NREL PV Module Reliability Workshop (Feb 24, 2015)
Adhesion - Considerations, Testing and Interpretation

Real world performance against the elements.

Presenter
Scott R. Meyer: Senior Specialist-Product and Application Development Engineer;
3M headquarters in St. Paul, MN, USA; Chemical Engineer B.S. degree from Iowa State University, 1985; 28 years at 3M Company in various divisions; experience with PSA tapes, epoxies, urethanes and fluoroelastomers; ~20 years of Experience with Adhesives; 6 years of tapes and adhesives experience related to the solar industry.

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Topics:

1. Adhesion and Testing
   • Failure Modes
   • Types of Forces
   • Types of testing

2. Material & Adhesive Characteristics
   • Perform differently – Difficult to compare materials

3. Many Variables Impact Test Results and Performance
   • Material types
   • Time & Temperature
   • Environmental
   • Aging (outside scope of this discussion)

4. Rigid PV Module Application
   • Relevant Forces & Testing
Why is Adhesion Important In PV Modules?

Many Adhesion Areas in a Module Can Fail

**Bulk** *(with-in a material)*
- Each material has its own bulk characteristics
- Some materials (e.g. Backsheets, EPEs) have layers within the material that may have additional Interfacial adhesion issues as well as different bulk characteristics

**Interfaces**
- Front Glass to Encapsulant
- Encapsulant to Cells and Ribbons
- Encapsulant to Backsheet or Backside Glass
- J.Box to Backsheet
- Rails to Backsheets or Backside Glass
- Frames to Backsheets or Backside Glass
- Edge Seals – Glass/Glass Thin Film
**Adhesion**
- Molecular attraction that holds material together (Single material or multiple layers)
- Does it stick together? Is it resistant to de-bonding?

**Modes of Failure (De-bonding)**
- Cohesive Failure (CO) – Bulk layer
- Adhesion Failure (AF) - Interface between layers

Not Always easy to identify failure mode
- Mixed failure modes (Some CO & some AF)
- Thin bulk layer surface failure (Can be difficult to see)
Can Be Difficult To Say If Cohesive (CO) or Adhesion (AF) Failure Some Times

- Not To Hard - But Some May Say Mostly AF
- But Really Thin CO Film

- Difficult – Most would Say Mostly Mixed with 35% CO and 65% AF to Glass
- But Really CO – 35% CO & 65% Thin CO Film
Types of Forces

1. Shear

Shear Force

\[ Stress = \frac{Force}{Area} \]

Force is Parallel to Bond area

2. Tensile/Pluck

Tensile Force

\[ Stress = \frac{Force}{Area} \]

Force/Width = Energy/Area

Fracture Mechanics
Fracture Energy to propagate a crack

Force is Perpendicular to Bond area

3. Cleavage

Tensile Force applied perpendicular to an edge

More complex to understand what cleavage results mean.
Force Applied In Different Test Modes

a. Constant Rate - Displacement (or Force)

Rate = Constant distance/time (mm/min)

b. Constant - Force (or Displacement)

Constant force (kg)

c. Cyclic – Displacement or Force goes up and down

Force oscillates with time
Constant Rate Displacement Lab Test Examples

Overlap Shear

T Block Tensile/pluck

Peel

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Comments on Peel Testing

- Peel is a special class of a cleavage test
- Easy to run
- Complex with regards to understanding what it means relative to performance in an application; Fracture Energy

- Many variables impact results – Difficult to compare materials unless identical:
  - Configurations of Peel Test (e.g. 90°, 180°, T-Peel, various fixtures, ……)
  - Pull speed (Rate)
  - Temperature
  - Humidity
  - Dwell time
  - Adhesive (Material Characteristics, thickness)
  - Substrates (Material Characteristics, thickness)
  - Backing (Material Characteristics, thickness) - Can have large Impact

\[
G = \frac{P}{b} \left( 1 + \epsilon \right) \cos \theta - h \int_0^\epsilon \sigma \, \epsilon \, d\epsilon - G_{db}
\]

- Fracture energy
- Total work done
- Energy used to stretch peeling arm material
- Energy dissipated in plastic bending of peeling arm

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Effect of Backing Thickness in Conventional Peel Test

Peel can be 50% higher due to backing effects
- Same adhesive
- Same backing except thickness

Backimg thickness range: 75 to 350 µm

Figure 14: Plot of ratio of total peel energy to de-adhesion energy $G/G_a$ to $h\sigma_y/G_a$ for Mylar backing and 200MP adhesive. Solid line form ICPeel
Comments on Peel Testing (Continued)

- Peel may not be the best test to use to simulate the forces of PV module applications
- Be cautious in the interpretation of peel data; conclusions can be misleading

  Only thing worse than no data is “bad” or misleading data!

When to use peel:

1. Understanding the impact of dwell on adhesion build – How much time should you give something to reach its best interfacial adhesion?

2. QC tests during manufacturing of an adhesive or identical construction - Are things changing?

3. If application is in a peel mode
Example Of Constant Load Lab Tests

One Condition
- Pass/Fail
- Measure Displacement as a function of time (f(time)).

Multiple Conditions
- Constant Force To Rupture (CFTR) Failure Analysis
  - Creates projections on expected failure points
  - Time Temperature Superposition

Can be Done in Shear or Tensile
Adhesive Types

Adhesive State Changes – During Bonding

- Curing Liquids
  - forms bond in liquid (unreacted) state; Crosslinks during cure
  - e.g. epoxies, reactive polyurethanes
  - Some may become glassy (e.g. structural epoxy & acrylics)

- Hot Melt Adhesives (thermoplastics)
  - melt crystals to form bond; solidifies on cooling to give strength
  - Can have crosslinking (e.g. encapsulants)
  - e.g. polyamides, thermoplastic polyurethanes, polyolefins

No Change in Adhesive State – During Bonding

- Pressure Sensitive Adhesives (PSA)
  - forms bond with contact time and pressure
  - relies on viscoelasticity to provide resistance to debonding
Many Variables Impact Adhesion Performance

- **Environmental Aging**
  - No Change
  - Crosslinking
  - Degradation (Breaking Molecular Bonds)

- **Dwell Time**
  - Time to each optimal performance - Surface wet out & chemical reactions
  - Be careful, Dwell can cause issues when comparing if not allowed to reach optimal performance

- **Adhesive, Substrate, & Backing**
  - Bulk Characteristics
  - Surface Chemistry
  - Thickness

- **Rate and Temperature**
  - Different for different material classes
Adhesive and Substrate Properties

Stiffness Dependence on Temperature for Polymers

• Stiffness is impacted by Temperature
• Stiffness is also impacted by Rate (Speed)

Tg examples:
- Silicons: < -100°C
- Acrylic PSA: -40°C to 0°C
- PET (oriented): 70°C to 90°C
- Epoxies: 70 to 250°C
- Glass (non polymeric): > 500°C

Tm examples:
- Silicones: Amorphous
- Acrylic PSA: Amorphous
- PET (oriented): 260°C
- EVA (40%-9%): 50°C to 100°C
- Glass: Amorphous

Semi-crystalline
Crosslinked
Increasing
crosslink
density

Glass transition
Amorphous
Crystal melting point
Temperature

Stiffness
(Modulus)
Temperature & Test Rate - Significant Impact On An Adhesive

- Some materials are influenced more by this than others... e.g. silicone versus acrylic PSA
- Need to ask what is important in the application

**Effect of Rate on Adhesive Strength**

<table>
<thead>
<tr>
<th>Speed</th>
<th>Force (N/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 mm/min</td>
<td>532%</td>
</tr>
<tr>
<td>50 mm/min</td>
<td>686%</td>
</tr>
<tr>
<td>5 mm/min</td>
<td>601%</td>
</tr>
</tbody>
</table>

**Effect of Temperature on Adh. Strength**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Force (N/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°C</td>
<td>99%</td>
</tr>
<tr>
<td>20°C</td>
<td>719%</td>
</tr>
<tr>
<td>0°C</td>
<td>687%</td>
</tr>
<tr>
<td>25°C</td>
<td>323%</td>
</tr>
<tr>
<td>70°C</td>
<td>535%</td>
</tr>
</tbody>
</table>

Technique that can be used to relate time & temperature
- time temperature super-positioning (hot is like slow; cold is like fast) → Master curve
What is the temperature and rate that should be used to represent the application?
Time Temperature Super-postioning Shear CFTR Example

Time and temperature dependence - failure times in constant shear load of 2204 foam tape

Time-temperature superposition

SAFT 2204 Constant Force to Rupture Failure

SAFT 2204 Master Curve - 23C reference temperature

log shift factor at 90C = -2.1
Same curve shape at 90C as at 23C
but everything happens 126 times faster ($10^{2.1}$) at 90°C

1,000,000 Minutes ~1.9 years
10,000,000 Minutes ~19 years

100,000 Minutes ~ 70 days

1,000,000 Minutes ~1.9 years
10,000,000 Minutes ~19 years

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Time Temperature Super-postitioning – When It Doesn’t Work

When does time-temperature superposition not work?

- **Semi-crystalline materials**
  - Not work with materials that are Crystalline - melting of crystal phase produces softening that will not be seen below $T_m$ regardless of time scale of test

- **Multi-phase materials**
  - Different phases have different sensitivity to temperature

- **Temperature causes irreversible changes/degradation of material**
Each Application is Unique - Need to ask the following

- What are the critical forces that can cause failure?
  - Type - Shear, Tensile, Cleavage
  - Mode - Constant Load, Constant Rate, cyclic
  - Limit - maximum forces requirement

- What are reasonable tests that can be run to help get a perspective on performance?
  - Usually have to make compromises to do the best you can on a small scale
  - Need to validate &/or correlation with field results
What are the type of forces on this adhesive?

What are test methods that simulate the forces?

- Fast Tensile/Pluck
- Fast Shear
- Constant Load Shear
Example of Forces on Rail Bonding Adhesives In Rigid PV Modules

- **Gravity**
  - Panel Weight – Above Ambient Temperatures
  - Long time Scale – 25+ years
  - Snow Load – Cold Temperatures

  What are the type of forces on this adhesive?
  - Shear & Compression

  What are test methods that simulate the forces?
  - Shear & Pluck

- **Wind Gusts**
  (Building codes use 3 second wind gusts)

  What are the type of forces on this adhesive?
  - Shear & Pluck

  What are test methods that simulate the forces?
  - Shear & Pluck

\[ F_{\text{shear}} = W \cdot \cos \theta \]
Mechanical Load Test - IEC & UL Standard

Step 1: 2400 Pa applied to front side – Hold 1 Hour

Compression

Step 2: 2400 Pa applied to back side – Hold 1 Hour

Tensile/Pluck

Repeat steps 1 & 2 three times.
If want heavy snow load approval, replace last front loading with 5400 Pa.

Concerns
• 1 hr load is not representative of a wind gust.
  • Building codes – 3 second wind Gusts

• Not representative of snow load because testing:
  • Does not include shear
  • Is done at room temperature
Solar Panel Stack Up – Adhesion Areas in a Module

Interfacial
- Front Glass to Encapsulant
- Encapsulant to Cells and Ribbons
- Encapsulant to Backsheet or Backside Glass
- J.Box to Backsheet
- Rails to Backsheets or Backside Glass
- Frames to Backsheets or Backside Glass
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Bulk
- Each material has its own bulk characteristics
- Some materials (e.g. Backsheets, EPEs) have layers within the material that may have additional Interfacial adhesion issues as well as different bulk characteristics

What are the forces acting on the layers in the module?
Gravity, Wind, CTE
Mismatches, installation

What are test methods that can be used to simulate forces?
Shear, Tensile, Cleavage
Key Points:

1. Peel
   - Easy to run but complex with regards to understanding what it means relative to performance in an application.
   - Influenced by many variables. (Backing, substrate, angle, stretching, …….)
   - May not be the best test to use to simulate the forces of PV module applications

2. Understand application stresses & simulate stress as best as possible to get most relevant information.

3. Various adh. & materials perform differently - makes it difficult to compare application performance.
Backup Slides
Time & Temperature Have A Significant Impact Failure Mode

Peeling PET film from rubber at different rates and temperatures

Figure 2. Average peel force $P$ against rate of peel $R$ for polymer $A$, $C$ and $I$ denote cohesive and interfacial failure modes.

Figure 3. Master relation for peel force $P$ against rate of peel $R$, reduced to 23 °C, for polymer $A$ adhering to Mylar. Broken curves denote the extreme values when stick-slip peeling occurred.

- Transition from cohesive to interfacial failure
- Transition from smooth to shocky peel
- If peel force exceeds backing, substrate, or adhesive strength, it could tear and never reach a shock Peel
Substrate Type Can Have A Significant Impact Failure Mode
Interaction of interfacial forces and material properties

Rate and temperature dependence comes from rheological properties of the adhesive and backing