Accelerated and Outdoor Aging Effects on PV Module Interfacial Toughness and Shear Strength

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ABSTRACT

Measurement of applied torque as a function of angle of twist during the core removal procedure has been developed at NREL to characterize the strength and durability of various interfaces within many types of PV modules. A large amount of data has been amassed to attempt to derive correlations between field-aged and accelerated chamber-aged modules exposed to ultraviolet dose and temperature.

1. Background

The Solar Program Multi-Year Technical Plan states that a major impediment for flat-plate PV systems is the limitation due to cost and reliability of module packaging.[1] We have used recommendations from a recent DOE Workshop on Accelerated Testing of PV modules[2] to set our reliability testing objectives. Module reliability is inextricably linked to the adhesion and cohesion of all the interlayers. Both the crystalline silicon and thin-film technologies require advanced module packaging to survive in harsh operating environments. Evaluating interfacial shear strength and toughness within PV modules has never been addressed in the detail and rigor that we present here. Our method to carefully evaluate these interfacial characteristics in virtually any module structure gives us a way to study new and existing fabrication materials for the as-processed module package, as well as the field-aged or accelerated chamber-aged module.

2. Technical Approach

We have extended the technique developed at Sandia National Laboratories[3] and the Florida Solar Energy Center (FSEC)[4] to include a stepper motor to control the rate of twisting, coupled with computerized data acquisition of the applied torque, to produce torque curves as a function of angle for a large number of modules. The modules are mono- or multi-crystalline Si from two manufacturers. For each type there are control, outdoor exposed, outdoor 1X and 3X tracking, and two types of accelerated chamber exposed modules. Knowledge of both the peak torque and angular dependence of torque at known twisting rates allows us to characterize one important aspect of the durability of the module package.

Figure 3 shows a typical measured torque curve as a function of twist angle. Three distinct segments of mechanical behavior are evident. In region I, the EVA core is torsionally stressed between the glass and Si boundaries as a linear elastic element. The shear modulus, G, is related to the initial slope, T/ϕ, as:

$$G = \frac{2L}{\pi r^4}\frac{T}{\phi} , \qquad (1)$$

where T is the applied torque, ϕ is the twist angle, L is the EVA thickness, and r is the radius of the core.

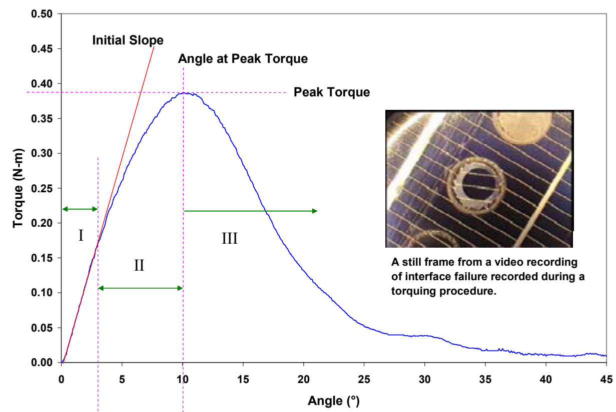

Fig. 1. Typical measured torque curve as a function of twist angle.

Viscoelastic effects dominate in region II as the EVA core begins to yield. This can be modeled as an inner elastic core and an outer plastic annulus in which the shear stress is constant and nonlinear shear strain occurs.

At some angle, a peak torque is reached, at which point delamination starts to develop radially inward. This can be seen in the inset in Fig. 1, where after the core has twisted ~23° the radius of the adhered section has been reduced from 4.76 mm to 3.23 mm. The corresponding torque-twist equation for region III can be expressed as a function of the decreasing core radius that is provided by the video signal.

The amount of energy required to completely shear the core is obtained by integrating the torque-twist curve. This parameter is known as the toughness of the material. We are interested in how exposure to various weathering conditions affects the quantities discussed above so that correlations between accelerated and in-service exposures can be derived.

3. Results and Accomplishments

Figure 2 presents shear modulus data computed from the initial slopes measured for mono-crystalline Si modules exposed to a variety of weathering conditions. The cumulative ultraviolet (UV) dose and temperature range are indicated for each type of exposure. For comparison, an unweathered control module was also characterized. Error bars here (and in succeeding figures) are ± one standard deviation, typically obtained from 5–6 core measurements. Although a slight loss in the average shear modulus is seen for some types of exposure, the data uncertainty is fairly large. Consequently, degradation of the modulus properties of the bulk EVA is not conclusive.

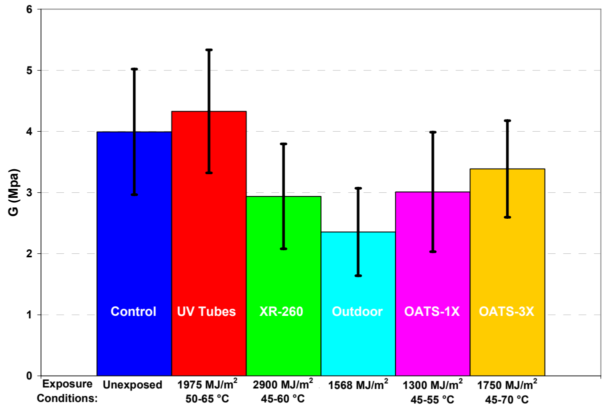

Fig. 2. Shear modulus of large mono-crystalline Si modules.

The effect of weathering on peak torque and angle at peak torque for multi-crystalline Si modules is shown in Fig. 3. For the control module, delamination initiated at peak torque values in the range 0.35–0.45 N-m at a twist angle between 13°–19°. These values were significantly reduced for the weathered modules. Temperature and UV exposure drastically reduced the peak torque values at which onset of interfacial delamination occurred (0.2–0.3 N-m). Delamination also takes place at greatly reduced twist angles for the weathered modules.

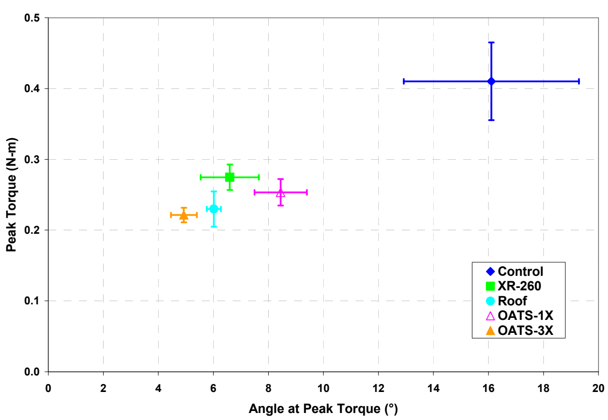

Fig. 3. Peak torque vs. twist angle for large multi-crystalline Si modules.

The quantity that most clearly demonstrates the effect of weathering on interfacial degradation is toughness. Loss in toughness by all of the exposed modules compared to the control module is readily apparent in Fig. 4. In addition, the scatter in the data is relatively small. It is important to note that this parameter can only be computed if the complete torque vs. twist angle curve is measured.

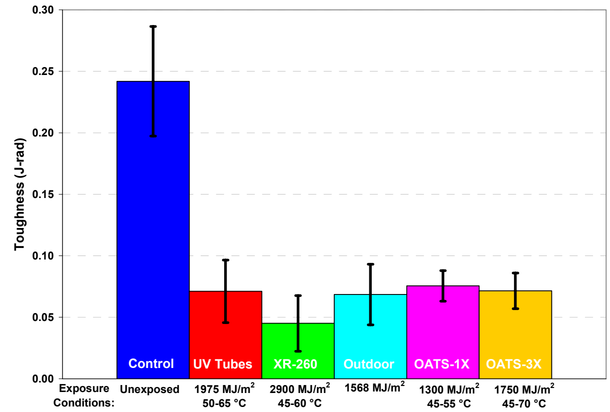

Fig. 4. Toughness of small mono-crystalline Si modules.

4. Conclusions

A unique apparatus for measuring torque vs. twist angle for cored PV modules has been developed. This device has been used to evaluate several parameters in terms of their ability to quantify degradation of interfacial adhesion in weathered PV modules. The usefulness of shear modulus in this regard is marginal. However, peak torque, angle at peak torque, and toughness are very sensitive parameters. We are in the process of further analyzing the data in an attempt to derive correlations between accelerated and in-service weathering.

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