

Mechanical properties of EVA-based encapsulants

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ABSTRACT

Since the 1980s, ethylene-vinyl acetate (EVA) has been the standard encapsulation material for crystalline photovoltaic modules. From a mechanical point of view, the encapsulant takes the function of a compliant buffer layer surrounding the solar cells. Therefore, understanding its complex mechanical properties is essential for a robust module design that withstands thermal and mechanical loads. In the cured state after lamination, its stiffness features a high sensitivity to temperature especially in the glass transition region around -35°C , and a dependence on time which becomes obvious in relaxation and creep behaviour. This paper outlines the viscoelastic properties of EVA and the corresponding standard experimental methods, as well as the impact on the accuracy of wind and snow load test procedures for PV modules.

Introduction

The use of EVA as an encapsulation material for photovoltaic modules as shown in Fig. 1, dates back to the Flat Plate Solar Array Project at the Jet Propulsion Laboratory from 1975 to 1986 [1]. The purpose of this project was to commercialize photovoltaic energy production which included the initiation of module warranties and a high reduction of the production cost. The findings of the research project concluded that EVA-based encapsulants offered a low-cost material that meets the technical requirements for long-term stability and easy processability in a lamination step. Since this research was conducted, the vast amount of commercially deployed crystalline PV modules contain EVA encapsulants. By now, the failure modes and the reliability of EVA-based modules have been intensively discussed and have led to a number of standard accelerated aging tests, as well as to a continuous improvement of the EVA material composition [2–5].

Although promising alternative encapsulants with superior material properties have been introduced in recent years [6], EVA has remained the favoured material choice for crystalline PV modules. The reasons for the dominant position of EVA in the market are its low cost and the industry's 25 years of experience with EVA-based modules in the field. The latter point is important in order to understand the conservative attitude of module manufacturers towards new materials as they give warranties of up to 25 years on 80% of the initial output power for their product.

Structure

EVA is a thermoplastic material which becomes an elastomer after crosslinking. The crosslinking takes place during the lamination step at 150°C , where the thermoplastic polymer softens before covalent C-bonds between the formerly

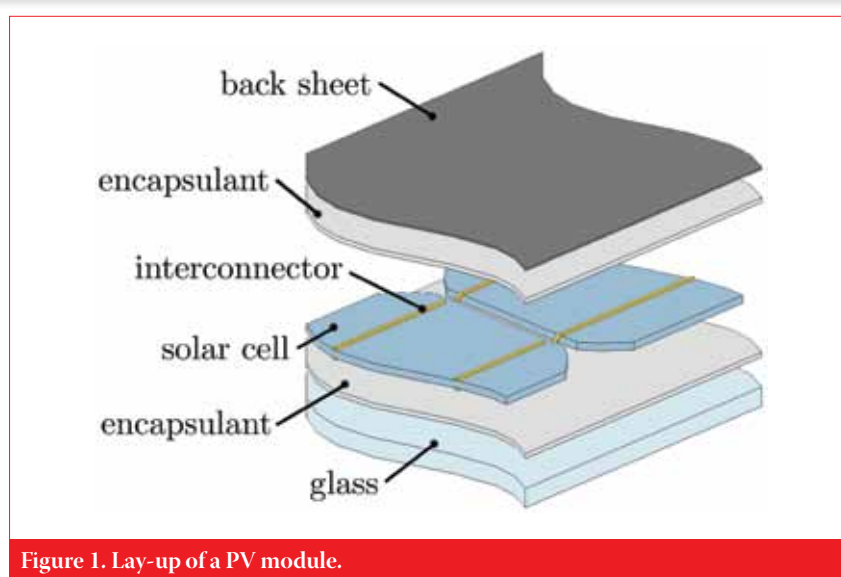


Figure 1. Lay-up of a PV module.

unconnected chain molecules are formed to create a polymeric network structure. In contrast to a purely thermoplastic material, this elastomeric macromolecule, obtained after crosslinking, cannot be melted in subsequent heating steps.

Elastomeric material behaviour

The chemical structure of the crosslinked EVA exhibits the typical mechanical properties of elastomers [7, 8]. These are closely related to the three different states: the glassy region, the glass transition region and the rubbery region. In the glassy region, which describes the polymeric behaviour at low temperatures and at high loading frequencies, the material is stiff and brittle. The macromolecular network structure is frozen so that a deformation causes the atoms to be shifted out of their energetic optimal position, resulting in a force response. When the deformation is relieved, the atoms move back into their energetic optimal positions. This kind of behaviour, found in the glassy state, is called energy-elastic.

Crosslinked EVA is in the rubbery state at room temperature. The chain segments of an elastomer are then free to rotate and to relocate so that they arrange in an optimal configuration of maximal entropy. Upon deformation, the material is stretched along the loading direction. Very high strains of up to several hundred percent are possible as the molecular chains are mobile. The reacting forces are driven by the molecular system's effort to get back into a state of maximal entropy. This behaviour is called entropy-elastic and explains the lower stiffness of the material in the rubbery state. The elastic moduli are two to three orders of magnitude lower than in the glassy state. The process of rearranging the chain segments into a configuration of maximal entropy does not occur instantaneously, and is known as relaxation or creep.

The transition between the glassy and the entropy-elastic states is not sharp but ranges over a temperature or a frequency interval, a region called glass transition. The glass transition temperature is used to quantify the centre of the transition region

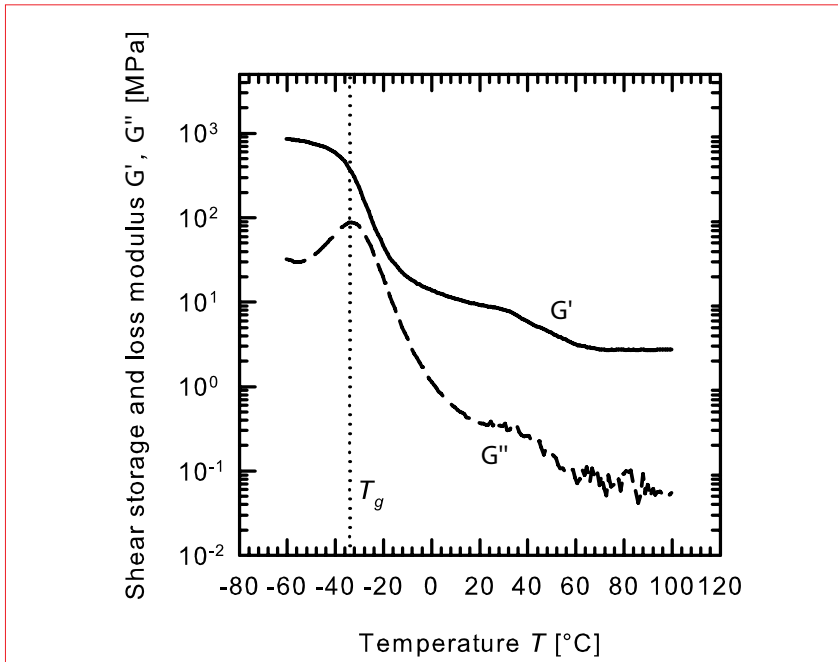


Figure 2. Dynamic mechanical analysis of EVA at 1Hz.

and is defined as the inflection point in the stiffness curve over temperature [8].

The rubbery region ends at temperatures where the elastomer is chemically decomposed. Crosslinked elastomers do not melt.

For an elastomer, the desired entropylastic properties of low stiffness and high deformability are given in the rubbery region. Elastomers should thus be used for applications with operating temperatures and loading frequencies that fall into the rubbery region.

Mechanical testing

A common measurement method to determine the mechanical properties of a polymeric material is dynamic mechanical analysis (DMA). A specimen is dynamically loaded by applying a sinusoidal strain or force and the material response in terms of force or strain are monitored. At the same time the temperature or the frequency is slowly changed at a constant rate. The measured response is plotted over temperature or frequency, split into the in-phase (elastic) signal and the off-phase (viscous) signal. The elastic part is called storage modulus G' while the viscous response is named loss modulus G'' . The DMA analysis is applicable in tension, torsion or shear deformation. Results of DMA measurements of EVA can be found in various publication, for example in [9] and [10].

Fig. 2 shows a DMA of cured EVA at a constant frequency of 1Hz in torsional loading as given in [11]. The strong dependence on temperature is shown in terms of the storage modulus in shear which changes between 800MPa at

-40°C and 0.2MPa at 100°C. The glass transition temperature is -35°C. A second phase transition is found at 40°C where semicrystalline parts in the EVA melt. The loss modulus G'' indicates the time dependence of the mechanical behaviour.

In order to assess the full time and temperature-dependence to set up a constitutive material law for EVA, additional experiments are necessary. It is either possible to perform the DMA as described above at various other frequencies or at different isothermal temperatures while sweeping over frequencies. Another alternative is to make use of relaxation and creep tests where a strain or stress is

applied in an instantaneous loading step. Here, different isothermal temperatures are required for a full description of the mechanical behaviour.

At ISFH, relaxation and creep tests were carried out at constant temperatures between -40°C and 140°C. Specimens of cured EVA in the shape of the ASTM D638 standard (type I) were loaded in tension in a 2s elongation step of approximately 5% strain. The elongation was held constant for several hours to monitor a decreasing force signal of the sample. The longitudinal and transverse strain was recorded with a stereo camera system in conjunction with digital image correlation technique. The relaxation modulus, which is the fraction of stress σ and strain ϵ ,

$$E(t) = \frac{\sigma(t)}{\epsilon(t)} \quad (1)$$

is shown in Fig. 3. Again, the time- and temperature-dependence become obvious. At high temperatures above 100°C the tensile relaxation modulus $E(t)$ is below 1MPa whereas at -35°C it is between 60 and 800MPa. In creep experiments a step in stress was applied to the tensile specimen in order to monitor the increasing elongation in terms of longitudinal strain.

Viscoelastic material model

The purpose of a valid mechanical material model for EVA is to fully describe the relation between stress, strain, time and temperature. The model can then be used for direct evaluation of simple load cases or for complex Finite-Element-Analyses (FEM) of a complete module. The measured behaviour of EVA is time-

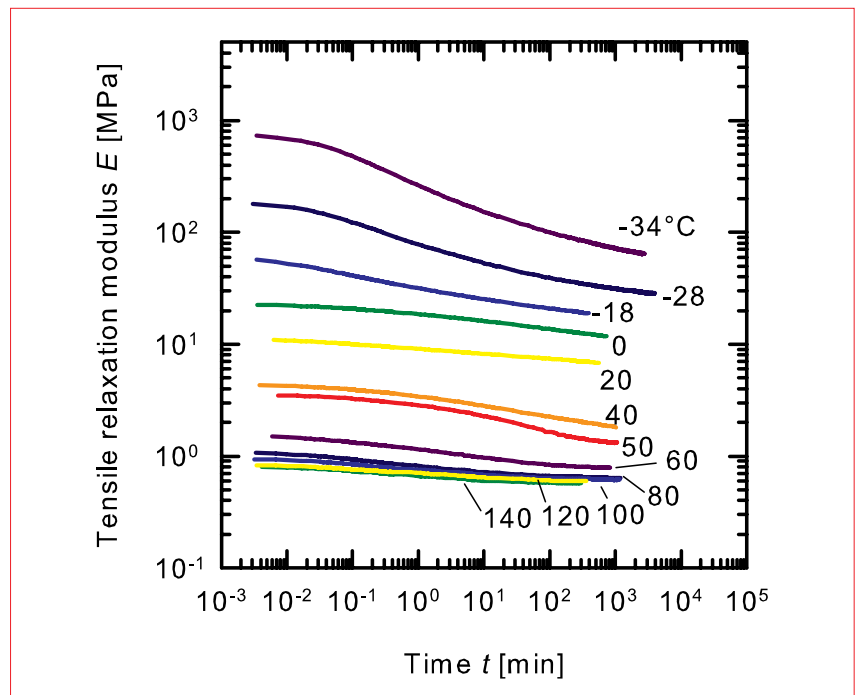


Figure 3. Relaxation curves of EVA.

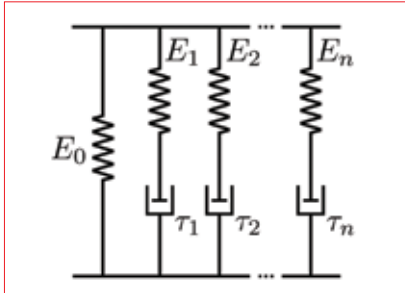


Figure 4. Generalized Maxwell model.

and temperature-dependent and can be described by a viscoelastic constitutive equation. For a constant temperature it is:

$$\sigma(t) = \int_0^t E(t-s) \dot{\epsilon}(s) ds \quad (2)$$

where $E(t)$ is the relaxation modulus at that temperature. The integral implies that the complete loading history is relevant for the actual stress state. The temperature-dependence is included with the help of the time-temperature-superposition. It is based on the observation that the isothermal relaxation curves (as shown in Fig. 3) overlap if they are shifted along the logarithmic time axis, resulting in a mastercurve. For each shifted curve the shift factor α expresses the amount of shifting and is formalized by the Williams-Landel-Ferry (WLF) equation:

$$\log_{10}(\alpha) = \frac{C_1(T - T_0)}{C_2 + T - T_0} \quad (3)$$

with $T_0 = -20^\circ\text{C}$, $C_1 = 48.4$ and $C_2 = 172.5$ K. To complete the viscoelastic material model for EVA the mastercurve needs

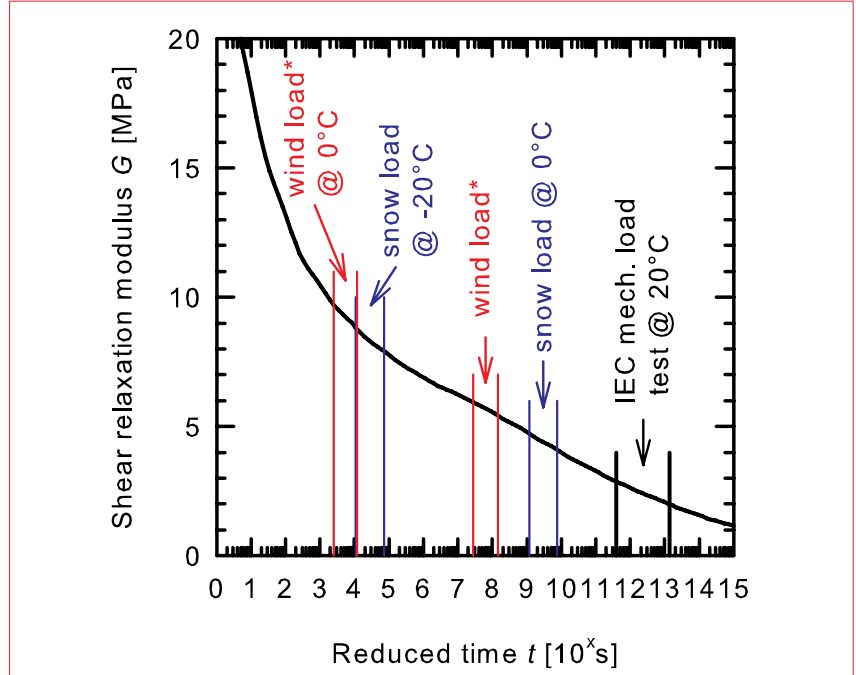


Figure 5. Behaviour of EVA in wind and snow load tests at different temperatures. *Time scales converted from [14].

to be expressed in terms of the reduced time t . The standard procedure is to use a generalized Maxwell model that consists of springs and dashpot elements as illustrated in Fig. 4. The corresponding equation is the Prony series:

$$E(t) = E_0 + \sum_{i=1}^n E_i \exp\left(-\frac{t}{\tau_i}\right) \quad (4)$$

The τ_i are set to one per decade while the E_i are treated as fit parameters; details of the modelling procedure are given in [11].

Consequences for module design and standard testing

The fact that the mechanical properties of EVA depend on time and temperature has direct consequences for the module design and the standard tests. First it should be noted that the glass transition region lies within the operating temperatures that range from -40°C to 85°C . At around -30°C the shear storage modulus drops from 800MPa to 10MPa as measured with the DMA at 1Hz. As stated in the discussion of elastomeric properties, such an overlap between operation temperatures and the glass transition region should be avoided.

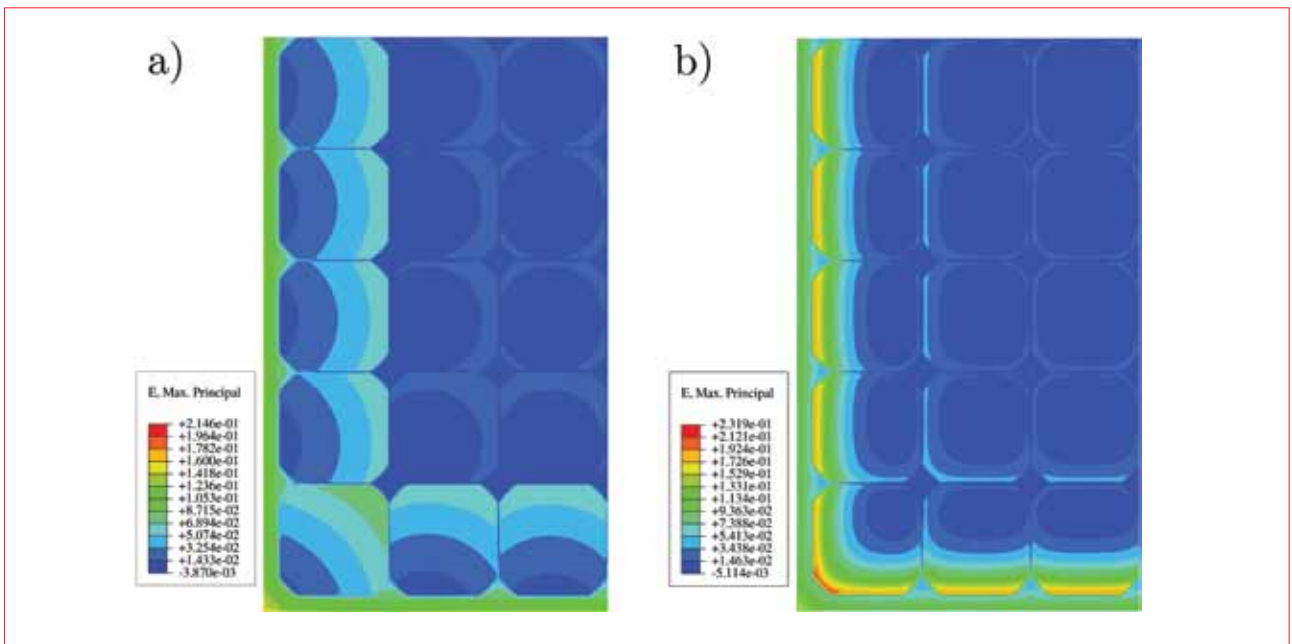


Figure 6. Simulated maximum principle strain in the EVA layer between glass and cells (a) and in the EVA layer between back sheet and cells (b) at -40°C . The lower left hand quarter of a 60-cell module is shown.

Of particular importance in regard to thinner cells that break at lower strains in the module, the compliant characteristics of the encapsulant have to be maintained for all thermomechanical loading conditions. The fact that the encapsulant creeps raises questions about the long-term deformation of modules as discussed in [12].

Second, the snow load and the wind load tests do not reflect the outdoor conditions as they do not imitate the correct temperature or loading frequency. Fig. 5 shows the stiffness of EVA over the reduced time and the testing conditions for the snow and wind load tests at different temperatures. In a worst-case scenario, the module survives the IEC 61215 load test at room temperature but fails with an equivalent snow load at -20°C as the EVA is not compliant enough to protect the cells from large strains. For PVB encapsulants, where the glass transition is around 25°C , the effect of less bending at lower temperatures due to higher stiffness of the encapsulant has been experimentally shown [13]. Another worst-case scenario is possible for the wind loads when relying on the frequencies reported in [14] as indicated in Fig. 5.

FEM-simulation of a module during thermal cycling

Along with accurate material models for all module materials, the viscoelastic model for EVA allows for a detailed simulation of a module during a thermal cycling test. When a 60-cell module with a 4mm-thick glass superstrate and $200\mu\text{m}$ -thick, $125 \times 125\text{mm}^2$ monocrystalline cells cools down from a stress-free initial state at 150°C lamination temperature, the largest deformation and stresses are found at -40°C . The reasons for this are the different coefficients of thermal expansion for the glass, the silicon solar cells and the back sheet. Fig. 6 shows the resulting strains at -40°C in the lower left-hand quarter of the module. The simulated strains exceed 20% which demonstrates that the EVA takes the function of a compliant buffer layer between glass, back sheet and solar cells. The deformation is higher between the back sheet and the cells than in the EVA layer between the glass and the cells due to the larger contraction of the back sheet compared to the glass. The maximum strain is found under the outer edges of the cells close to the module edges. The interconnects are not part of the simulation.

Conclusions

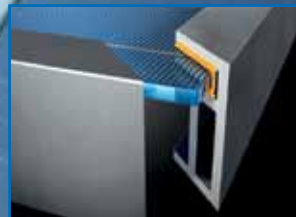
The complex mechanical properties of EVA-based encapsulants, i.e. the time- and temperature-dependence have been discussed in this paper. The elastic modulus of EVA was determined in DMA and relaxation/creep experiments to range from almost 1GPa at -40°C to below 1MPa at 140°C . Furthermore, relaxation and creep experiments reveal the time-dependent characteristics of EVA. The glass transition region overlaps with the operating modules' temperatures around -20°C , representing a possible weak point in the standard module design, especially when it comes to the encapsulation of thin fragile cells. Another direct consequence of the time- and temperature-dependence is the limited validity of the standard snow and wind load tests. The fact that they are usually performed at room temperature where the EVA is very compliant does not guarantee a correct operability at temperatures below 0°C where the stiffness of EVA increases by several orders of magnitude. The Finite-Element-Analysis of a module during thermal cycling demonstrates that the soft and compliant material properties of EVA are needed to provide a mechanical buffer layer between the glass, the crystalline solar cells and the back sheet. The simulated strains exceed 20% which are in general best borne by a polymeric material with entropy-elastic properties such as EVA in the rubbery state.

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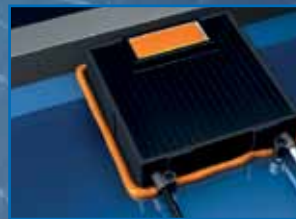
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About the Author



Ulrich Eitner studied technical mathematics at the University of Karlsruhe (TH) and joined the PV module technology group at ISFH in 2006. He

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