OPTIMISATION OF THE FRONTSHEET ENCAPSULANT FOR INCREASED RESISTANCE OF LIGHTWEIGHT GLASS-FREE SOLAR PV MODULES

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ABSTRACT: The aim of this work is to propose a BIPV module design that is contemporarily lightweight, rigid and resistant to the relevant climatic and mechanical stresses (e.g. exposure to DH, UV, hail impacts, etc), supporting structure and reliability at the same time. Encapsulants represent a key part in the PV structure, acting as the bonding layer between the front or back sheet and the PV cell. Therefore, they need to provide excellent adhesion between these components, which is achieved via lamination. They also have to be transparent and provide outstanding electrical insulation and impact resistance to the module. All these properties must be retained after years of exposure to the UV from the sun or other severe weather conditions. With this work, we want to provide a “recipe” to define and qualify the optimum front sheet encapsulant for the proposed lightweight composite PV modules.

Keywords: lightweight PV modules, encapsulants, frontsheet, hail resistance

1 INTRODUCTION

Conventional solar photovoltaic (PV) modules made with c-Si solar cells are typically glass/foil modules with a weight of 12-16 kg/m², or glass/glass modules weighting 14-20 kg/m² or more, depending on the glass thickness. For BIPV applications, glass/glass modules are generally preferred for the higher structural stability and for safety reasons. Lightweight PV modules based on glass-glass technology exist [1], however the standard glass sheets are being substituted by polymeric material as front sheet and a glass fiber reinforced polymer as back sheet [2]. Ensuring the reliability and long-term performance of these devices requires a careful optimization of module structure and processing methods and a careful selection of the materials. The front sheet, as one of the main constituents of lightweight modules, has to provide high transparency, allowing as much light as possible reaching the solar cells, protection for the solar cells from airborne pollutants, hail precipitation and also additional benefits, including mechanical stability, electrical insulation, protection and preservation from mechanical damage. EVA has dominated the PV industry as the encapsulant of choice; however, numerous studies from late 1990s until today, report that PV module performance reduces, due to the degradation of the encapsulant. Browning/yellowing (which reduces the light reaching the solar cells), moisture absorption and acetic acid formation (which causes corrosion of metallization), delamination and bubble formation are the typical forms of EVA degradation. Various other encapsulants like silicone, ionomer, polyvinyl butyral (PVB), and polyolefin elastomers (POE), thermoplastic polyurethane (TPU) are also known in the industry as alternatives to EVA. Most of these alternative encapsulants need a cocktail of chemicals like multiple stabilizers, additives, peroxide curing agent, UV absorbers, etc. to function properly [3].

The aim of this work is to provide a “recipe” to define and qualify the optimum frontsheet encapsulant for the proposed lightweight composite PV modules.

2 AIM OF THE WORK AND STRUCTURE OF OUR LIGHTWEIGHT PV STRUCTURE

We already demonstrated the possibility to produce a lightweight PV module with a weight of ~6kg/m², by substituting the typical front glass with a thin polymer sheet and the standard back sheet by a composite sandwich structure [4]. These composite structures are usually composed of two skins bonded to a core, using a stiff adhesive. Such a lightweight PV module is sketched in Figure 1 [2]. With this work, we want to identify the optical, mechanical, morphological, physical and electrical properties, required to choose the optimum frontsheet encapsulant for lightweight composite PV modules. With those identified characteristics, the lightweight structure will be then able to withstand UV exposure, DH and mechanical tests (following the UV preconditioning test combined with Sequence E for module qualification as defined in IEC 61215 [5]).

Figure 1: Schematic diagram of the Lightweight PV module structure.

3 EXPERIMENTAL WORK

With this work crosslinking encapsulants, thermoplastic and elastomeric polyolefins will be investigated, by using Differential Scanning Calorimetry (DSC), rheology, UV-Vis spectrophotometry, and SEM analyses to study and compare their properties with the final aim to choose the candidate encapsulant to be integrated in the PV lightweight modules frontsheet. Hail test, mechanical and DH tests will be also performed to investigate the reliability of the module structure with the candidate encapsulants. These modules will be then characterised electrically (to extract IV parameters) and by means of electroluminescence (EL) to visualize the induced damages.

3.1 Encapsulant preparation

Since providing high transparency is one of the main requirements for a front sheet material, optical analysis (T% and R% measurements) have been performed. To understand/simulate the behavior of these materials,
before and after the lamination process (using the ETFE-polymer-ETFE configuration), optical measurements were carried out, both on the pristine investigated encapsulants and the ones subjected to lamination. Following the same configuration *ETF*-polymer-ETFE, the thermal, electrical and morphological properties have been also studied.

3.2 Mini-modules production

One- and Two-cells (156 x 156 mm² Al-BSF c-Si solar cells with 5 busbars) mini-modules are produced according to Figure 1. The same backsheets (BS) structure was used in the manufacturing of all samples. The BS is made by glass fiber reinforced polymer (GFRP) skins (~0.7 mm thick), glued to a light honeycomb core (6 mm thick) with an elastomeric encapsulant. The lightweight PV modules differ only for the materials used at the frontsheet; the structure contains an external 100 µm fluorine-based polymer (ETFE) layer, testing a range of different encapsulant materials, ethylene-vinyl acetate (EVA), thermoplastic (TPO1, TPO2) and elastomeric (POE) polyolefins.

3.3 Encapsulants and PV modules characterizations

3.3.1 Ultraviolet-Visible (UV-Vis) spectroscopy is used to measure the optical properties (Transmittance, T, Reflectance, R) and the yellowness index (YI) of the investigated polymeric PV materials. The yellow index is a number that indicates the degree of deviation of a test sample from colorless (or white) towards yellow. The YI was measured according to the ASTM Standard C313-10 [6]. A UV-Vis-near-infrared spectrophotometer (Lambda 950 equipment from Perking Elmer), dual-beam, has been used, covering the spectral range from 250 to 2500 nm, with a measurement increment of 1 nm. The system is equipped with an integrating sphere to measure the total transmittance and reflectance [7].

3.3.2 Differential Scanning Calorimetry (DSC) is a thermal analytical technique used to measure enthalpy variations due to changes in the physical and chemical properties of a material as a function of temperature or time. A heat-cool-heat cycle is applied to each sample; this cycle simulates the real behaviour of the encapsulant film when a PV module experiences extremely low temperatures (e.g. -30°C, cold climatic zones) and extremely high temperatures (e.g. 180°C, hot climatic zones). It also allows to understand the complete thermal history of the samples; before and after lamination each sample has gone through a heat-cool-heat cycle from -30°C to 225°C, including a heating, a cooling step and 2 isothermal ones. With this analysis, the transitions as melting temperatures, Tm, crystallinity, Tc, and crosslinking reaction region can be identified. DSC measurements were performed on a mettle Toledo DSC1 system. Thermograms were recorded from -10°C (or -30°C) to 225°C at a heating rate of 10°C/min, held at 225°C and then cooled back at 10°C/min.

3.3.3 Rheology is used to describe and assess the flow and deformation of materials under the effect of an applied force [8]. It is useful to understand the mechanical behaviour of materials as a function of stress, strain, temperature and pressure. An oscillatory deformation is applied to the encapsulant, their resulting response to stress-strain is time-dependent and their deformation partially reversible. With this work the storage modulus, G’ (which is a measure of the elasticity of the materials), has been investigated to better understand and predict the viscoelastic behavior of the different encapsulants, once incorporated in the PV module stack. The measurements were performed by using an MDR 3000 Professional by Montech Werkstoffprüfmaschinen GmbH in a temperature range 50-170°C.

3.3.4 Peel and tensile tests were performed to measure the adhesion strength between the different encapsulants integrated in the PV stack (as shown in Figure 2).

![Figure 2](image_url)

Figure 2: Peeling test set-up used to measure the adhesion strength between the encapsulants.

The Young modulus, or elastic modulus, E (expressing the encapsulants rigidity and the maximum stress which a material can withstand before failure), has been estimated. The test was performed using an Instron Zwick Roell Z020 mechanical testing instrument equipped with a 1kN load cell in a displacement control test at a fixed rate of 100 mm/min at room temperature.

3.3.5 The Hail test was performed according to IEC 61215-2:2016 [9]. Figure 3 represents the 1-cell PV module used for the test and the impact spots selected. Ice balls of 25 mm diameter are shot at a velocity of 23.4 ± 1.5 m/s.

![Figure 3](image_url)

Figure 3: Hail test setup (a) example of 1-cell mini-module used and (b) impact spots for the hail test. (c) EL images obtained after the hail test for 1-cell lightweight coupons. Numbers at the top sketch represent 1-TPO or POE, Solar cell; 2-TPO or POE, 3-ETFE; 4-Ice ball.

The lightweight mini-modules were hit in four critical locations: (1) at the border of the solar cell, (2) at the electrical connection, (3) in between the fingers and (4) in any point vulnerable to hail impacts. The electrical characterization of the mini-modules was performed at standard test conditions (STC: AM1.5G, 25°C, 1000 W/m²) by means of current–voltage (IV) characteristics using a LED-halogen based sun simulator. The electroluminescence images (EL) are also obtained before
and after testing. From these preliminary results, it is evident the effect of the different encapsulant on the mechanical performance of the PV structure.

4 RESULTS AND DISCUSSION

4.1 Optical properties

Usually, encapsulant materials show a UV cut-off wavelength, between 300 and 400 nm, below which the transmittance is lower than 10% [10]. Figure 4 a) shows that polymers like EVA and the polyolefin TPO2 follow this typical behavior, whilst there is no significant change in the UV cut-off wavelength for both TPO1 and POE. EVA, as POE, transmits ~90% light, effectively from ~350 nm to ~1100 nm, while the TPO1 transmits ~90% from the UV region to the entire visible spectrum. Polyolefin TPO2 shows a slightly lower transmittance values (just below 90%). One of the two TPO shows ~90% of transmittance, almost along the entire UV-vis spectrum, whilst the other one presents the UV cut-off, perhaps due to UV absorbers added in the formulation. The highly transparency of the TPO1 and POE, makes these materials good candidates to be used in the frontsheet structure. The hazing effect of some encapsulants (e.g. P0s) results in the milky appearance, before and in some cases even after the lamination step. The milky appearance is then responsible for the reduced transmittance (and higher reflectance) due to the light-scattering effect [11]. Most of the laminated-encapsulants showed reflectance values lower than 10%, meaning that these materials can potentially provide antirefective properties, if properly tuned, bringing an extra value to the module structure. These encapsulants have been exposed to extended DH conditions (3000 hours) and the optical properties have been monitored. As known from literature, EVA degrades under long exposure to UV radiation and high temperature, and induce yellow color that converts to dark brown as degradation progresses over time [12]. Discoloration is generally visible from naked eyes and Figure 5 shows, the change in colors occurred for some of the materials investigated for this work.

4.2 Thermal properties

Photothermal degradation results in a dark EVA browning ultraviolet (UV) exposure. Indeed, thermal degradation as critical as the one due to photothermal effects, i.e., ultraviolet (UV) exposure. Indeed, thermal degradation usually results in a light EVA yellowing, whereas photothermal degradation results in a dark EVA browning.

The aforementioned changes in the color of the encapsulant material produce a variation of the transmittance of the light reaching the solar cells and, as a consequence, a reduction of the power generated [9]. This is an important aspect that needs to be considered during the choice of materials for the final LW structure. The degradation related to thermal effects does not seem to be as critical as the one due to photothermal effects, i.e., ultraviolet (UV) exposure. Indeed, thermal degradation usually results in a light EVA yellowing, whereas photothermal degradation results in a dark EVA browning. 

Figure 6 shows the clear trend of Y1 for the different encapsulants; as for the visual inspection the change in colour was observed for the EVA and POE polymers, which turned into different grades of yellow. A milky, hazed appearance was observed for the TPO2, as shown in Figure 5. The photos have been taken before and after 3000 hours of DH exposure.
Figure 6: YI trend of EVA, TPO1, TPO2 and POE versus DH exposure.

4.2 Thermal properties
Thermal properties of TPOs, POE and commercial EVA (before and after lamination) will be here discussed. Figure 7 shows DSC curves for the commercial EVA and one of the TPOs. Figure 7 a) shows 2 cycles of DSC of EVA before lamination. As expected, EVA is a crosslinking reaction based encapsulant and its crosslinking reaction occurs in the range 135-180°C. After the first cycle of DSC, EVA is clearly fully cross-linked (no peak observed in that region). After the lamination process, the polymer experiences the same trend (not presented here). Figure 7 b) shows the DSC profiles of TPO2 before and after lamination. There are no significant changes observed for the polyolefin, before and after lamination. The crosslinking reaction region is not present in this case, confirming the thermoplastic nature of the encapsulant. Tc and Tm positions remained almost unchanged after lamination. TPOs are cross-linked physically and their thermo-mechanical properties are mainly defined by the cooling conditions. The degree of crystallinity was calculated by using the DSC analysis; the thermoplastic polyolefins were the polymers with a more ordered structure, showing ~20/30% of crystallinity, while EVA and POE ~11% and ~10%, respectively.

In the following table the crosslinking reaction region, melting temperature range and crystallinity degree are listed for each investigated encapsulant.

Table I: cross-linking region, melting temperature and crystallinity for each encapsulant investigated.

<table>
<thead>
<tr>
<th>Encapsulant</th>
<th>Cross-linking region (°C)</th>
<th>Melting temperature, Tm (°C)</th>
<th>Degree of Crystallinity, Xc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA</td>
<td>135-180</td>
<td>50-80</td>
<td>-10</td>
</tr>
<tr>
<td>TPO1</td>
<td>-</td>
<td>-115</td>
<td>-20</td>
</tr>
<tr>
<td>TPO2</td>
<td>-</td>
<td>-120</td>
<td>-30</td>
</tr>
<tr>
<td>POE</td>
<td>145-160</td>
<td>40-80</td>
<td>-11</td>
</tr>
</tbody>
</table>

4.3 Mechanical Properties
Thermo-visco-elastic properties of the encapsulant [11] also have an important role on the final composite stucture of the LW modules.

Thermal expansions, peeling, adhesion properties of the materials used in a module (solar cells, interconnects, skin–backsheets) need to be investigated to avoid over-stress, cracks in the structure [9]. Measurements of the Young modulus, E, showed that ~0.14 GPa was found for the TPO1, while lower values, in the order of 0.012-0.004 GPa were measured for the other encapsulants (POs and EVA), at room temperature. TPO1 and TPO2 showed good resistance to high temperatures, with their high storage modulus, G’. The rigidity offered by TPO1 and the elasticity of the other POs, could represent the optimal combination of mechanical properties to provide, the LW stack, appropriate resistance to loads.

In addition, the volume resistivity of the pristine materials was measured (EVA, 1.5*10^14 Ω*cm, TPO2, 1.5*10^15 Ω*cm and TPO1, 7.2*10^17 Ω*cm).

Table III summarizes the optical, mechanical and electrical properties of the encapsulants used for this work.
Table II: Optical, mechanical and electrical properties measured for each encapsulant before aging testing.

<table>
<thead>
<tr>
<th>Transmittance</th>
<th>Young modulus, $E$ (GPa)</th>
<th>Volume resistivity ($\Omega$cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 550nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td>$&gt;90$</td>
<td>0.015</td>
</tr>
<tr>
<td>TPO1</td>
<td>$&gt;90$</td>
<td>0.14</td>
</tr>
<tr>
<td>TPO2</td>
<td>$&lt;90$</td>
<td>0.012</td>
</tr>
<tr>
<td>POE</td>
<td>$&gt;90$</td>
<td>0.004</td>
</tr>
</tbody>
</table>

According to these results, observing the changes of the optical, morphological properties with physical age of the materials, the preferential candidates to be used as frontsheet in LW PV structures seemed to be the TPO1 and POEs encapsulants. However, an important aspect needs to be considered: the characterization analyses discussed so far were focused only on each encapsulant, considered by itself. This study wants to investigate whether these properties could be maintained, also once the pottans are incorporated in the PV stack. Prior to manufacturing the LW PV-stack, the adhesion test between TPO1 and POE was performed, to assess the adhesive strength between each encapsulant. Values $>40$ N/cm showed optimal adhesion between TPO1 and POE. Also, similar adhesion values were measured between the encapsulants and the other components of the LW PV stack (skins, ETFE).

4.4 Mini-modules tests

4.4.1 Electrical performances vs different frontsheet configurations

The hail test was chosen as the ‘pass/fail’ control-test to identify the encapsulant to be used as frontsheet in lightweight PV modules. A preliminary selection of the potential pottant was performed after a deep characterization presented in the previous paragraphs. The hail test was useful to cross check/understand whether the intrinsic properties of the material were still valid, once incorporated in the LW PV module stack. The initial screening of materials brought the attention towards the use of TPO1 and POE, since EVA, even from previous studies [2] failed the hail test. Focusing on these other pottants, several configurations have been tested and the electrical performances of the mini-modules have been investigated. Figure 8 shows the Pmax losses against the frontsheet configurations and next to each point investigated.

Table III shows different frontsheet configurations (FSx) investigated with the respective thicknesses and numbers of layers used. (S.C. stands for solar cells).

Figure 8: Schematic diagram showing Pmax losses versus the FS configurations.

This preliminary test was useful to understand the importance of placing the TPO1 layer underneath the solar cell and a combination of POEs (in particular POE*) and TPO on top of the stack. This layers-composition guaranteed quasi-zero Pmax loss, due to the mechanical and thermal properties of the TPO1 and the POE, which gave strong support to the PV structure, as reported in Figure 8.

Figure 9 shows in detail, the electrical performances of the 1-cell mini module *configuration H, from the Table III, before and after Hail Test. Also, the EL images are shown to confirm the resilience of the structure.

Table III: Frontsheet (FS) configurations investigated with thicknesses and numbers of layers of encapsulants.

<table>
<thead>
<tr>
<th>FS configurations, FSx</th>
<th>Ref A</th>
<th>B</th>
<th>C</th>
<th>F</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPO1 (-100µm)</td>
<td>TPO1 (-100µm)</td>
<td>TPO1 (-100µm)</td>
<td>TPO1 (-100µm)</td>
<td>TPO1 (-100µm)</td>
<td></td>
</tr>
<tr>
<td>(1layer/1layer)</td>
<td>(5layers)</td>
<td>(2layers/1layer)</td>
<td>(2layers/1layer)</td>
<td>(2layers/1layer)</td>
<td></td>
</tr>
<tr>
<td>POE</td>
<td>POE</td>
<td>TPO1</td>
<td>TPO1</td>
<td>TPO1</td>
<td></td>
</tr>
<tr>
<td>(4layers)</td>
<td>(1layer)</td>
<td>(4layers)</td>
<td>(4layers)</td>
<td>(4layers)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9: IV curves and electrical parameters of the 1-cell mini module (FS configuration H), before and after exposure to the Hail Test.

As a comparison, Figure 10 shows the electrical performances of 1-cell mini module (configuration C).
The Power max loss was higher than 5% and the EL images showed the cell damaged after the hail impact, even though by visual inspection no defects were detectable.

![Initial and After HT](image)

**Figure 10:** IV curves and electrical parameters of the 1-cell mini module (FS configuration C), before and after exposure to the Hail Test.

Further investigation is currently carrying out, performing bending tests, mechanical load tests to understand the mechanical properties required for the LW composite structure. A secondary, not less important, goal to achieve with this study, was the optimization of the PV stack LW modules, by minimizing the material costs, while maintaining high performances (electrical, mechanical). Reducing the amount of TPO1 layers and investigating instead the combination of TPO and POE gave the opportunity to realise a stable, robust, efficient, structure. DH, UV, mechanical load tests (EUPVSEC2020_4AV.2.14) are currently in progress and preliminary results are supporting the use of the combined TPO1-POE layers as the optimum configuration for the frontsheet LW PV modules.

5 CONCLUSIONS

An optical, electrical, mechanical, morphological characterization of different type of encapsulants was performed to preliminary select potiants suitable as part of the frontsheet-stack of LW glass-free PV-modules. High transmittance values in the visible range are obviously the main requirements. However, intrinsic mechanical properties of the polymers seem to play a key role to provide the mechanical stability to the whole PV stack to withstand wind load and hail impacts. As the hail test showed, the optimal configuration for the frontsheet of LW glass-free PV modules seems to be a combination of TPO and POEs encapsulants, placed on top of the solar cell (as in Figure 8). A local dissipation of energy after the hail impact occurs below the impact point, protecting the solar cells from mechanical damage. We also understood the importance of using a quite stiff, robust polymer (TPO1), as a support, directly underneath the solar cell, to minimize the local deformation of the stack, after the hail impact.

The different viscoelastic properties of the thermoplastic and elastomeric POs, combined together, provide the optimal mechanical integrity/stability/resilience to the designed PV stack. This configuration helped not only to mitigate the hail impact effect, but also to withstand other accelerated stress conditions (such as DH exposure, UV), due to the optical, thermal properties of the selected encapsulants. Further work is currently on progress.

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5.1 References


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