Understanding the Mechanisms of Surface Cracking of Multilayer Photovoltaic Backsheets after Accelerated Aging

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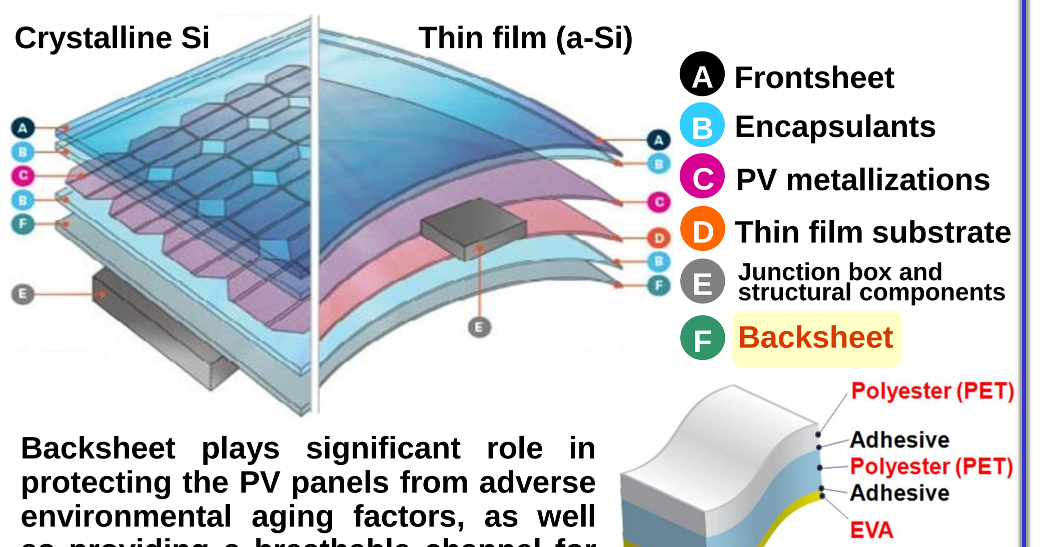
Introduction

In the field, surface cracking of polymeric multilayer backsheet can be detrimental to photovoltaic (PV) modules, causing catastrophic failure and safety concerns. This is a costly problem for industry due to the lack of comprehensive knowledge of multilayer system during weathering.

In this study, surface channel crack that was occurred under externally applied tensile stress/strain was characterized using a channel cracking fragmentation testing approach. The mechanisms of surface cracking of multilayered PV backsheet after accelerated aging is investigated and presented.

Silicon PV Module



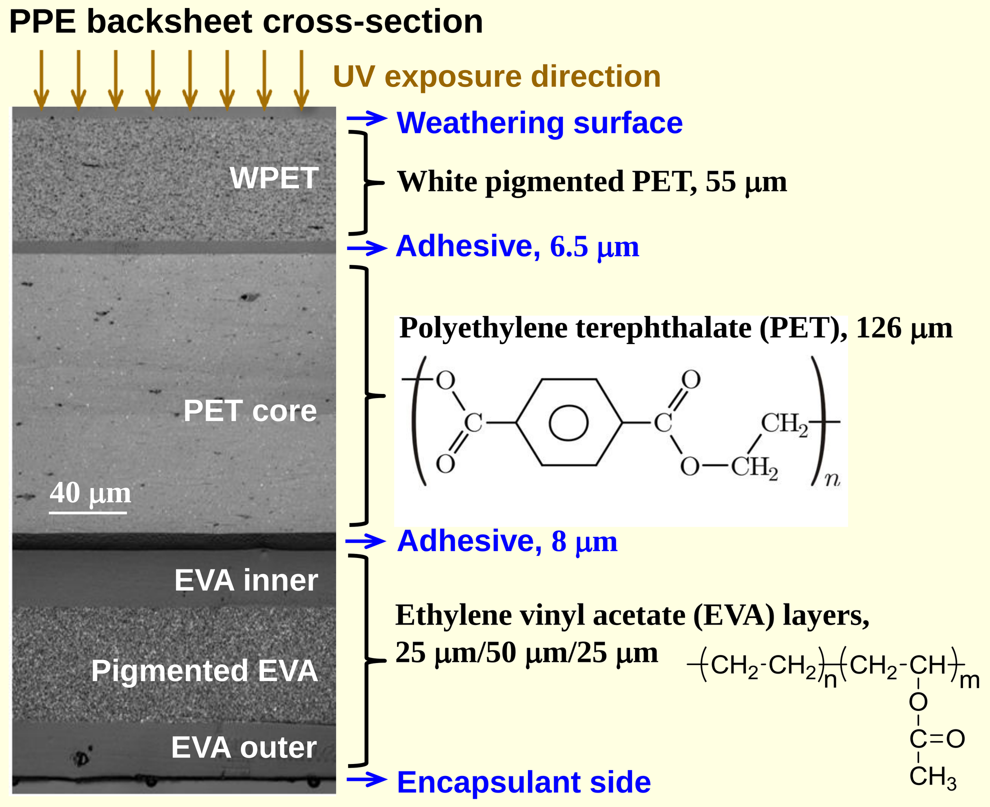
Backsheet plays significant role in protecting the PV panels from adverse environmental aging factors, as well as providing a breathable channel for egress of deleterious chemicals.

*Source of schematics: http://www.dupont.com

Experimental

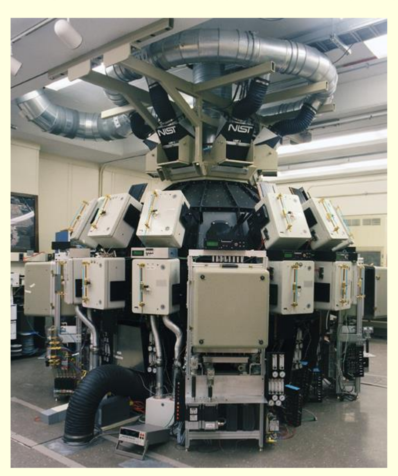
PPE Backsheet

PPE backsheet cross-section



Accelerated Weathering

NIST-Patented 2-meter SPHERE*



- Sample: Free standing PPE backsheet, 70 mm x 104 mm
- UV exposure : 140 W/m² on WPET
- Aging conditions: UV irradiation and temperature/moisture; T = *85* ℃; RH = *5%* (dry) and *60%* (humid)
- Control sample: Aged without UV irradiation
- Aging periods: 255 h, 510 h, 700 h (510 h is comparable to 5- to 6- year field exposure)

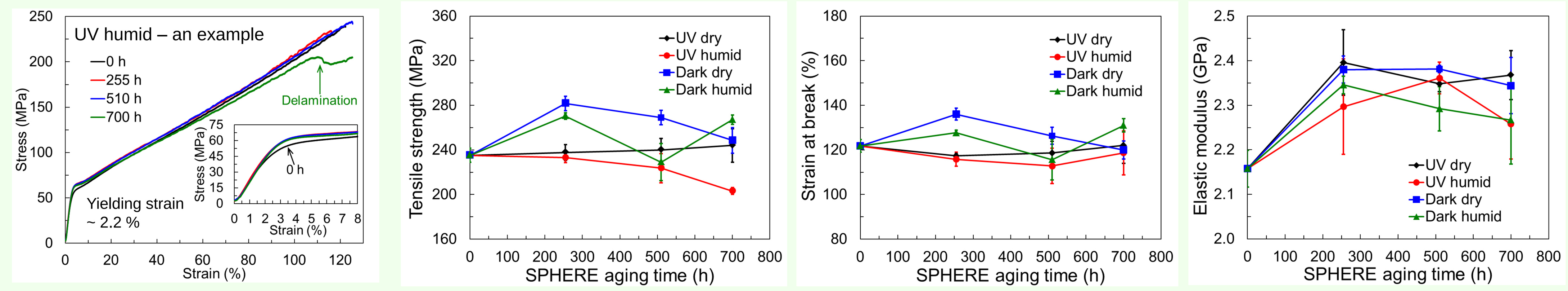
* *Martin and Chin, U.S. Patent 6626053.*

Characterization

- Tensile testing,
- Channel cracking fragmentation testing,
- ATR-FTIR (WPET surface),
- Atomic force microscopy (WPET surface),
- Laser scanning confocal microscopy.

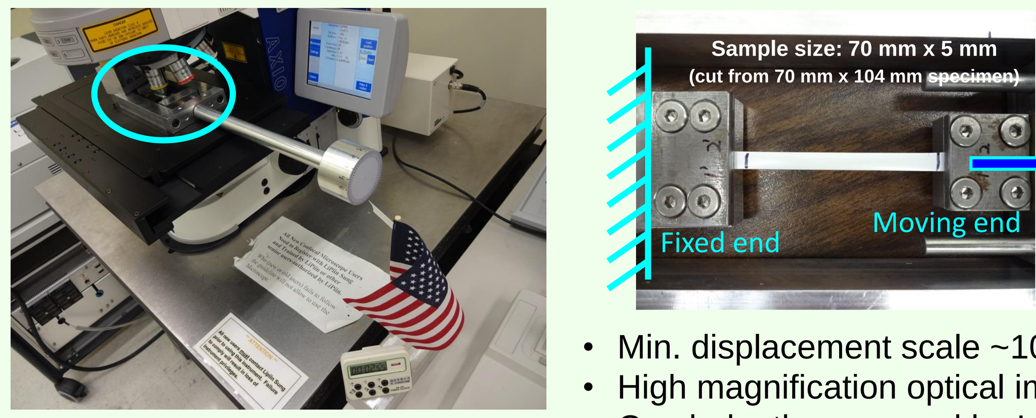
Results and Discussion

Tensile Testing Results



Channel Cracking Fragmentation Testing

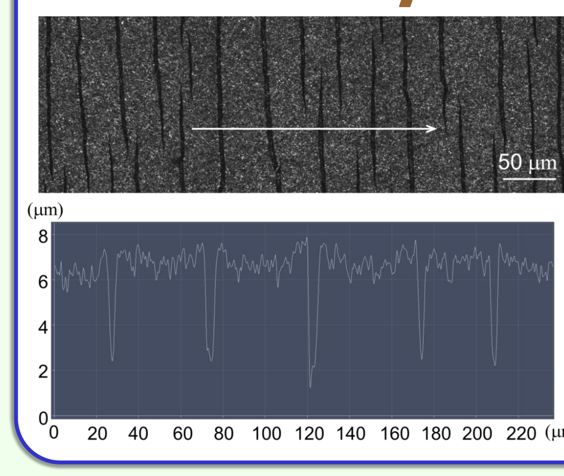
Laser scanning confocal microscope (LSCM) + Displacement controlled tensile fixture



*Certain commercial equipment, instruments or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

- Min. displacement scale ~10.4 μm
- High magnification optical imaging
- Crack depth measured by LSCM
- Capability of automatic testing

Crack Depth Measurement

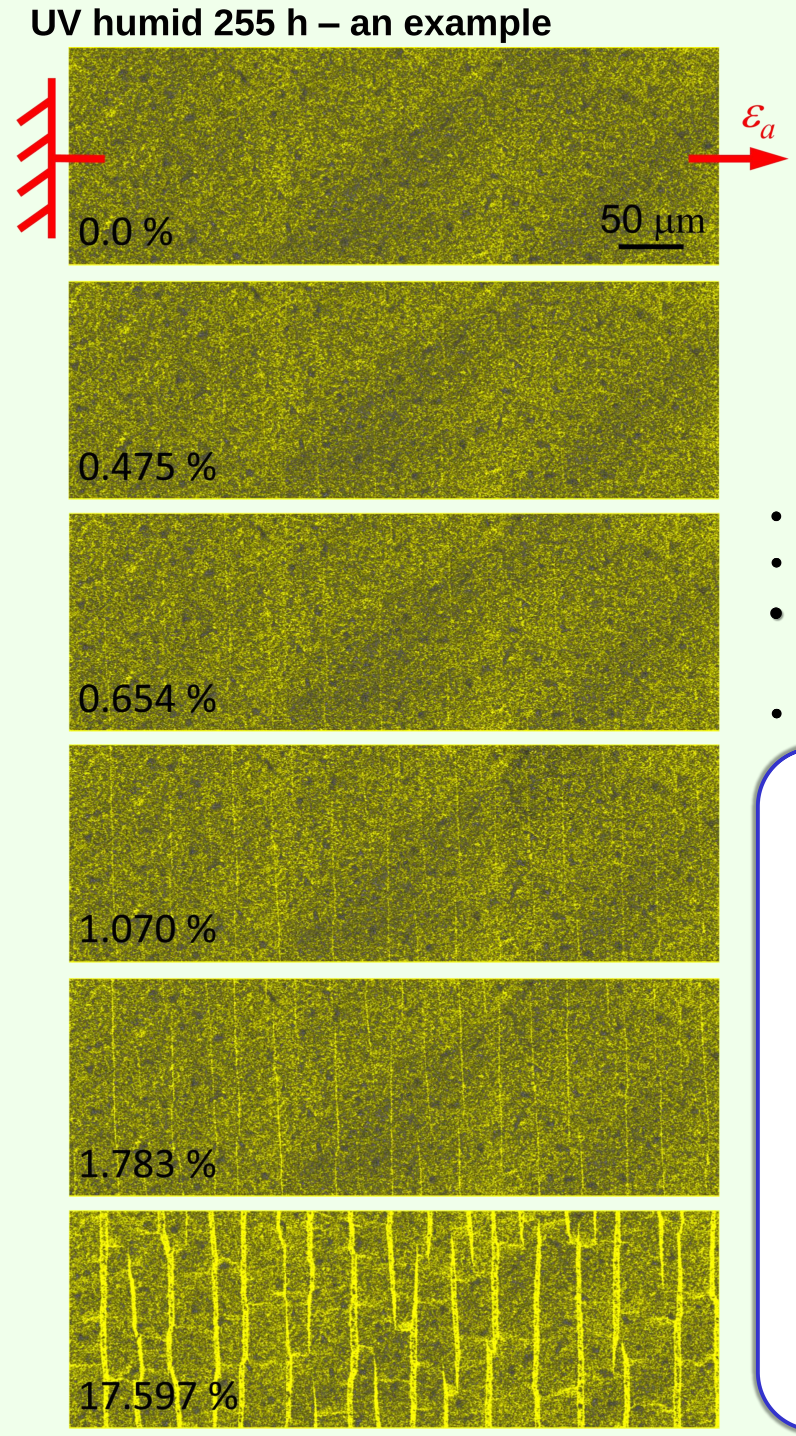


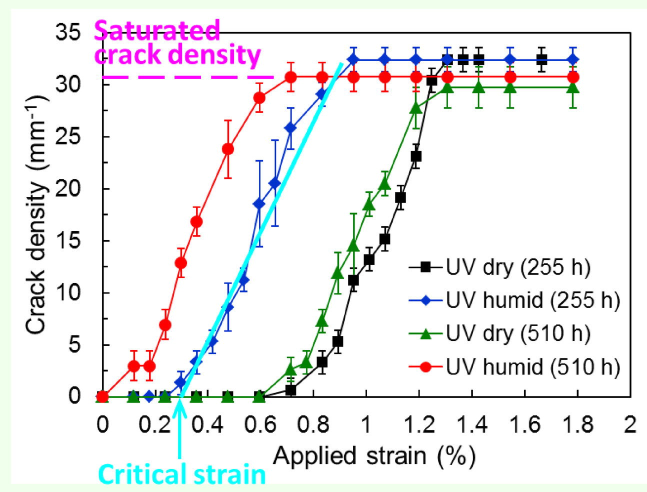
Aging conditions	Crack depth (μm)
UV dry 255 h	4.78 ± 0.58
UV humid 255 h	4.89 ± 0.65
UV dry 510 h	5.06 ± 0.43
UV humid 510 h	4.74 ± 1.07

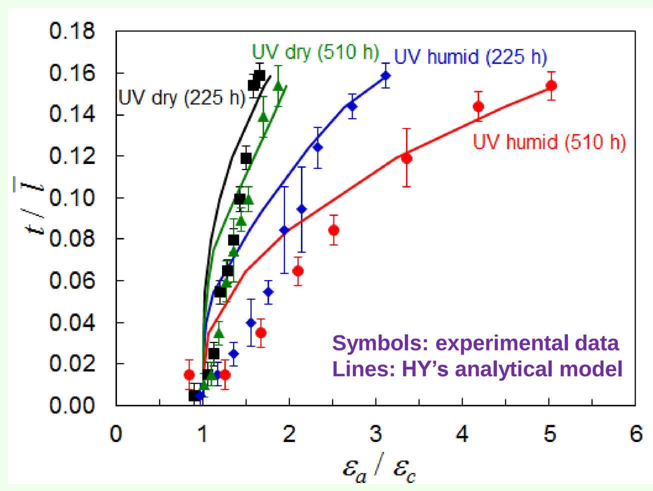
- Similar crack depth (about 5 μm) was found for all humidity levels and aging times.

Surface Cracking Behaviors

UV humid 255 h – an example







- RH levels and aging times influence critical strain (ε_c) only.
- Similar saturated crack density was reached despite of RH levels and aging times.
- **There was no surface cracking occurred on the unaged sample and samples aged without UV!**
- A nominal 5 μm crack depth into the surface is taken for the analytical model.

Hsueh & Yanaka's Analytical Model

$$\frac{\varepsilon_a}{\varepsilon_c}=\sqrt{\frac{3}{2R}}\text{, with } R=4\tanh\left(\frac{\alpha l}{2}\right)-\frac{e^{\alpha l}-e^{-\alpha l}+2\alpha l}{e^{\alpha l}+e^{-\alpha l}+2}-2\tanh(\alpha l)+\frac{1}{2}\frac{e^{2\alpha l}-e^{-2\alpha l}+4\alpha l}{e^{2\alpha l}+e^{-2\alpha l}+2}$$

$$\text{where } \alpha=\left[\frac{3}{2st(1+v_s)}\left(\frac{t}{s}+\frac{(1-v_f^2)E_s}{(1-v_f v_s)E_f}\right)\right]^{1/2}$$

Curve fitting of $\varepsilon_a/\varepsilon_c$–$t/l$ experimental results by the equations can be performed, so that the *effective* substrate thicknesses (s) can be solved!

$$\text{Fracture energy } \Gamma=\frac{3}{4\alpha}\left[\frac{E_f\varepsilon_c^2(1-2v_f v_s+v_s^2)}{(1-v_f^2)}\right]\text{, and } \Gamma=\frac{K_{IC}^2}{E_f}$$

$$\text{Film strength } \sigma_{str}=\frac{E_f}{(1-v_f)}\left[\frac{(1-v_f v_s)\varepsilon_c}{(1+v_f)}\right]$$

For more details, please see:
- C.-H. Hsueh and M. Yanaka, *J. Mater. Sci.*, 38 (2003) 1809.
- C.-H. Hsueh *et al.*, *J. Appl. Phys.*, 96 (2004) 3501.
- H.-R. Choi *et al.*, *ACS Appl. Mater. Interfaces*, 2 (2010) 2471.

Analysis results based on experimental data and analytical model

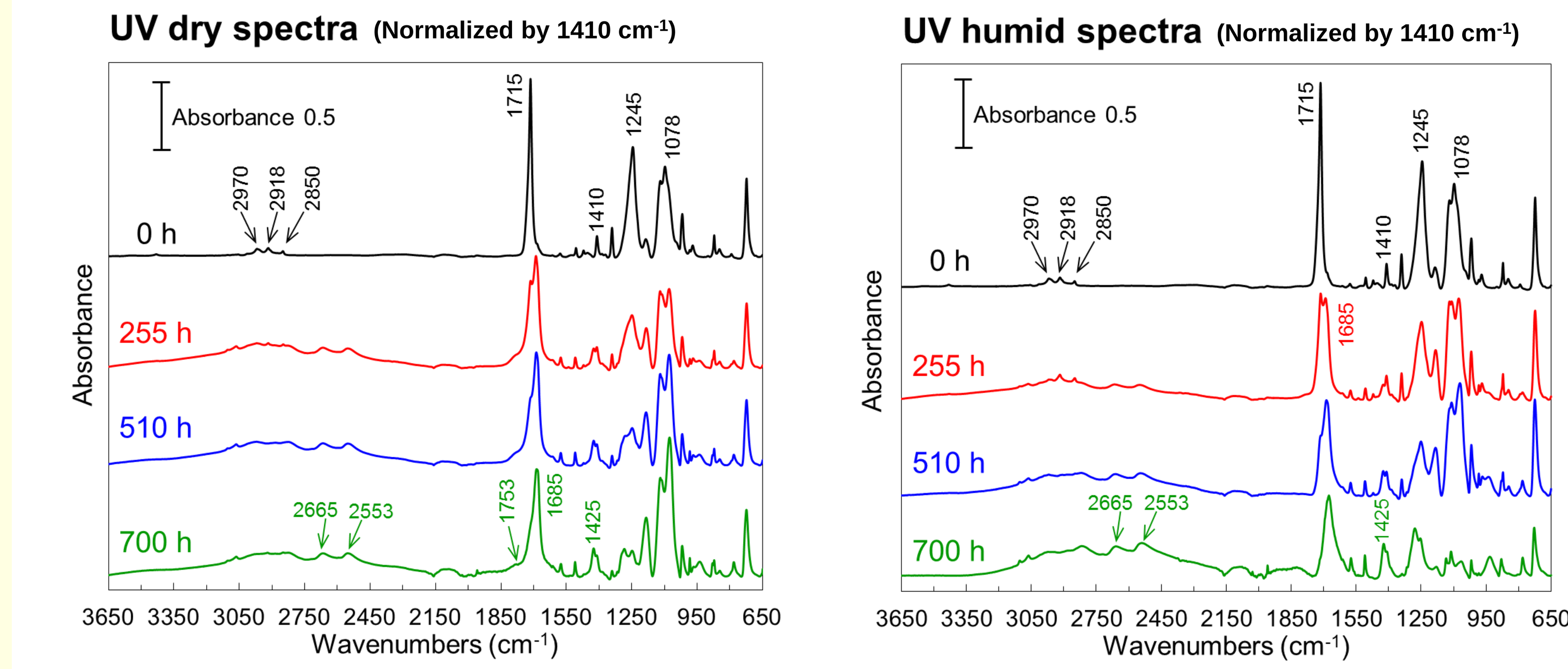
Aging conditions	Aging time (h)	ε_c (%)	s (μm)	Γ (J/m²)	K_{IC} (MPa·m$^{1/2}$)	σ_{str} (MPa)
UV dry	255	0.792±0.018	21.6±2.2	2.73±0.31	0.122±0.007	38.4±0.9
	510	0.702±0.010	27.5±2.2	2.50±0.24	0.117±0.006	34.0±0.8
UV humid	255	0.306±0.016	44.4±3.4	0.64±0.07	0.059±0.003	14.8±0.5
	510	0.142±0.008	74.4±4.0	0.18±0.03	0.032±0.002	6.9±0.4

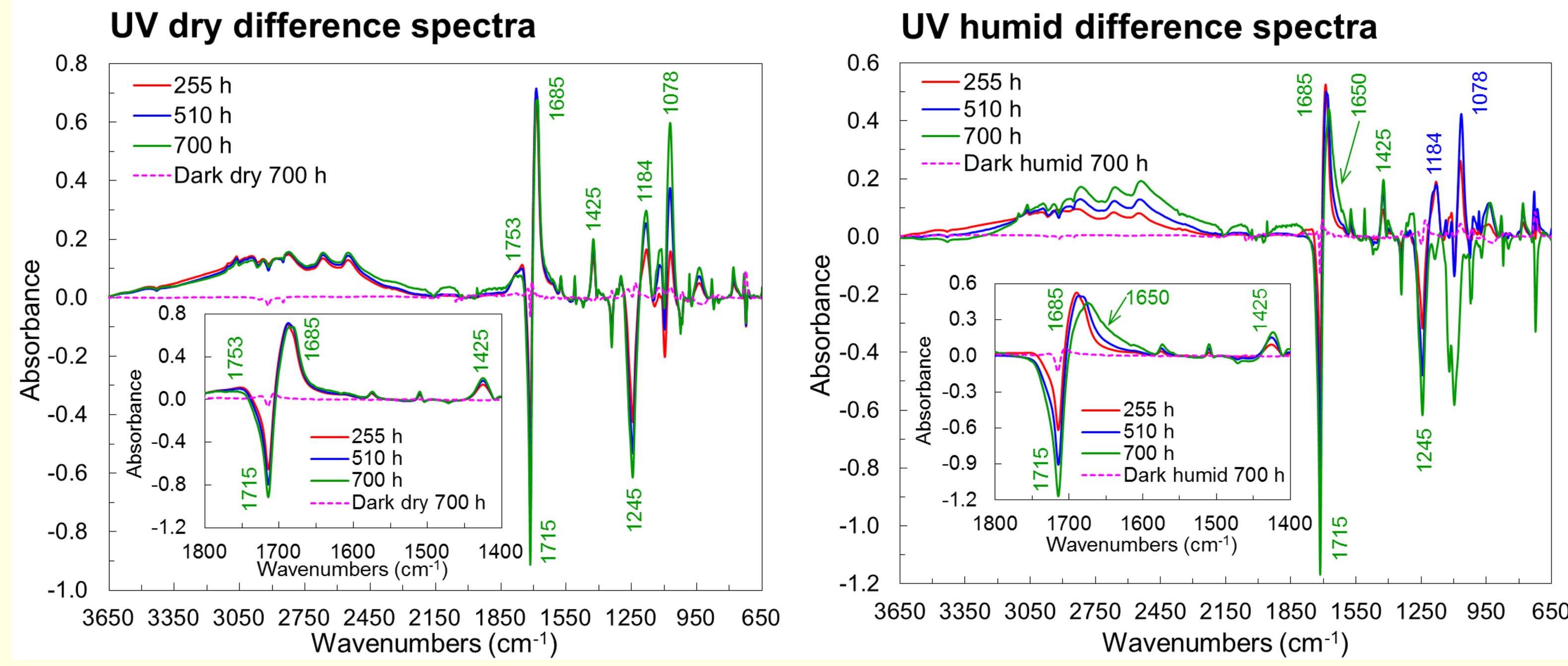
- The reported K_{IC} for a typical fresh PET is 4.5 MPa·m$^{1/2}$ to 5.5 MPa·m$^{1/2}$ [1].
- The strain caused by thermal and mechanical stresses in the backsheet of a typical silicon PV module is estimated to be in the order of 0.1 % [2,3].
- The analysis results provide good explanation to the observed PET-type backsheet surface cracking after 5- to 6-year fielded exposure [4].

References:
[1] Cambridge University Engineering Department, Materials Data Book, *Cambridge University*, Cambridge, 2003.
[2] M. Sander *et al.*, *Sol. Energy Mater. Sol. Cells*, 111 (2013) 82.
[3] S. Dietrich *et al.*, *Proc. SPIE*, 8825 (2013) 882505.
[4] W. Gambogi *et al.*, *IEEE J. Photovolt.*, 4 (2014) 935.

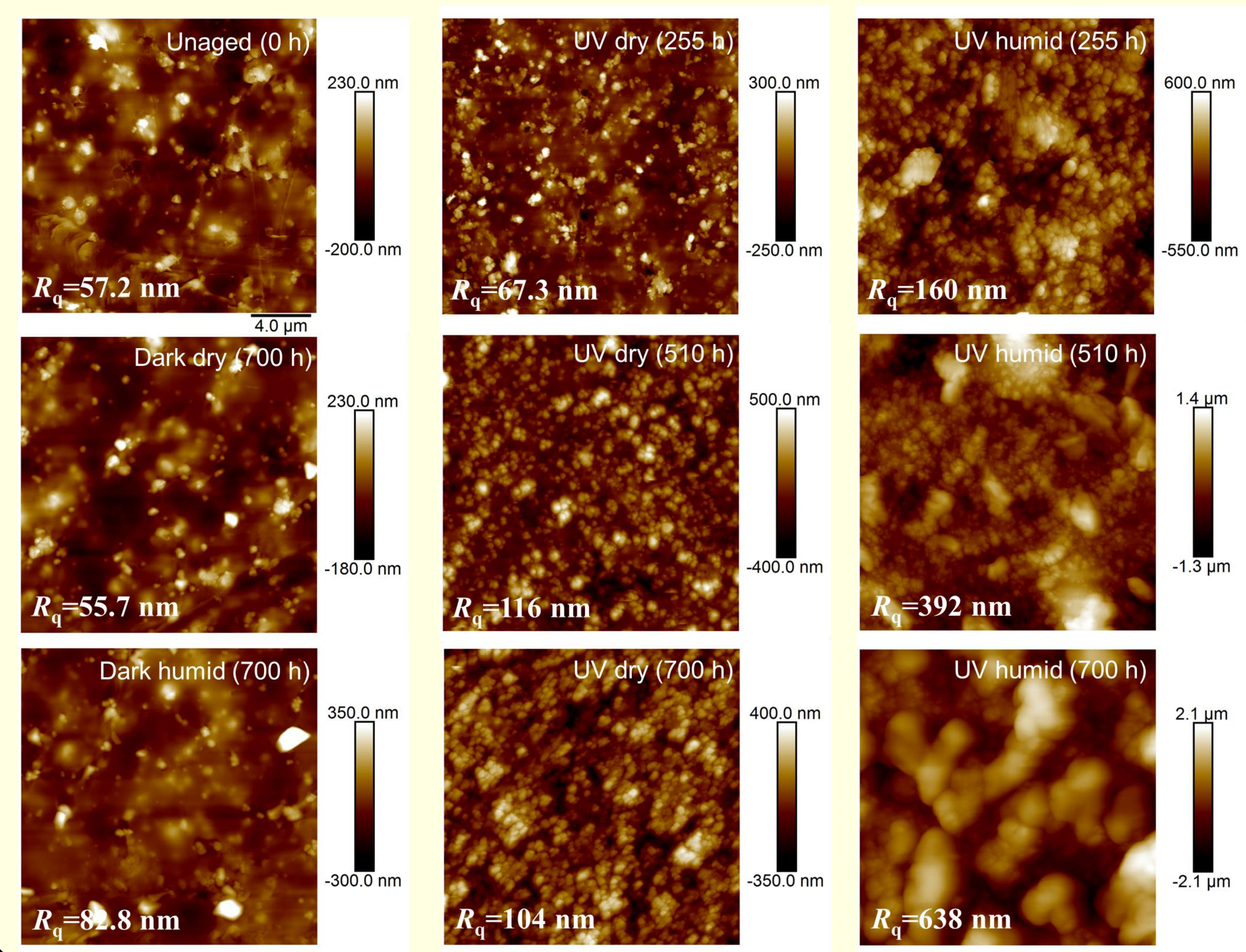
Chemical and Morphological Change

ATR-FTIR Results





AFM Results



Summary

- The embrittled surface layer resulting from the UV photo-degradation is responsible for surface cracking. Moisture plays a synergistic effect in the degradation mechanism.
- The mode I fracture toughness (K_{IC}) of the embrittled surface layer aged under UV humid conditions is lower than that under the UV dry conditions, which is consistent with their chemical and morphological degradation.
- The channel cracking fragmentation testing approach is possibly used to assess the tendency of cracking formation for PV backsheet after weathering.