NON-LINEAR MECHANICAL PROPERTIES OF ETHYLENE-VINYL ACETATE (EVA) AND ITS RELEVANCE TO THERMOMECHANICS OF PHOTOVOLTAIC MODULES

Ulrich Eitner[1], Sarah Kajari-Schröder[1], Marc Köntges[1] and Rolf Brendel[1,2]
[1]Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany
[2]Institute of Solid State Physics, Leibniz University Hannover, Appelstraße 2, D-30167 Hannover, Germany

ABSTRACT: Polymers such as ethylene-vinyl acetate (EVA) encapsulants are known for their non-linear mechanical material behavior. We identify the time and temperature dependence of EVA with the help of dynamic mechanical analyses (DMA) and relaxation/creep experiments. Mechanical investigations of PV modules that address the issue of reliability and long-term stability need adequate models that incorporate these non-linear properties. A detailed description for a stepwise derivation of a viscoelastic material model that is based on relaxation and creep tests is presented. Besides the relevance for Finite-Element-Simulations (FEM) it is obvious from the experiments and the derived model that static snow load tests at room temperature cause a different amount of stress in the solar cells than tests at 0°C. At temperatures below 0°C the stiffness of EVA rises by 2 orders of magnitude.

Keywords: Encapsulation, Mechanics, PV Module, Modeling, Polymer Film

1 INTRODUCTION

The increasing number of publications in the field of mechanics of solar cells and modules during the last years [1-9] reflects the importance of understanding the amount and origin of thermomechanical strains and stresses. This knowledge is required to develop reliable photovoltaic devices and mechanically gentle processes. In the field of module technology the recent studies focus either on the interconnection and lamination technique [1-6] or on the mechanical performance of the entire module, the frame and the mounting [7-9]. Different loading conditions are matter of investigation: thermal loads (soldering, lamination, thermal cycling tests, inhomogeneous temperature distribution in the module), static mechanical loads (snow load) and dynamic loads (transportation, wind loads).

The widely used encapsulation material for PV modules is ethylene-vinyl acetate (EVA). It is thus essential for mechanical module and lamination studies to be able to accurately describe EVA's thermo-mechanical properties. Within the classification of polymeric materials the cross-linked EVA belongs to the group of elastomers which exhibit the following mechanical features: it is soft and compliant within the operating temperatures, it can be reversibly deformed to very large strains, it becomes stiff when the temperature falls below the glass transition temperature, it is entropy-elastic and has time-dependent material properties (creep and relaxation) [11]. In general, polymers are designed for a certain range of operating temperatures where they possess a desired stiffness. It is therefore necessary that the polymer's glass transition region is outside the range of operating temperatures. We will see that for the EVA under investigation that this demand is not entirely fulfilled.

In polymer science the material behavior of elastomers is described by the theory of viscoelasticity which incorporates time-dependent and temperature-dependent material properties [10]. In contrast to linear elastic materials the young's modulus of viscoelastic materials is no longer constant but a function of time and temperature. A dynamic mechanical analysis (DMA) and relaxation/creep tests provide clear experimental evidence that EVA is indeed a viscoelastic material. In particular, the glass transition region overlaps with the operating temperatures, so that significant changes in the material properties can already be observed within this temperature range. Finally we then model the material behavior using a generalized Maxwell model.

2 EXPERIMENTAL

2.1 DMA experiments

We perform a DMA to investigate the dependency of EVA on the temperature. A 50 x 10 mm^2 strip of cured EVA with a thickness of 1.0 mm is dynamically loaded in torsion. The torque is measured over time and the signal is split in an elastic in-phase answer to the rotational excitation and a phase-shifted signal.

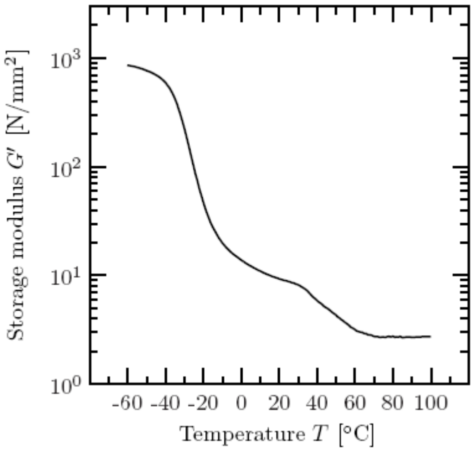

Figure 1: DMA of EVA at 1 Hz (torsional cyclic loading). The storage modulus is the elastic part of the measured stiffness.

Fig. 1 depicts the elastic fraction G' of the mechanical stiffness of EVA in the range of –60°C to 100°C. The stiffness increases by two orders of magnitude when falling below 0°C. This region between 0 and –40°C is called the glass transition region. We determine the glass transition temperature in accordance to [11] as the inflection point in the non-logarithmic T-G'-graph to be $T_G = -35.2$°C.

2.2 Creep and relaxation tests

In order to generate data that allow a complete modeling of the time- and temperature-dependence of EVA, tensile creep and relaxation tests are performed. The experiments are carried out in a CTS climate chamber which is shown in Fig. 2. The chamber is equipped with a window and a notch in the top. A tensile tester is mounted on top of the chamber and the clamps are fixed on a bar that reaches into the chamber. The other sample holder is fixed on the base in the center of the chamber. A digital image correlation system monitors the strain from outside the chamber. The force is read from the tensile testing machine and a thermocouple monitors the temperature directly at the sample.

Figure 2: Measurement setup for the tensile relaxation and creep experiments, consisting of two cameras for the non-contact measurement of strain with digital image correlation, the climate chamber and a dogbone sample clamped into the tensile testing machine.

The specimens are cut from a 1.0 mm thick lamination sheet of cured EVA having a bone shaped geometry according to the ASTM D638 standard (type I). The force (creep) resp. the elongation (relaxation) is applied to the sample within two seconds and is then held constant over a period of minimum 5 to maximum 52 hours.

The measured forces and strains are converted to stress-strain data for each test. For the relaxation data, where the elongation is held constant over time and the force diminishes, the relaxation modulus *E(t)* is calculated as

$$E(t) = \frac{\sigma(t)}{\varepsilon(t)}$$

and is shown in Fig. 3. As already observed in the DMA, the modulus shows a strong dependency on the temperature. For temperatures below 20°C the values are higher by orders of magnitude compared to temperatures above 60°C. Furthermore, the decreasing values for *E* with time indicate that the modulus is also dependent on time. Thus, the loading history is important for the determination of present stress in the material. The creep data is not shown.

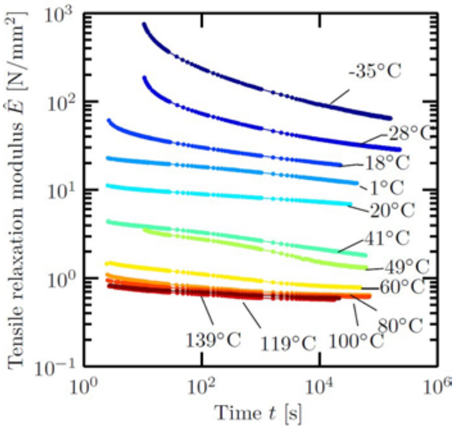

Figure 3: Isothermal relaxation curves of EVA in form of the relaxation modulus over time for different temperatures.

3 VISCOELASTIC MODELING

The time-temperature superposition is a phenomenological principle that holds true for most polymeric materials. Details on the the different steps in the modeling can be found in [10]. According to this principle the material behavior at lower temperatures is equivalent to the behavior at shorter time scales. Creep and relaxation data at different temperatures can therefore be shifted along the time axis to yield an overlapping mastercurve which in our case covers a time range from 10^{-5} s to 10^{25} s. The resulting time axis is then called reduced time. The amount of shifting is expressed in a shift factor α. We use the common Williams-Landel-Ferry (WLF) equation to relate the shift factor to temperature,

$$\log_{10}(\alpha_{T_0}(T)) = \frac{-C_1(T-T_0)}{C_2+T-T_0}\,.$$

For EVA we find $C_1 = 48.44$ and $C_2 = 172.55$ K for a reference temperature $T_0 = -20$°C. The tensile curves from Fig. 3 are interconverted to shear relaxation data (*E(t)* to *G(t)*) and are then shifted in accordance to the WLF equation. The result is depicted in Fig. 4. Finally, the grey colored shear relaxation points are fitted with a generalized Maxwell model, that consists of springs and dashpots, to account for the time-dependent material behavior. This model takes the form of a Prony series

$$G(t) = G_0 + \sum_{i=1}^{n} G_i \exp(-t/\tau_i)$$

where G_i are the fit parameters and the τ_i are chosen to discretize the reduced time axis in one value per decade. The Prony fit with 20 elements is shown as a continuous thin curve in Fig. 4. The prony fit reasonably matches the shifted curves. This model covers the whole temperature and time range and can now be used as a material description of the thermomechanical behavior of EVA in Finite Element Simulations (FEM).

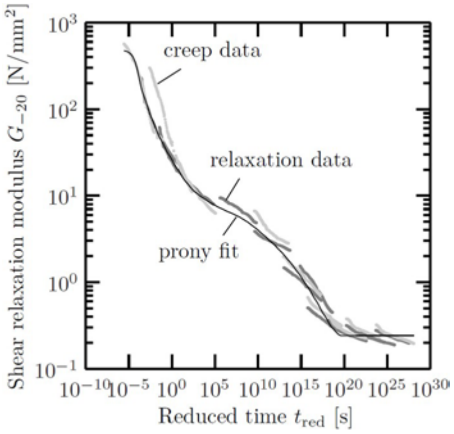

Figure 4: Shifted experimental data and model fit.

4 RELEVANCE FOR MECHANICAL STUDIES

As EVA is only one part of a PV module it is essential to investigate how these non-linear properties affect the deformation of complete modules or laminates. We give two examples where viscoelasticity seems to play an important role.

We recently measured the thermal deformation of the gap between two crystalline solar cells in a laminate [6]. The experimental data is plotted as dots in Fig.5. The lines represent linear elastic simulations of the experiment and reveal that in this context linear elastic models for the materials in the laminate always result in straight lines for the gap deformation. The experimental data, however, deviates from a straight line at low temperatures. This behavior correlates with the increase of the EVA's stiffness at low temperatures. We thus assume that only a FEM simulation with a viscoelastic model for EVA will be able to reproduce the experimental results.

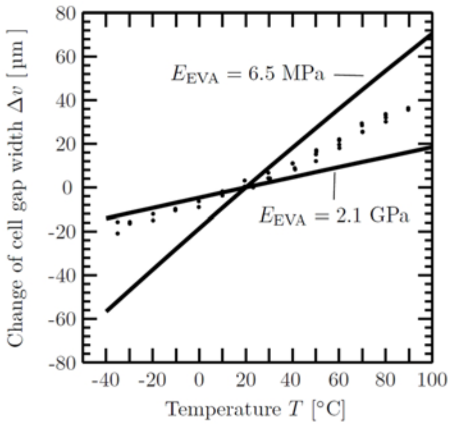

Figure 5: Measured deformation of cell gap between two solar cells (dots) and results of two linear elastic simulations using constant Young's moduli of 6.5 MPa and 2.1 GPa, respectively.

Another consequence of the viscoelastic material properties is the fact that the solar cells are no longer embedded in a very soft and compliant material if the loading times are very short (impact on module, high frequencies during dynamic measurements) or the temperatures are very low. It is expected from the experimental results presented here that in these cases the EVA behaves rather stiff and can thus no longer compensate high stresses in the module. On the other hand static loads at low temperatures are expected to lead to less bending as the EVA is stiffer than at room temperature and thus enforces the module's resistance to bending.

5 CONCLUSION

The viscoelastic properties of EVA exhibit a strong dependence on time and temperature. Depending on the loading speed and the temperature we measure the elastic modulus to vary from 1 MPa to about 1 GPa. As FEM simulations are the key tool to determine mechanical stresses in PV modules and embedded solar cells, it is therefore necessary to accurately include these properties in a viscoelastic FEM model when simulating high dynamic loads or temperature loads below 0°C. Due to the increased stiffness of EVA at low temperatures we expect a snow load test at 0°C to cause less bending of the PV module than at room temperature. Attention has to be drawn to the loading speeds and frequencies of wind load tests when the stresses of the solar cells in the laminate are computed.

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