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Surface science methods and their application to the study of module soiling

Craig L. Perkins, Mowafak Al-Jassim, Chun-Sheng Jiang, Helio Moutinho, Lin Simpson, Bobby To

Soiling is a serious issue in solar power production. One estimate of module soiling cost is ¢1/kWh, translating to billions of dollars/year in lost energy production.

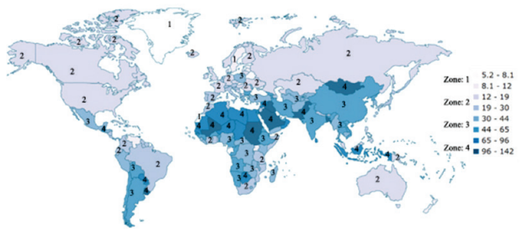


Fig. 12. PM10 world map [μg/m³]. [92].

Renewable and Sustainable Energy Reviews **33** (2014) 742

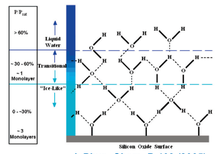
In FY16, NREL began work under SuNLaMP 1658: "Addressing Soiling: From Interface Chemistry to Practicality"

PIs: L. Simpson and M. Muller

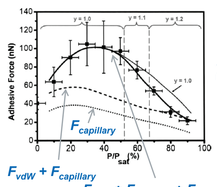
Soiling inherently involves a variety of surface phenomena

Why adhesion depends on surface chemical composition

- *Ice-like layers from Si-OH that are present on clean SiO_2 at ambient conditions dominate adhesion in AFM experiments*
- *Strongly adsorbing molecules such as organic acids can disrupt or replace the ice-like layer and thicker liquid layers*
- *vdW forces depend on chemical composition*
- *Ion exchange processes between glass and sodium-containing particles could play a role in adhesion*



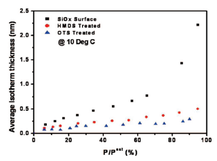
J. Phys. Chem. B 109 (2005) 16760



J. Chem. Phys. 124, 174712 (2006)

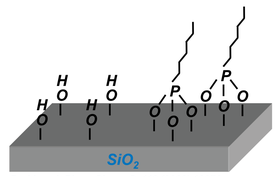
$F_{vdW} + F_{capillary}$

$F_{vdW} + F_{capillary} + F_{ice}$



J. Phys. Chem. C 113 (2009) 2128

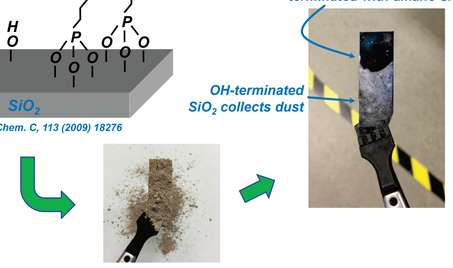
Disruption of the water layers on SiO_2 with strongly adsorbing molecules affects soiling



Perkins, J. Phys. Chem. C, 113 (2009) 18276

Little soiling on portion of wafer terminated with alkane SAM

OH-terminated SiO_2 collects dust



- *Dust accumulation is easily visible to eye, but mass gain is less than 80 μg/cm².*
- *C-10 alkyl monolayer disrupts main adhesion mechanism in this case, probably forces that result from ice-like Si-OH layer.*
- *Results on glass are similar to that shown above for SiO_2/Si.*
- *Organic acids found in the environment will act similarly to the phosphonic acid used here.*

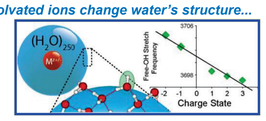
Does sodium in glass and in dust participate in adhesion?

Soda glass undergoes ion-exchange processes that can control the surface density of Si-OH.

$SiONa + H_2O \rightarrow SiOH + Na^+ + OH^-$

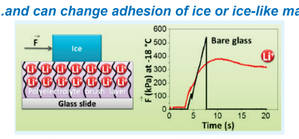
Surface Science 100 (1980) 53

Solvated ions change water's structure...



JACS 134 (2012) 10228

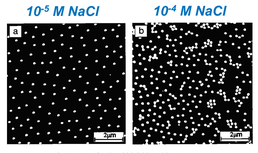
...and can change adhesion of ice or ice-like materials.



ACS Appl. Mater. Interfaces 6 (2014) 6487

Coulombic forces among glass and charged particles are modified by dilute dissolved ions.

10^{-5} M NaCl *10^{-4} M NaCl*



Langmuir 14 (1998) 5127

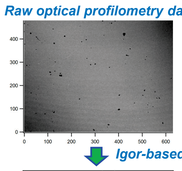
Aged modules surfaces are chemically distinct

sample	Atomic Concentration (%)									
	N	O	F	Na	Mg	Al	Si	K	Ca	Fe
Siemens control	1.0	67.9	0.3	1.4	0.8	2.7	23.4	1.1	0.8	0.6
Siemens 18 yr AZ	1.2	68.1	0.5	0.7	1.9	4.5	20.0	0.6	1.1	1.4
Siemens 18 yr CA	1.4	68.5	0.4	0.7	1.0	3.9	21.1	0.3	0.7	2.0
ASE 17yr AZ	1.1	67.9	0.2	0.3	2.8	5.7	18.3	0.6	1.3	1.9
ASE, in fracture	0.1	68.3	0.2	3.7	---	0.5	25.1	---	1.9	0.2

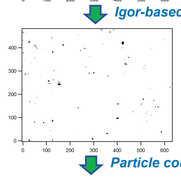
Surface and bulk also have different compositions.

Sodium adhesion hypothesis tested by AFM force-distance measurements and particle accumulation/counting

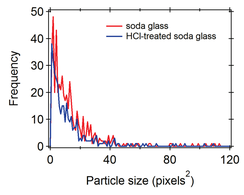
Raw optical profilometry data



Igor-based filtering



Particle counting, bin



AFM tips show higher adhesion on Na-free glass

Sample	Adhesion Force (nN)	
	Single measurement	Average ± 95% confidence interval
Control	11.5	15.7 ± 3
	11.9	
	15.6	
	17.1	
	18.7	
	19.1	
HCl-modified	26.6	26.9 ± 4
	24.8	
	21.6	
	28.5	
	27.5	
	32.5	

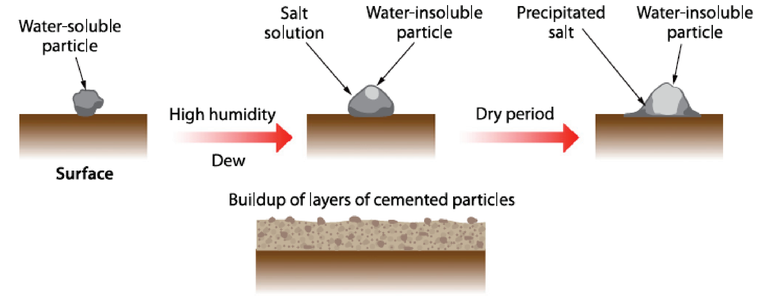
	Particles/mm²	Total particle area
Soda glass	5.7	8256
HCl-treated	4.0	5549

Natural dust appears to accumulate more on surface having more alkali and alkaline earth metals.

Cementation in films is poorly defined and is a major problem in some regions of the world

Multiple mechanism are involved in initially adsorption of dust
- *e.g., gravity, electrostatics, van der Waals, H-bond, capillary effects with dew*

Interactions w/ water & other pollutants forms stronger bonds (e.g., chemical)
- *These bonds may be strong on even superhydrophobic surfaces, where micropores can become effective attachment points.*
- *Must distinguish between increased physical adhesion and true chemical bond formation.*

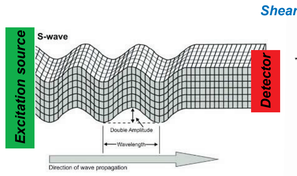


What is cementation? Can we detect it? Is it a discrete process or is there a continuum?

- *Cementation is a type of phase transition known as a percolation transition.[1]*
- *Whether or not it is first order (abrupt) or second order (continuous) is a matter of debate.[2]*

In practice, there is a qualitative, discrete difference between cemented and uncemented particles: cemented particles transmit shear, uncemented particle ensembles do not.[3]

Shear waves do not propagate in uncured cements.



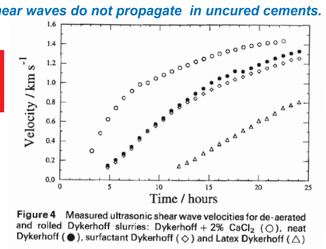


Figure 4 Measured ultrasonic shear wave velocities for de-aerated and rolled Dykerhoff slurries: Dykerhoff + 2% $CaCl_2$ (○), neat Dykerhoff (●), surfactant Dykerhoff (◇) and Latex Dykerhoff (△)

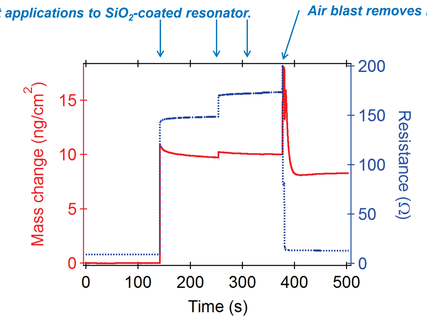
From [3]

1. *Advanced Cement Based Materials 3 (1996) 94.*
2. *Science 323 (2009) 1453*
3. *Ultrasonics 31 (1993) 147.*

Cementation studied via QCM-based measurements of dust layer viscoelastic properties

Crystal resistance is proportional to shear wave damping in non-rigid layers. Mass loading is derived from Δfrequency.

Three dust applications to SiO_2-coated resonator. *Air blast removes loose dust*



- *ΔR in initial dust application shows that some dust is not strongly adhered to SiO_2-coated crystal.*
- *Subsequent applications show further damping.*
- *Third application is detectable only by resistance change (no Δf; ΔR not visible in scaling above).*
- *Air blast removes loosely-bound particles, leaving only strongly-adhered dust.*
- *These results imply that a QCM should be able to detect cementation and enable its study.*

Summary and future work

- ***Literature suggests what we believed to be a new hypothesis: sodium from glass is involved in module soiling. However, Cuddihy alluded to this in 1980. Still unproven!***
- ***Results from AFM and particle counting methods are not totally consistent, and Na-effect if any is unclear at this point.***
- ***Disruption of the Si-OH layer by strongly adsorbing organic acids strongly decreases adhesion forces between AZ road dust and glass or glass-like surfaces.***
- ***We have developed a working definition of thin film cementation and have begun studying this process using a combination of lab and field experiments.***

DuraMat Workshop
10/10/2016-10/11/2016