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Correlation between Material Degradation Behavior and PV module Performance

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***Abstract*—** the primary objective of the study was to identify and evaluate appropriate degradation indicators for PV encapsulation materials to predict the lifetime of PV modules, commercially available poly-crystalline 60-cell solar PV modules were fabricated and subjected to damp heat exposure (85°C ambient temperature and 85% relative humidity). The modules were withdrawn from the chambers every 1000 hours exposure until 4000 hours. EVA samples were randomly collected on each module at every 1000 hours for property measurements. Specific test laminates of EVA/glass based on the similar module design were fabricated and applied with the same lamination process as in the manufacturing for the interfacial adhesion tests. The material properties and the aging behavior were characterized by Thermo Gravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), Dynamical Mechanical Analysis (DMA), Infrared (IR) spectroscopy in attenuated total reflection mode (ATR), Pyrolysis-gas Chromatography/Mass Spectrometry (Py-GCMS) and interlayer adhesion test (Instron). The correlation between the materials degradation behavior and the performance of the PV module was studied. These degradation indicators served as input data for lifetime modeling and assessment.

***Keywords*—** Reliability, EVA, damp heat aging, performance degradation, degradation indicator

I. INTRODUCTION

TO survive in harsh operating environments, PV modules rely on packaging materials including protective superstrate, substrate, sealants and encapsulants to provide requisite reliability. Several key properties associated with PV module reliability are critical for commercial success. These include (1) low-interface conductivity, (2) adequate adhesion of encapsulants to substrate, superstrate and PV cells, (3) low moisture permeation through all packaging materials, and (4) good mechanical properties such as tensile elongation, and creep resistance at all operating conditions. Therefore, it is important to investigate how properties change and/or degrade in polymeric materials used in PV modules and understand the correlation among materials degradation and failures of PV module and system performance in the field. Fig.1. illustrates the failure modes of PV modules caused by packaging materials degradation under multiple stresses including heat, moisture and UV. The suggested degradation pathways are also specified.[1-4]

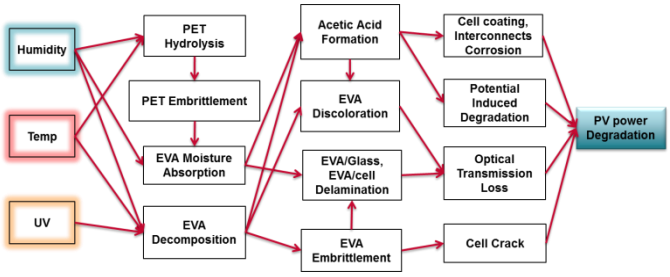

Fig. 1 Material caused PV failure modes

II. EXPERIMENTAL

Ten commercially available polycrystalline 60-cell PV modules made with TPE backsheets were fabricated and used for accelerated exposures. Eight PV modules were subjected to damp heat aging and two modules were not exposed and used as control samples. The accelerated aging conditions under laboratory-controlled exposure chambersis 85°C ambient temperature and 85% relative humidity, as described in the test 10.13 of IEC 61215 Ed.2.

The I-V performance of the modules was tested with every 500 hours of exposure, and two of the eight modules were removed from the exposure, disassembled and their packaging materials collected and tested, at every 1000 hours until the final time point of 4000 hours.

III. RESULTS AND DISCUSSION

A. Module Properties Investigation

Electrical current vs. voltage (I-V) test was conducted for the modules at every 500 hour exposure, and the results were plotted, as shown in Fig. 2. They showed that the power output of the DH-exposed modules sharply declined right after 2000 hrs. This result was quite consistent with findings in other studies.[5]

B. Material Properties Investigations

The main purpose of the study was to evaluate and identify the indicator of materials degradation. Therefore, the study was focused on investigating material properties exposed with more

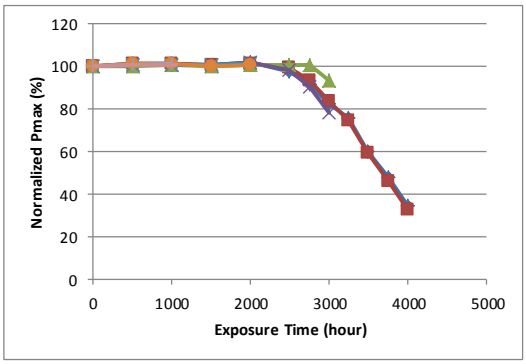

Fig. 2 Material caused PV failure modes

serious aging, in general, under the damp heat condition. In our study, two of the aged modules were withdrawn from the chambers at every 1000 hours exposure, and samples were randomly collected on each module for material properties measurement.

1) Spectroscopic Investigations

Attenuated Total Reflectance (ATR)-Fourier Transform InfraRed (FTIR) using a Nicolet 6700 model was applied to investigate any functional group changes for damp heat aged EVA. As the exposure time increases, the acetate C=O (1735 cm^{-1}) peak decreased continuously, whereas the aldehyde/ketone C=O (1716 cm^{-1}) and O-H (near 3400 cm^{-1}) peaks increased, as shown in Fig. 3. This indicates decomposition of vinyl acetate in the EVA and the formation of aldehydes, ketones and alcohols during this process.[6] The results were determined by the ratio 3373 cm^{-1}/2850 cm^{-1} for vinyl alcohol -OH/overall CH absorbance, and 1236 cm^{-1}/2850 cm^{-1} for ester ether C-O-C /overall CH absorbance to measure the relative acetate content. The increasing -OH/overall CH ratio was attributed to the EVA hydrolysis reaction during the damp heat aging process, and the decreasing C-O-C/CH_3 ratio was attributed to the EVA deacetylation reaction during the damp heat aging process (Fig. 4).

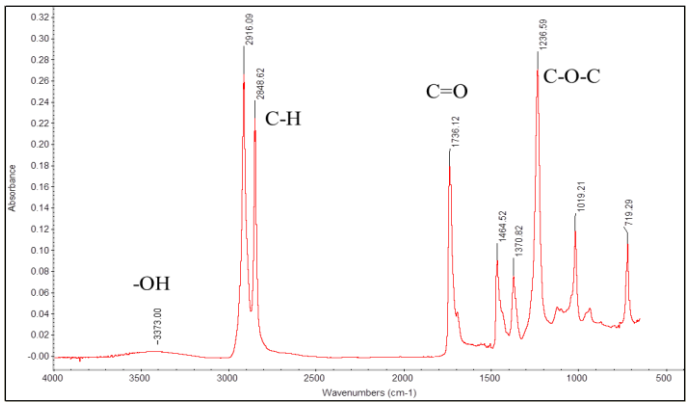

Fig. 3 ATR-FTIR spectrum of damp heat exposed EVA

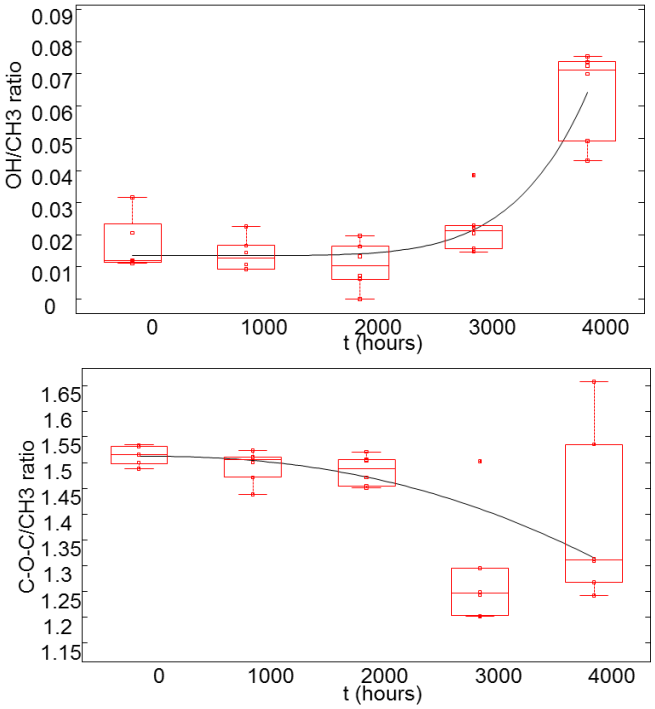

Fig. 4 EVA functional groups –OH/ CH_3 and C-O-C/CH_3 ratio change under damp heat aging

2) Thermal Properties Investigation

The thermal degradation of EVA was investigated by Thermo Gravimetric Analysis (TGA) using a Q5000 TGA (TA Instruments). In Fig. 5, the thermogram demonstrates two steps of the weight loss, the first step was due to vinyl acetate content in EVA degradation, and the second was corresponding to fragments from the degradation of polymer backbone. When EVA exposed with damp heat for a longer time, it showed decreasing mass loss at the first step of materials degradation. This was attributed to the deacetylation reaction during the aging process.[7] The percentage of the mass decrease for EVA under the damp heat aging caused by the deacetylation was about 0.06%, 0.1%, 0.36% and 1.1% at 1000, 2000, 3000 and 4000 hours, respectively (Fig. 6).

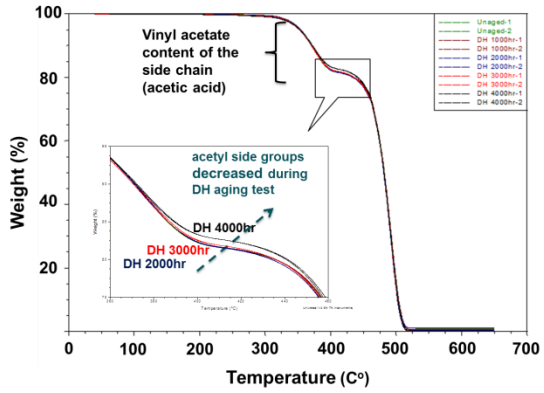

Fig. 5 Thermo gravimetric analysis (TGA) of unaged and damp heat aged EVA

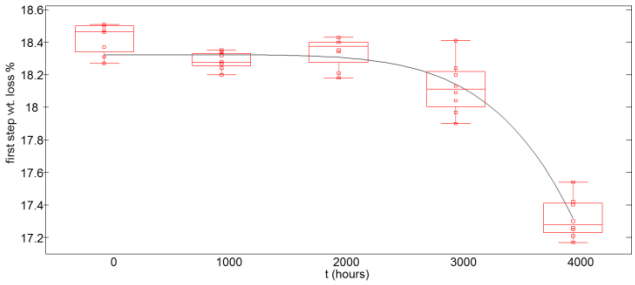

Fig. 6 EVA first-step weight loss% under damp heat aging

A damp heat aged Differential Scanning Calorimetry (DSC) thermogram for EVA is displayed in Fig. 7. The double endothermic peaks in the melting region are due to imperfect crystalline regions of EVA copolymer.[8] The result showed that the melting enthalpy of the EVA increases with longer DH aging time (Fig. 8). This may be associated with the decrease of vinyl acetate content, which induced the perfection and growth of the crystalline region under the aging condition.

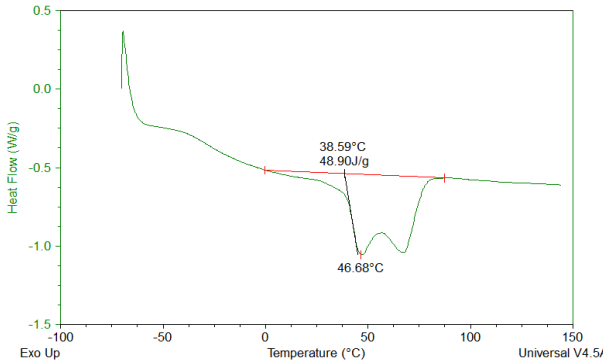

Fig. 7 Differential Scanning Calorimetry (DSC) damp heat aged EVA

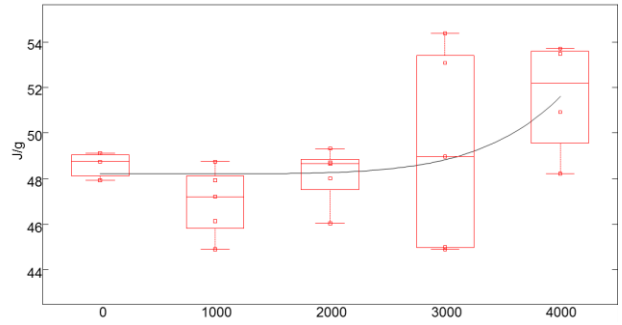

Fig. 8 EVA melting enthalpy change under damp heat aging

In addition, the Tg of EVA was also measured as a function of aging time by Dynamic Mechanical Analysis (DMA). (Fig. 9) A sinusoidal load was applied with a frequency of 1 Hz From -70 to 100°C at a heating rate of 3°C/min. The results showed that glass transitions temperature shifted to higher temperatures for longer damp heat aged EVA (Fig. 10).

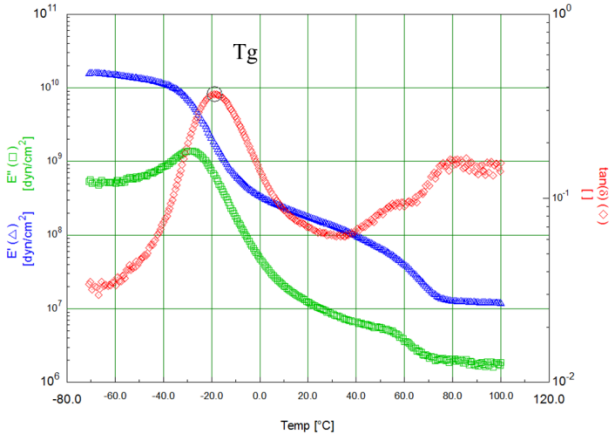

Fig. 9 Dynamic Mechanical Analysis (DMA) of damp heat aged EVA

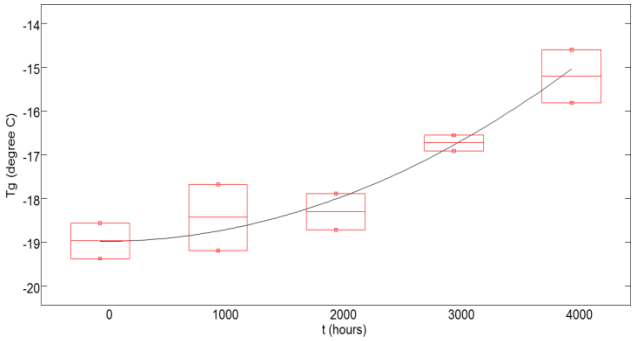

Fig. 10 EVA glass transitions temperature shifted to higher temperatures for longer damp heat time

3) Acetic Acid Investigation

Hydrolysis of vinyl-acetate monomers resulted in generating acetic acid that can accelerate the corrosion of electrical interconnects. Recently, scientists at Mitsui Chemical were using Infra-Red (IR) and Hot Water Extraction Method (HWEM) to evaluate the amount of free acetic acid desorbed in EVA encapsulant. They proposed that the desorbed acetic acid in EVA was useful as an indicator for module degradation.[9-10] In our study, the free acetic acid was evaluated by a Pyrolysis GC-MS (Frontier Lab) on full size PV modules. The Pyrolysis GC-MS technique only needed a small amount of EVA sample (about 5 mg), and we believed this provided better detection sensitivity and more accurate analysis for acetic acid.

Also in our study, two of the aged modules were withdrawn from the chambers at every 1000 hours exposure, and 3 to 6 samples were randomly collected on each module for acetic acid measurements. As shown in Fig. 11, for damp heat aged samples, the desorbed acetic acid sharply increased from 5 ppm to 56 ppm, 619 ppm and 1348 ppm at 0, 1000, 2000, and 3000 hrs., respectively. We noted that the free acetic acid may evaporate faster at room temperature in the air, so the test must be conducted immediately after the sample was obtained from the module, otherwise the level of acetic acid might be underestimated, as shown in Fig. 12.

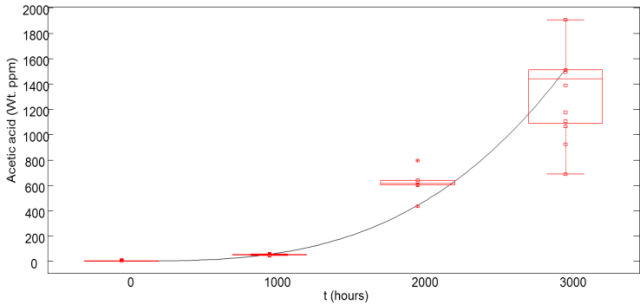

Fig. 11 The amount of free acetic acid desorbed in damp heat aged EVA

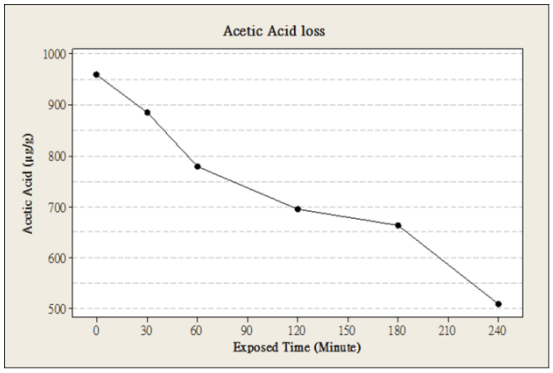

Fig. 12 The amount of free acetic acid decreased after exposing the sample to the air

4) Interlayer Adhesion Investigation

Peel strength of polymeric encapsulants such as EVA to the glass substrates of PV modules is an important factor that can affect delamination. The peel strength between the glass and EVA of the test laminates was measured with an Instron test system using 90-degree peel test. The results in Fig. 13 showed that the adhesion strength of damp heat aged samples gradually decreased from 15 N/mm^2 to 10 N/mm^2 and 3 N/mm^2 at 1000 and 2000 hrs., respectively. And, it remained stable at around 3 N/mm^2 for a longer aging time. Damp heat exposure caused adhesion loss could be associated with continuous moisture diffusion into the interfacial sites.

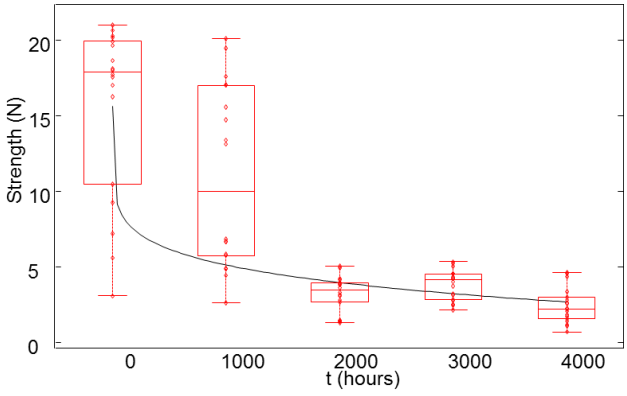

Fig. 13 The adhesion strength between EVA and glass for aged coupon samples

C. Correlation of Power Reduction and Material Properties Degradation

In this study, we considered an extension of the linear degradation models proposed by Peng and Tseng[11] to nonlinear degradation models as follows:

$$Y(t) = g(t;\boldsymbol{\lambda}) + \sigma B(t),$$

where $Y(t)$ denotes the power loss of a PV module under damp-heat condition at time t; $g(t;\boldsymbol{\lambda}) = \lambda_1 t^{\lambda_2}$ is mean degradation path of power loss; $\boldsymbol{\lambda} = (\lambda_1, \lambda_2)'$ is a fixed unknown parameter vector; σ is a diffusion coefficient; $B(t)$ is the standard Brownian motion. Fig. 14 shows the degradation paths for power loss of PV modules. By using the maximum likelihood method, the estimated mean degradation path is obtained as

$$g(t;\hat{\boldsymbol{\lambda}}) = 0.001758 \times \left(\frac{t}{1000}\right)^{4.305980}. \quad (1)$$

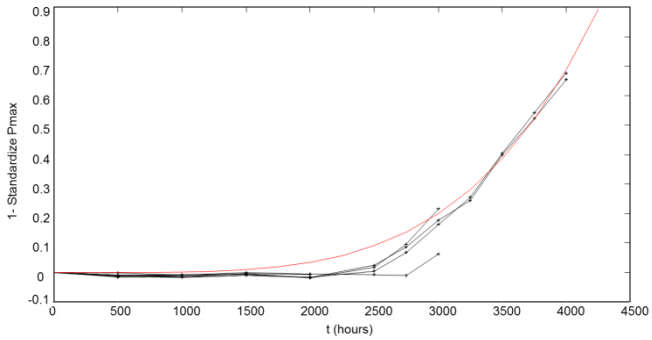

Fig. 14 The degradation paths for power loss of PV modules

With regard to material properties of degradation, a power-law destructive degradation model, which suits with all material properties measurements in this study[12, 13], is assumed to be

$$X(t) = f(t;\boldsymbol{\theta}) + \varepsilon_t,$$

where $X(t)$ denotes the material property measurement under damp-heat condition at time t; $f(t;\boldsymbol{\theta}) = \theta_1 t^{\theta_2} + \theta_3$ is the mean degradation path of the material property measurement; $\boldsymbol{\theta} = (\theta_1, \theta_2, \theta_3)'$ is the fixed unknown parameter vector; ε_t is the measurement error and follows $N(0, \sigma_t^2)$; σ_t^2 is an unknown parameter and can be estimated by the sample variance at time t. [14, 15]

Taking acetic acid measurement as an example, Fig. 11 shows the box plot of destructive degradation data at each measurement for desorbed acetic acid and the corresponding estimated mean degradation path. By using the weighted least squares method, the estimated mean destructive degradation path is obtained as

$$f(t;\hat{\boldsymbol{\theta}}) = 3.542441 \times 10^{-8} \times t^{3.057204} + 4.599428. \quad (2)$$

From (1) and (2), the correlation coefficient between the mean degradation path of power loss and acetic acid can be evaluated as 0.9916, which is a highly positive correlation. In other words, the mean desorbed acetic acid increases, the mean power loss of PV modules increases. The correlation coefficient between the mean degradation path of power loss and other material properties can also be calculated by using the same approach, and the correlation quality for each of them was specified in the Table 1.

Table 1 Correlation Quality

Indicator	Analyte	Measuring Tool	Correlation coefficient	Correlation Quality
EVA functional group	Ratios of -OH/overall CH	ATR-FTIR	0.9915	**Good**
EVA functional group	Ratios of C-O-C/overall CH	ATR-FTIR	-0.9709	**Good**
EVA TGA wt. loss	Fist step wt. loss	TGA	-0.9940	**Good**
EVA Melting enthalpy	Crystallinity	DSC	0.9943	**Good**
EVA Glass Transition Temp.	Tan delta peak	DMA	0.9585	**Good**
Acetic acid	Absorbed acetic acid in EVA	Py-GCMS	0.9916	**Good**
Interlayer adhesion	EVA/glass adhesion strength	INSTRON	-0.4787	**Fair**

IV. CONCLUSION

In this study, we successfully developed test methodology and identified the property changes in polymeric materials used in PV modules that result in degradation of module performance. The material properties such as IR absorptions for certain functional groups, EVA melting enthalpy, EVA glass transition temperature, EVA TGA weight loss, and the free acetic acid desorbed in EVA degradation can be deemed strong indicators that attribute to the power degradation seen in accelerated aging tests under damp heat condition. On the contrary, the adhesion strength between EVA/glass showed little impact on the power reduction of PV module. Such results indicate that interfacial adhesion between EVA/glass may not be an important factor related to the power reduction of PV modules.

ACKNOWLEDGMENTS

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