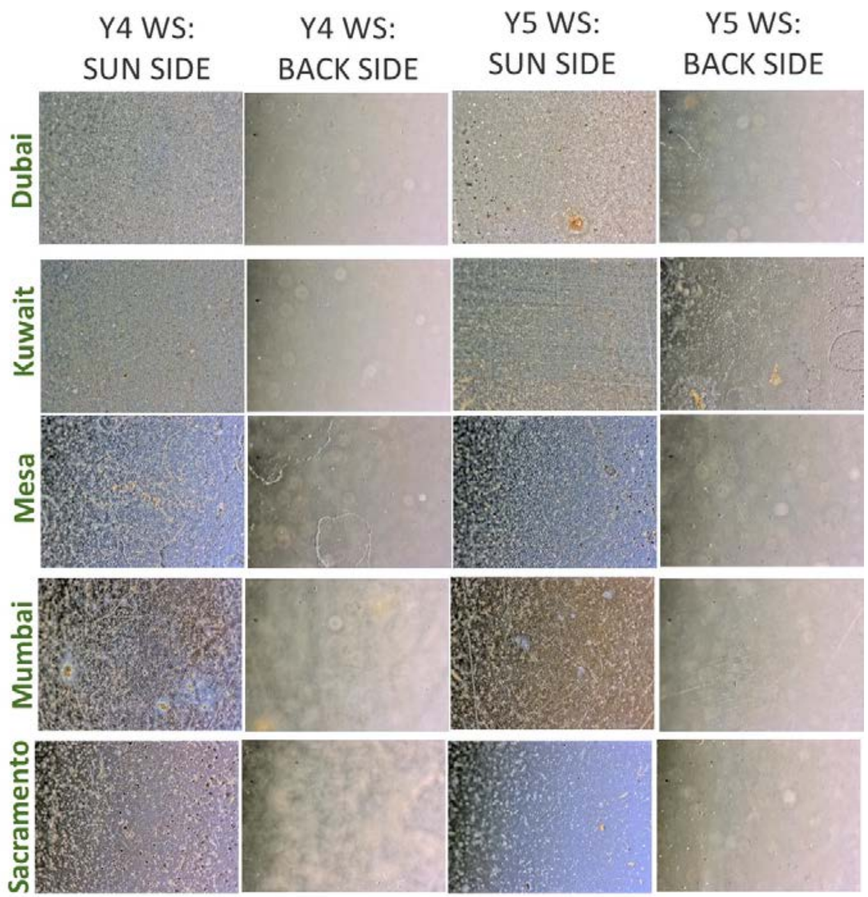
Visualization of the presence and integrity of the B (porous silica) coating on the incident surface through no clean (NC) and water spray (WS) cleaning in Mumbai. From its thickness, the coating appears blue in oblique imaging (years 0, 1, 2, and 3). In contrast, the bare glass substrate appears brown in oblique imaging (years 4 and 5).

Oblique Microscopy of Latter NC Samples (Magnification Setting of 200x)



Representative examples shown for index B, for all five sites.

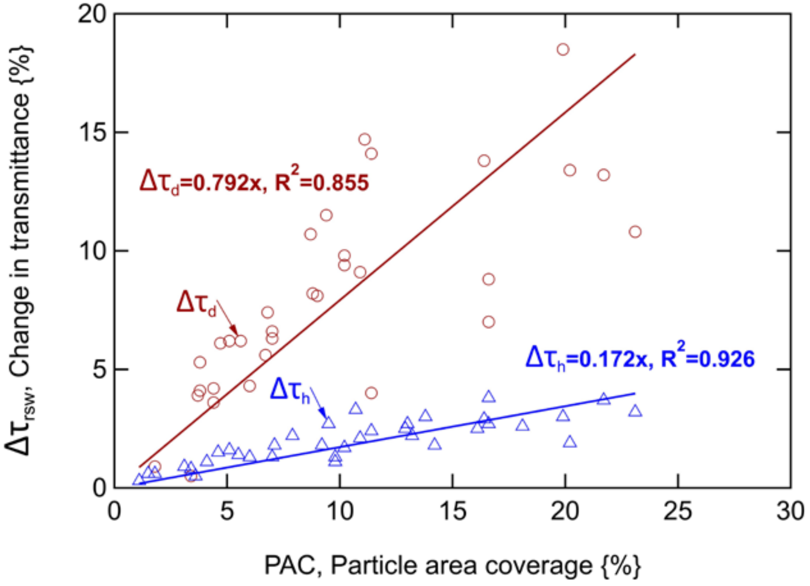
Oblique Microscopy of Latter WS Samples (Magnification Setting of 200x)



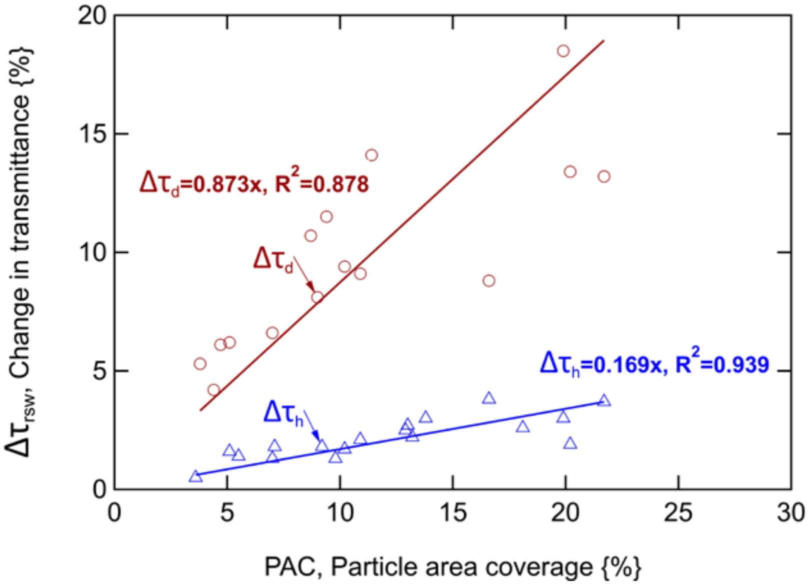
- While the NC coupons were not affected, the specimen cleaning was interrupted at some sites by the CoViD pandemic.

Representative examples shown for index B, for all five sites.

Comparison By Contamination Type



Fits for all locations
(including inorganic and no organic contamination).

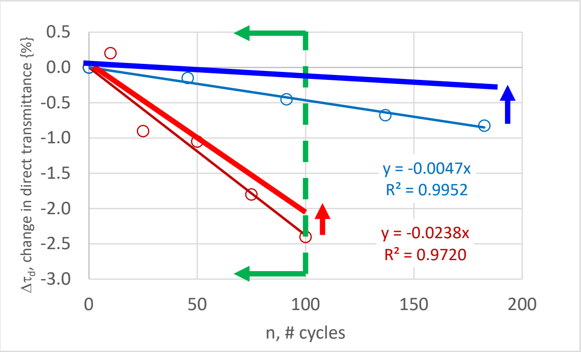


Fits for the locations of Dubai, Kuwait, Mesa only
(no organic contamination).

Method of Comparing the Artificial Abrasion and Field Coupon Studies

- AF, acceleration factor is the ratio of rate of optical performance degradation, artificial:field.
  - -Example shown, fit forced through 0. No abrasion cycles, no degradation.
  - -Delicate coatings: limit examination to range of known durability, n<100.
  - -*n*: logarithmic scale compared to linear scale.
- Analyze dry dust and slurry linear brush tested samples relative to Dry Brush cleaned coupons (field soiling study).
  - -Materials: B (porous silica coating). J (glass with no coating).

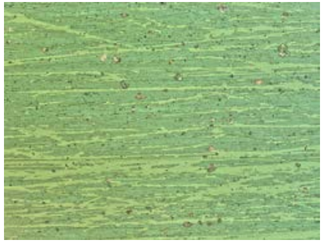
$$AF = \frac{\frac{\Delta\tau_a}{\Delta n_a}}{\frac{\Delta\tau_f}{\Delta n_f}}$$

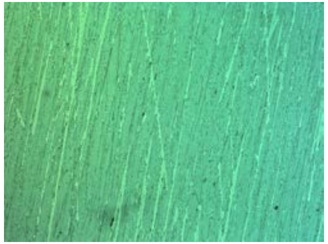


Arbitrary example: basic AF analysis.

***τ {%} examined relative to unaged specimen, from 300-1250 nm.**

- DB samples are not perfectly clean!
  - Focus on abrasion damage. Use non-contact cleaning of test surface using: mild detergent (Liquinox), DI rinse, CDA spray to –*improve*- cleanliness.

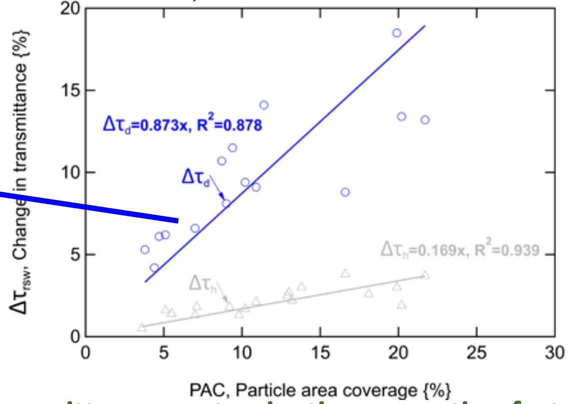




Example of uncleaned (left) and cleaned (right) Kuwait samples.

$$\tau_c = \tau_m + c_1 \cdot PAC$$

$$\Delta\tau_{d,rsw} = c_1 \cdot PAC + b$$



- DB samples remain partially contaminated!
  - -Perform correction of transmittance measurements based on contamination quantified from microscopy (NC + WS samples).
  - -Comprehensive optical analysis: optical loss primarily absorptance.

Correlation for transmittance:contamination correction factor.

Results of Comparing the Artificial Abrasion and Field Coupon Studies

- AF for dry brush cleaning of PS coating was on the order of unity.
  - -Consistent with damage from accumulation of individual scratches. Similar scratch morphology, despite: location (contamination density), the dust (composition and morphology), personnel (contact pressure for cleaning), and the brush (IEC vs. study).
  - -10k cycles of artificial abrasion can be performed in hours; field takes years.

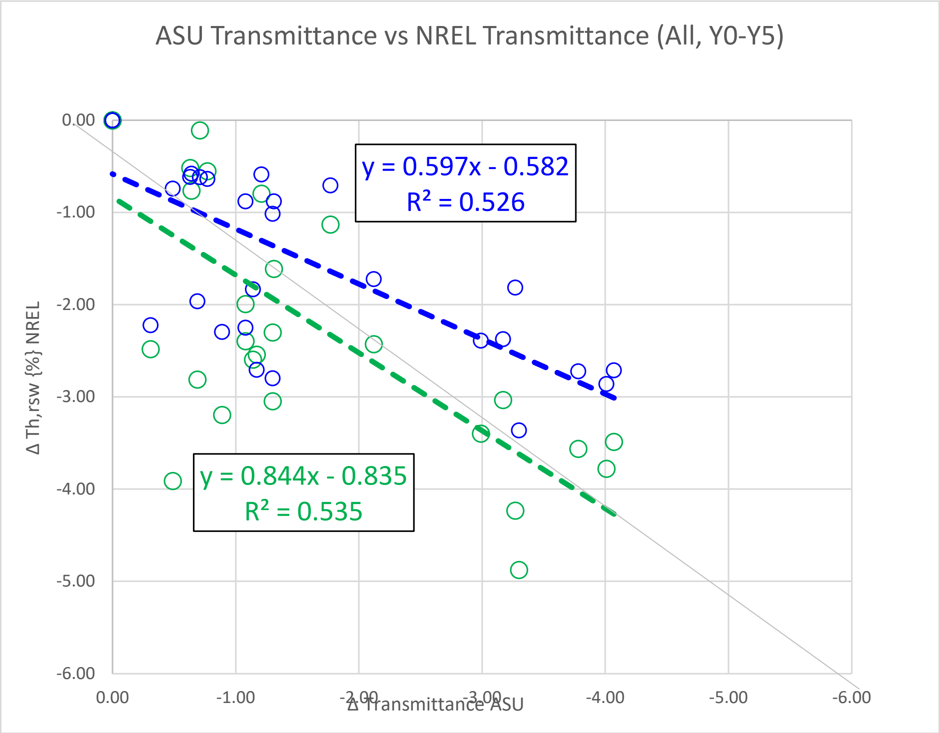
- Observations:
  - -Dubai different magnitude. (contamination density)
  - -Kuwait was cleaned daily, not monthly. (limited to 2y)
  - -Different order of magnitude observed for J glass with no coating.
  - -Lesser AF for slurry. Water previously identified to act as lubricant.

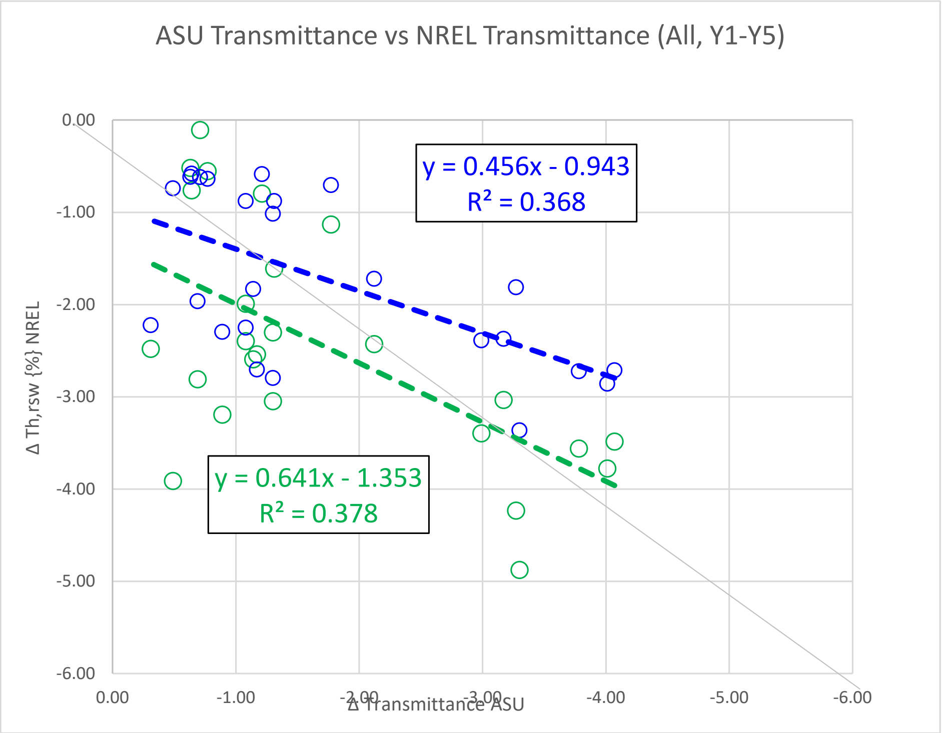
- Discussion:
  - -PS coatings are very delicate (life of 50 < n < 200).
  - -From AFM scratches (dust object) wear deep or completely through coating.
  - -AF for more robust coatings (metal oxide films) may be very different.

LOCATION	ARTIFICIAL ABRASIVE	$AF[\tau_d]$	
		B	J
Dubai	dry dust	0.53	-0.51
Kuwait City	dry dust	1.7	23
Mesa	dry dust	0.97	0.42
Mumbai	dry dust	1.9	0.59
Sacramento	dry dust	2.8	0.16
AVG	dry dust	**1.6**	**4.7**
ST DEV	dry dust	**0.9**	**10.1**
Dubai	slurry	0.33	-0.055
Kuwait City	slurry	1.1	2.4
Mesa	slurry	0.61	0.045
Mumbai	slurry	1.2	0.063
Sacramento	slurry	1.7	0.017
AVG	slurry	**1.0**	**0.50**
ST DEV	slurry	**0.5**	**1.1**

Results for logarithmic analysis.

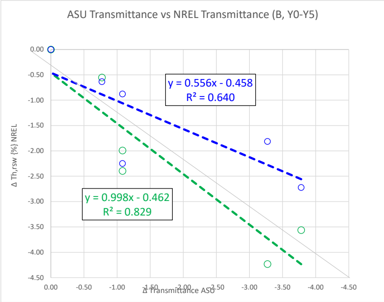
Comparison of Mesa and NREL Transmittance Measurements

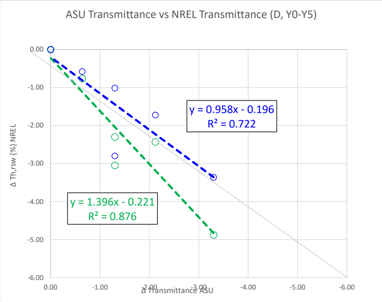


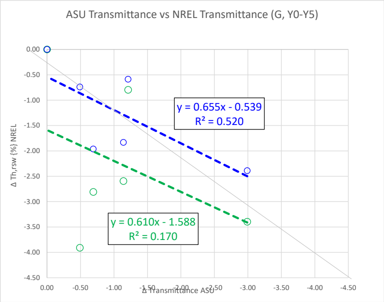


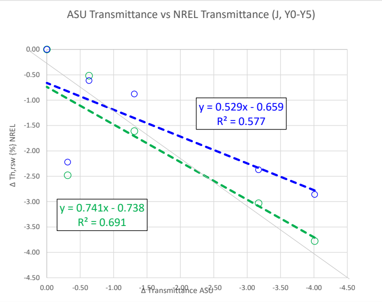
For NC coupons: all data (left) vs. fielded specimens only (right).

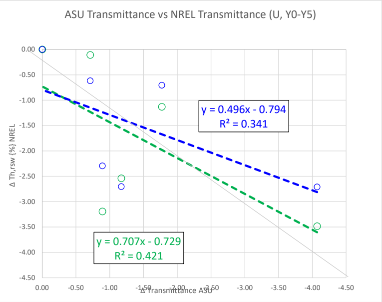
Comparison of Mesa and NREL Transmittance Measurements

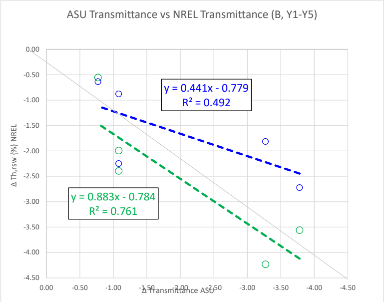


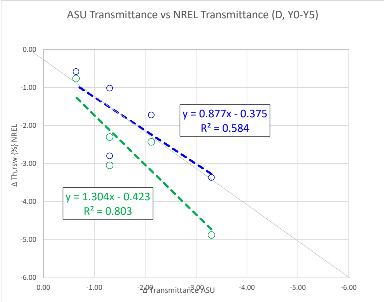


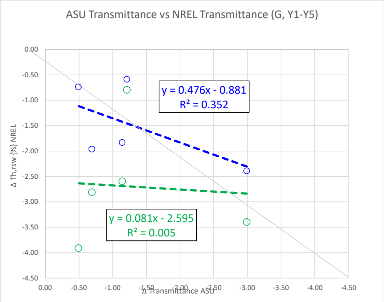


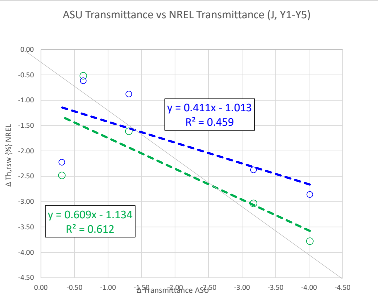


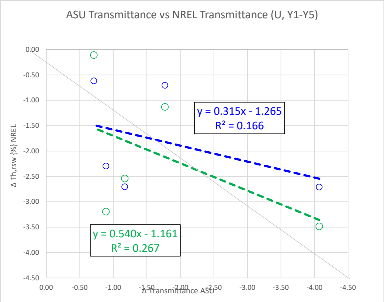












For NC coupons, by coating: all data (top) vs. fielded specimens only (bottom).

3y NC Samples: Camera Photos and Microscopy

J (phone, white background) | J (phone, black background) | J (200x)

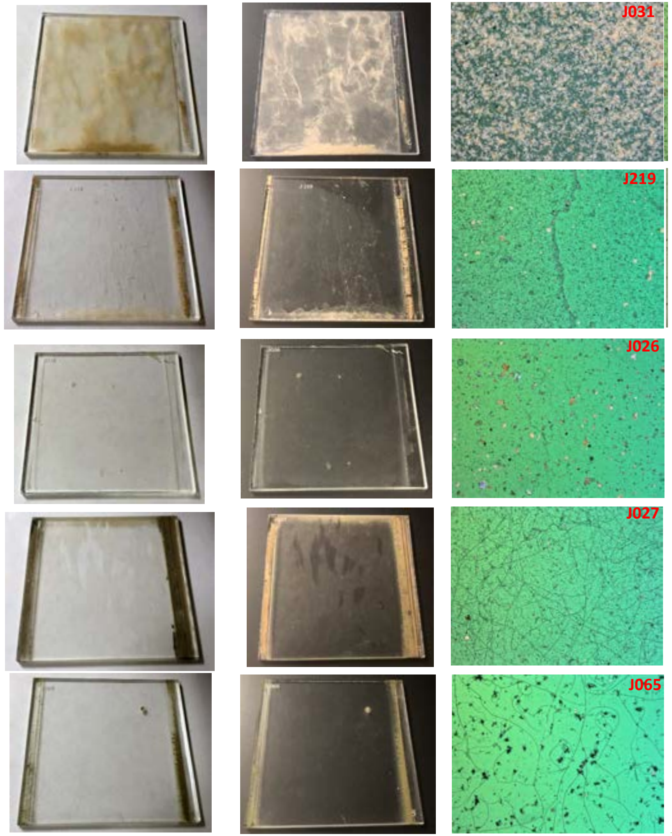
Dubai — J031

Kuwait (2v) — J218

Mesa — J026

Mumbai — J027

Sacramento — J051



Representative examples shown for all five sites.

Method of Comprehensive Optical Analysis

- Goal: verify the optical modes affecting optical performance as a function of wavelength.
- Spectrophotometer can measure τ_h, τ_d , ρ_h, and ρ_s.

  --h: hemispherical (with integrating sphere); d: direct (no sphere); s: scattering (reject direct light).

  -Analyze subsequent characteristics, α_h and scattering.

  -Examine No Clean (worst case) J (no coating) samples at 3y.

  Results analyzed relative to unaged (not fielded) J sample.

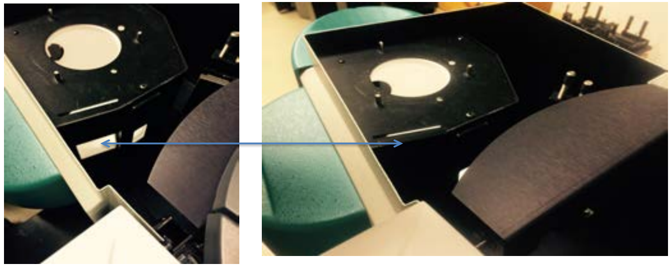
$$\rho_d = \rho_h - \rho_s$$

$$\alpha_h = 100 - \tau_h - \rho_h$$

$$haze[\tau] = \frac{(\tau_h - \tau_d)}{\tau_h}$$

$$haze[\rho] = \frac{(\rho_h - \rho_d)}{\rho_h}$$

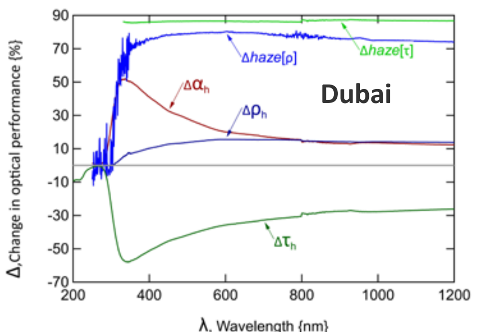
Cary 7000 (stock photo).



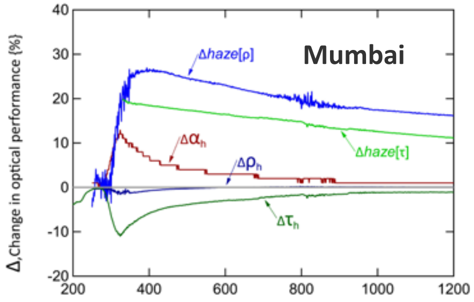
Rejecting the direct light for ρ_s measurements.

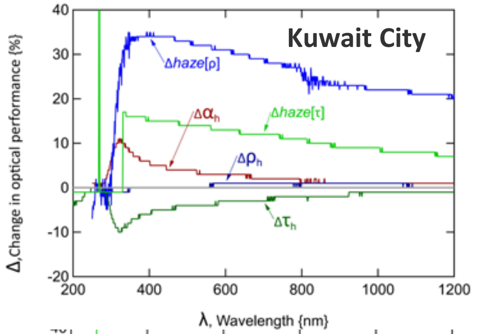
Lessons Learned From Comprehensive Optical Analysis of NC Specimens

- Optical performance (τ_h) is reduced by soiling $\Rightarrow$ reduced electricity generation.
- Much of the loss results from absorptance. Compare the symmetry of τ_h and α_h. Little $\Delta\rho_h$. Approach of correcting transmittance from correlation seems legit.
- Scattering is increased for both τ and ρ.
  - In most cases magnitude[ρ_h] is not changed significantly, light is just scattered.

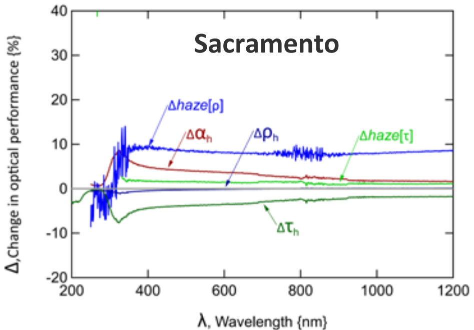


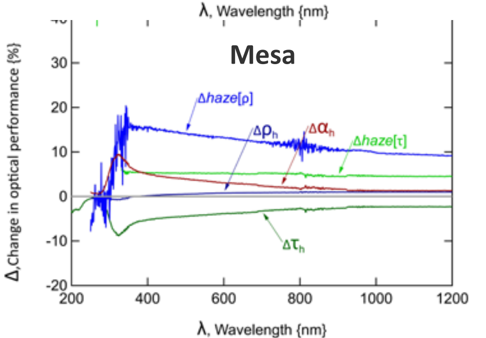
- ρ is substantially increased for Dubai.
  - Result is unexpected, unique to that location.
  - ρ results from composition (calcite), magnitude (near complete cemented layers), and/or condition (substantial cementation) of the contamination.





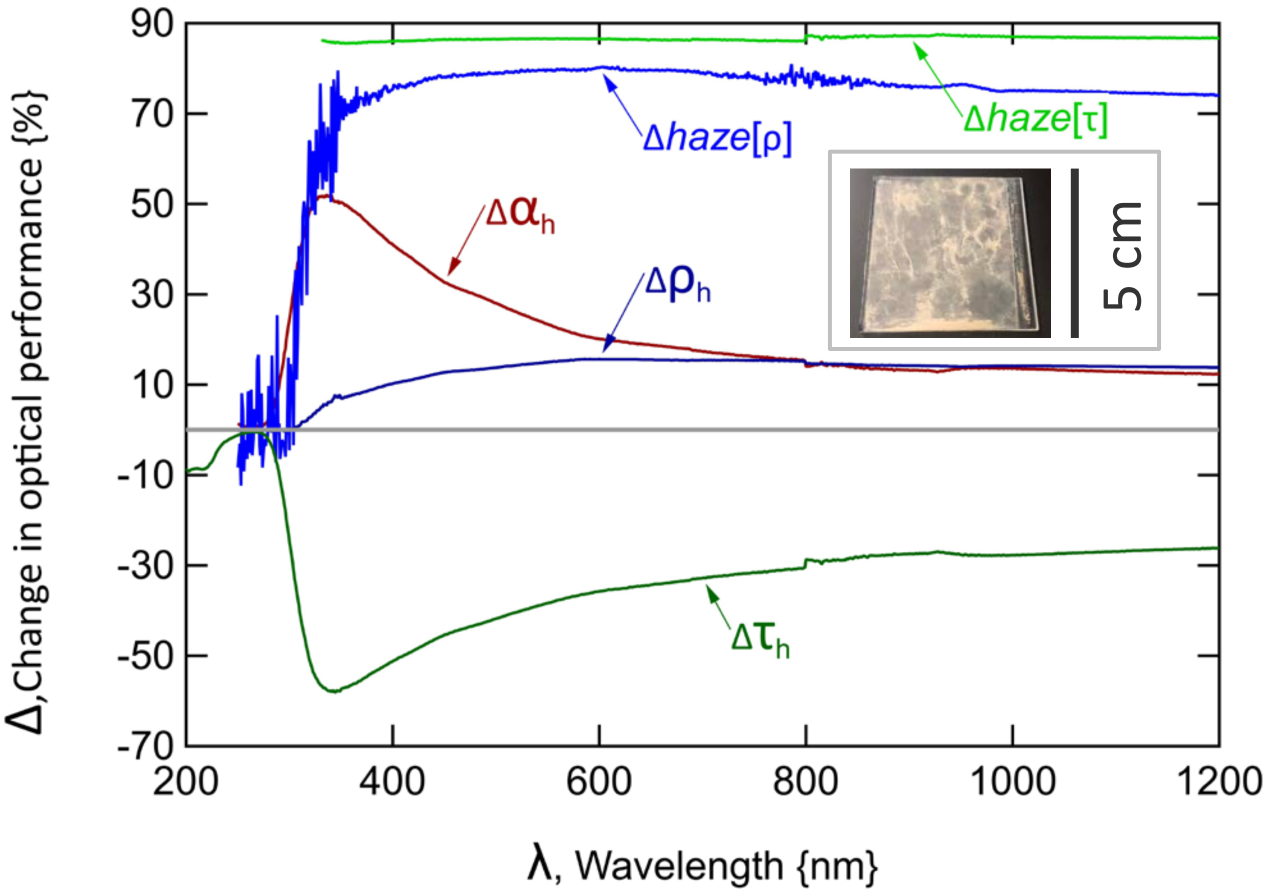
$$haze[\tau] = \frac{(\tau_h - \tau_d)}{\tau_h} \qquad haze[\rho] = \frac{(\rho_h - \rho_d)}{\rho_h}$$





Comprehensive optical analysis of transmittance (τ), reflectance (ρ), and absorptance (α) for NC coupons (typically 3y). Hemispherical (integrating sphere) are given, in addition to the haze for transmittance and reflectance.

Dubai, 3y vs. unaged



Dubai, 3y vs. unaged