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## Analysis techniques of polymeric encapsulant materials for photovoltaic modules: situation and perspectives

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### Abstract

The properties of the encapsulant are critical to the long-term performance of photovoltaic (PV) modules under the influence of sunlight including UV, elevated temperature, humidity and diffusion of oxygen. Encapsulation process represents about 40% of the whole PV module cost. The introduction of new non-EVA encapsulant material type "Low-Cost, High-Performance" should provide a solution to outdoor yellowing degradation problems. The emerging encapsulant materials exhibit a good compatibility with emerging PV solar cells for long term durability. This new generation of encapsulant materials has the advantage to improve the PV module performances and long term durability for specific climate like desert regions. This scientific contribution presents an overview of the different encapsulant materials currently on the market, the general requirements of the emerging encapsulant materials and characterizations techniques for degradation, diagnostic and reliability lifetime estimation in the framework of Algerian renewable energy strategy.

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## 1. Introduction

Several technological encapsulation processes for PV modules with various materials were used during the last decade. Glass-back sheet and glass-glass encapsulation processes are used in PV module manufacturing. Figure 1 shows the Glass-back sheet technology.

The polymer encapsulant used in PV modules is constituted typically of molecules in the shape of long chains, where the chemical structure can vary to a large extent. The detailed knowledge of the relations existing between the chemical structure of chains and their microscopic organization is an essential condition for understanding the numerous physical properties of the polymer materials. In general, amorphous polymer is characterized by the absence of long-range order. On the other hand, a crystalline polymer presents an ordered structure. One important application of encapsulant material is the encapsulation of solar cells in PV modules, where the material has to fulfil several basic functions, like protection against environmental exposure (heat, humidity, high voltage, mechanical stress, ultraviolet radiation and others). Actually, the main parameters for the quality control of the PV modules after production are sun simulation tests for electrical output evaluation. The current qualification tests (e.g. IEC 61215) did not appear to provide any information on the changes in the internal structure of the encapsulant material as a consequence of encapsulation process, environmental exposure or accelerated qualification test [1].

Generally, encapsulant materials can be divided into non-crosslinking thermoplastic or thermoplastic elastomeric (TPE) materials and elastomeric materials by constituting covalent bonds between the polymer chains. The crosslinking or vulcanization of elastomeric materials is a complex process, which is crucial to the final material properties [2]. The most widely used encapsulant materials like EVA, silicone and urethane have to be subjected to a chemical crosslinking process which can be induced by high temperature levels or UV irradiation. The thermoplastic or TPE materials like PVB, TPSE and ionomers, as well as modified polyolefines (PO), melt during the module manufacturing process without formation of chemical bonds (crosslinks) between the polymer chains [3,4,5].

Actually, high-efficiency crystalline solar cells achieve their high power output by increasing the spectral response in the UV light spectrum. It therefore becomes more important to shift the UV cut-off of the encapsulant to below 350 nm by Low shift down (LSD) technique, which can lead to a relative power increase of more than 1%. Otherwise, Nanostructured transparent polymer (NSTP) technology is a very promising challenge for PV conversion [6,7]. Generally, NSTP are compatible with the various processes used in the manufacture of the PV module. The major advantages of the PV Modules encapsulated with NSTP materials are: No acetic acid is formed with thermoplastic polyolefines; Encapsulation with different emerging solar cells; More resistant to degradation by UV radiation (LID degradation); Stability against high temperatures and relative humidity.

## 2. Methods

Thermal analysis of polymers is a common method for polymer characterization relevant to PV encapsulant material for PV conversion. Using thermal analysis, it is possible to determine fundamental properties of a polymer such as phase transition temperatures, rheology and molecular mobility. It is the summation of these properties that enable us to determine whether a polymer is a good candidate as an encapsulant for PV device. In this work, we have investigated different analysis techniques to understand the behavior of the polymer encapsulant materials as [8]: Differential Scanning Calorimetric (DSC), Dynamic Mechanical Analysis (DMA), Thermally Stimulated Current (TSC), Rheology and Ultrasound analysis techniques.

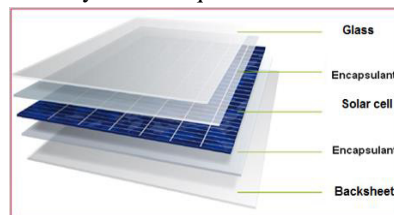


Fig. 1. Glass-back sheet PV module.

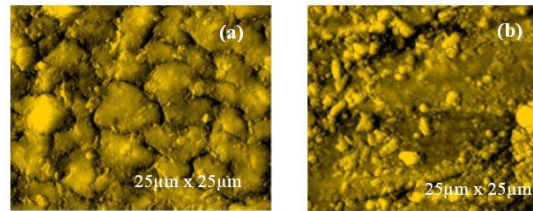


Fig. 2. AFM image observation (a) Original EVA, (b) aged cross-linked EVA.

### 3. Results and discussion

#### 3.1. Surface structure

The surface roughness of EVA encapsulant before and after outdoor exposure in desert climate of Algerian Sahara for 7 years is calculated to be 124 nm and 70 nm respectively. AFM topography images illustrated in Fig. 2 are not homogenous and reveal roughness diminution, due to the combined effect of EVA thermal process in laminator chambers and high irradiance-temperature parameters resulting from outdoor exposure.

#### 3.2. Thermally Stimulated Current

By TSC analysis technique, cured EVA has a somewhat broad low temperature peak at about  $-38^{\circ}\text{C}$ , and a high temperature peak at about  $26^{\circ}\text{C}$  as described by Fig. 3. The significance of the peaks that are observed in these experiments relates to the modes of structural relaxation that occur as the temperature is increased. The observation of two relaxations suggests that the EVA material is heterogeneous with relaxations occurring in two distinct domains. The TSC spectra of cured EVA at polarization temperature of  $60^{\circ}\text{C}$  before and after exposure at the PV plant of Adrar (south-west of Algeria) under desert environmental conditions characterized by high irradiance and temperature levels for eight years of continuous exposure. We found that the exposed cured EVA encapsulant showed considerable decrease in current intensity for the high temperature peak. The difference of the magnitude of peak current suggests increased crosslinking occurring selectively in the high temperature phase as a result of exposure [9].

#### 3.3. Thermogravimetric Analysis

In Fig. 4, by TGA analysis it is revealed two peaks located at about  $350$  and  $460^{\circ}\text{C}$ , corresponding to the

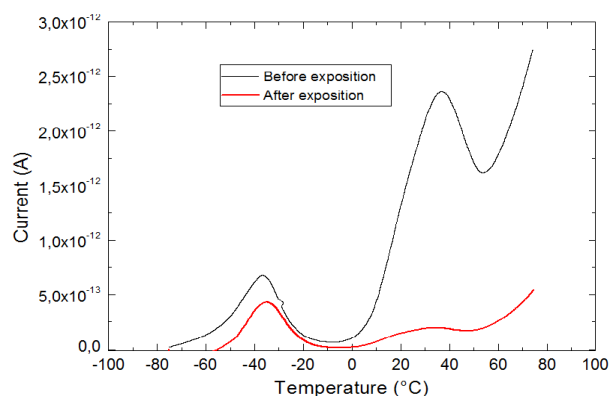


Fig. 3. TSC spectra for cured EVA before and after outdoor exposure at  $60^{\circ}\text{C}$  polarization temperature.

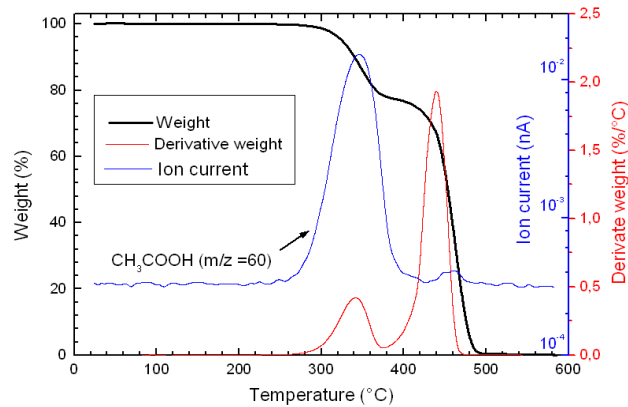


Fig. 4. TGA, DTGA and TGA-MS curves of crosslinked EVA (Atmosphere: N<sub>2</sub>; heating rate: 10°C/min).

evolution of the acetic acid (deacetylation reaction) and the main-chain degradation, respectively, verifying the general theory of a two-step process in the thermal degradation of EVA [10,11].

### 3.4. Melting and transition temperatures

Figure 5 shows the first and second heat data profile on the DSC instrument for crosslinked EVA sample. The first heating is designed to remove the possible thermal history of the sample and also it ensures good contact with the DSC pan to enable good data to be taken. On first heating there is one endothermic process clearly visible with peak at 47.5°C with a shoulder at 55°C [12]. The enthalpy change for a given phase transition may be found by integrating over the area in which the transition is seen to occur on the DSC plot according to ISO 11357. The magnitude of the integrated temperature peak for EVA is 31.9 J/g. The endothermic temperature peak is described as the result of melting of larger, more regularly formed crystallites. After cooling, the second heating is designed to remove the possible thermal history of the sample and also it ensures good contact with the DSC pan to enable good data to be taken. On the second heating, the endothermic peak is no longer observed due to the fact that the structure of the material has changed. Instead, there is a very broad endothermic with peak at 55°C and the magnitude of the integrated temperature peak for EVA is 14.4 J/g. The broad endothermic on the second heating is suggestive of a broad distribution of crystallite sizes. Apparently during the rapid cooling cycle, the crystallization process is not fast enough to develop well-formed crystal structures.

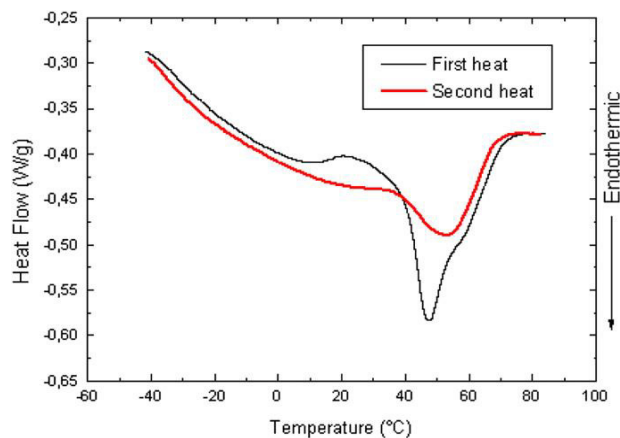


Fig. 5. DSC curves of the cross-linked EVA in heat-cool-heat mode with expanded heating cycles.

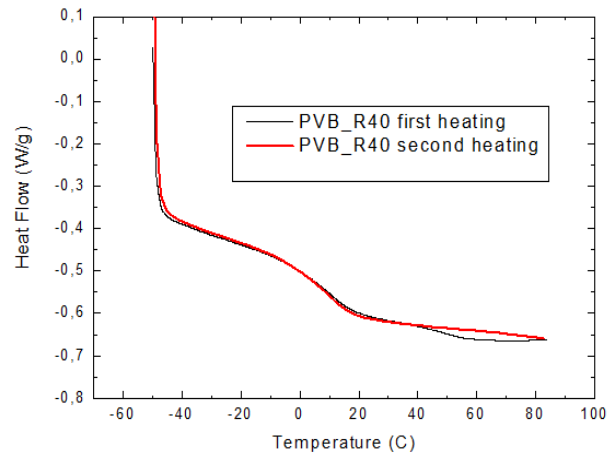


Fig. 6. DSC curves of the PVB-R40 in heat-cool-heatmode with expanded heating cycles.

Since the previous thermal history of a polymer affects the calculated degree of crystallinity, EVA crystallinity was evaluated from a second heating run. Based on EVA formulation used in our experiments, the degree of crystallinity of EVA is not affected after crosslinking reaction and is calculated to be 5%. Based on this result the cross-linked EVA is a semi crystalline material.

### 3.5. Thermal transitions

PVB is a thermoplastic polymer which has been used as encapsulant in PV conversion. It represents the second most processed encapsulation material, with similar material costs to EVA. In contrast to other encapsulation materials, PVB is very sensitive to hydrolysis because of a higher water uptake; it therefore has to be combined with a low WVTR back sheet. Plasticizers are added to PVBs to improve their mechanical processability and to modify their phase-transition temperatures. Advantages over EVA are better UV stability and better adhesion to glass. The UV transparency is almost as good as that of EVA. The lamination processing time can be reduced by about 50% compared with EVA.

Figure 6 shows the heat-cool-heat results for PVB-R40. In contrast to what was observed for EVA encapsulant,

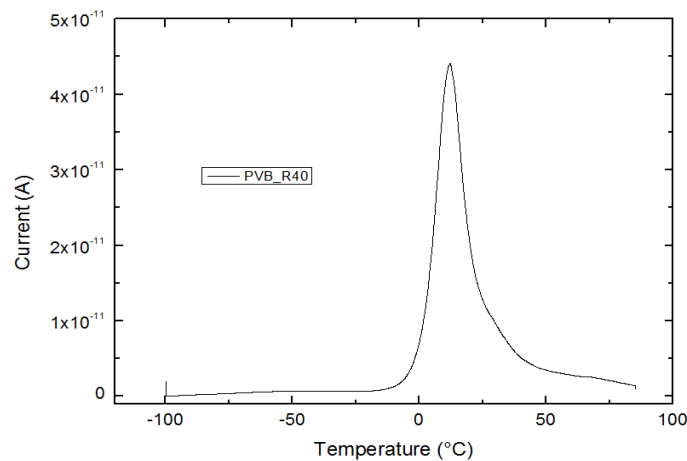


Fig. 7. TSC curve of the PVB-R40 at 85°C polarization temperature.

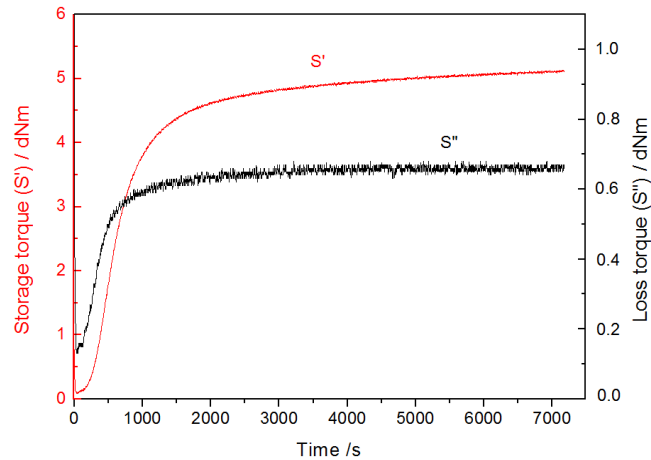


Fig. 8. Torque over time curves at 140 °C measured with the curemeter [15].

no endothermic and exothermic processes are evident. The only visible event is the glass transition that occurs when the materials vitrify. In this temperature range, the PVB material appears to show a glass transition temperature at 11°C. Figure 7 shows the results of TSC analysis on the PVB- R40 sample. The result displayed a peak at about 12 °C, which is in good agreement with DSC analysis [13,14].

### 3.6. Cure behaviour

The result of a typical curemeter measurement is given in Fig. 8. The storage torque and the loss torque show three typical sections. The drop in the first 30s is caused by the quick heating to 140°C and melting of the material. After that, the loss torque  $S''$  increases rather quickly to a value of 0.6 dNm after 600 s, but the storage torque  $S'$  shows only a very slight increase for the first 250 s, and then starts to increase substantially. This time is often called scorch time in the rubber industry, where it is associated with a 5% rise in the storage torque indicated by the standard ISO 6502 [15]. The growing polymer network increases the stiffness of the material drastically, and therefore, the measured torque value  $S'$  rises. The storage torque overall shows a typical S-shape, with an inflection point observed at about 600s, after which the slope levels off. From about 1500 s, the storage torque values show a nearly linear increase with time. In the chosen measuring time (2 h), the reaction does not come to an end. In rubber curemeter measurements this behavior is called marching modulus.

A typical result of the ultrasound measurement at 140°C is given in Fig. 9.

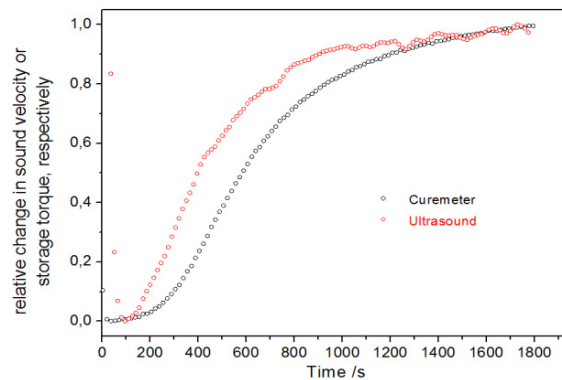


Fig. 9. Normalized sound velocity (red line) and the storage part of the storage torque (black line) over time of cure [15].

As in curemeter results, three regions are seen in measured ultrasonic variables. In the first region, the sound velocity drops due to the softening and finally melting of the material caused by the temperature increase when it comes in contact with the heated mould. After about 150 s, the second region starts where the sound velocity begins to rise. The rise becomes steeper, runs through an inflection point and then levels off again, showing a typical S-shaped curve. After about 900 s, the third region starts where the sound velocity passes over into a region with a smaller rise. The analogy between curemeter and sound velocity data is evident. Obviously, softening in curemeter measurement is finished in a shorter time. This may be due to better heat transfer from the mould to the material. However, a distinct increase appears earlier in the ultrasound measurement. The deviations at the beginning of the rise may come from the influence of the specifics of the measuring methods. The curemeter uses relatively large scale deformation of the sample and thus measures the overall stiffness of the sample, whereas the ultrasound wave exerts only minor deformation. Hence, it may detect crosslinking at an earlier state where a local network begins to rise. The curemeter mainly shows the formation of a macroscopic network, so that a distinct increase is expected when a gel structure is formed.

#### 4. Conclusion

Because of the strong influence of the encapsulation material on efficiency and reliability, the selection of an appropriate material is an important aspect in module design. PV encapsulant material having a good cost-performance ratio is a very big challenge for PV market. With regard to durability and safety, encapsulant materials have to fulfil very demanding requirements over long periods of time in various climatic and operational conditions. Thus, the selection of an adapted combination of materials for encapsulation is absolutely vital. This field of interest is actually under scope of the technical committee 82 (TC82) at IEC. Actually, various new proposals regarding polymeric encapsulant materials requirements for PV conversion are already submitted and are under study. The development of the emerging PV encapsulant materials in Algeria, characterized by high irradiance and temperature levels in some regions, is a very promising target to improve PV module reliability in the frame of Algerian Renewable Energy program. The implication of African and European specialized research institutes as collaboration network is fundamental for the success of this program.

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