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Thermo-mechanical stability of lightweight glass-free photovoltaic modules based on a composite substrate

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ABSTRACT

Lightweight PV modules are attractive for building-integrated photovoltaic (BIPV) applications, especially for renovated buildings, where the additional load bearing capacity is limited. This work focuses on the development of a lightweight, glass-free photovoltaic (PV) module (6 kg/m^2) composed of a composite sandwich backstructure and a polymeric front layer. Sandwich structures are usually manufactured with a vacuum bag process and thermosetting liquid glues (e.g. epoxy resin). However, due to the long manufacturing process (> 24 h), liquid adhesives are not compatible with conventional solar industry processes. This work presents the development of a robust glass-free PV module based on a composite sandwich architecture manufactured with a simple process. To simplify the production, the standard thermoset epoxy is substituted by different PV encapsulant foils (EVA, ionomer, polyolefin). The results show that a particular formulation of polyolefin is the ideal adhesive to produce a stable backsheet structure. The use of this polymer with a high thermal conductive core (aluminum honeycomb) allows a reduction of processing time from 24 h to 30 min. The mechanical properties of the composite sandwich structure showed an excellent stability under thermal cycling and damp-heat with only 1% and 3% loss in bending stiffness, respectively. Two-cell lightweight PV modules manufactured with this backsheet show good electrical performance after thermal cycling and damp-heat tests, for which, respectively, an output power loss of only 3% and 2% is observed. This configuration is up scaled to a sixteen-cell module for which a power loss of only 3% is measured after damp-heat.

1. Introduction

Building integrated photovoltaic (BIPV) has been confined to a niche market for many years. However, the demand for BIPV (a photovoltaic element fully integrated in the building skin installed as a replacement of another building component) is expected to strongly increase in the coming years. The main drivers favoring BIPV are (i) the adoption in several countries, as in Europe, of new energy efficiency codes [1], (ii) the high demand for renewable energy and (iii) the "green building" movement in the construction sector [2]. Estimations predict that the annual global growth rate of installed BIPV capacity will be around 12.2% for 2016–2021, reaching an annual installed capacity of about 11 GW in 2020 [3–5]. The existing energy-efficiency codes, such as the Energy Performance of Buildings Directive in Europe [1], requires that all the new constructions become nearly zero-energy buildings by the end of 2020, meaning that all energy consumed by the building must be produced on-site by renewable sources. Unfortunately, the high weight of conventional photovoltaic (PV) modules ranging from 12 to 16 kg/m^2 for glass-backsheet modules to 16 to 20 kg/m^2 for glass-glass modules is still a limiting factor [6] when considering PV integration in a roof or façade, especially for old buildings for which this extra load was not taken into account during the building design phase.

In a previous work [7], it was demonstrated the possibility to produce a lightweight PV module with a weight of 5 kg/m^2, by substituting the typical front glass with a thin polymer sheet and the standard backsheet by a composite sandwich structure. These composite structures are usually composed of two skins bonded to a core, using a stiff adhesive [8]. Such a lightweight PV module is sketched in Fig. 1. This work [7] showed that using appropriate PV lamination guidelines, the use of ionomer as a sandwich adhesive allows the module to reach a high bending stiffness. The produced modules successfully resist the

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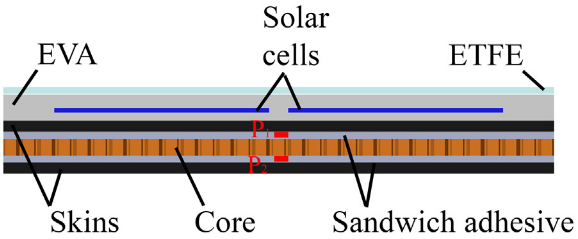

Fig. 1. Sketch of the glass-free lightweight PV module developed for BIPV applications with the description of all layers. PT1000 sensors are introduced during lamination to access temperature at P_1 (sandwich adhesive close to the heating plate) and P_2 (sandwich adhesive far from the heating plate) (picture from [7]).

aging tests with less than 5% power loss as required by IEC 61215 [9]. However, the mechanical stability of the sandwich after aging and at the module operating temperatures was not investigated.

The operating temperature (OT), depends on ambient temperature, wind speed, incident sunlight, solar cell technology, packaging and also on the mounting configuration [10–13]. Usually, BIPV modules are fully integrated into the building envelope with no ventilation from the rear side and can reach operating temperatures as high as 86 °C for a sunny summer-day, as reported by the authors [14] for a location in Northern Italy (see Table 1). Moreover, according to the guideline ETAG 002 [15], 80 °C can be considered as a temperature limit for practical purposes in civil engineering.

In the present work, we investigate the impact of humidity, temperature and temperature cycling on the mechanical behavior of our lightweight composite-based PV modules. Based on these results, the optimal properties for the sandwich adhesives are identified in order to enhance the module thermo-mechanical stability and to further shorten its processing.

2. Experimental procedure

2.1. Module design

Our glass-free lightweight PV modules are composed of two main components: (i) the composite backsheet (skins / sandwich adhesive / core) and (ii) the frontsheet (encapsulant foil / solar cells / polymeric frontsheet). The optimization of the composite backsheet, a key element in providing the adequate mechanical stability to the full module, is the main subject of this study.

The skins of the composite sandwich are fabricated using unidirectional (UD) E-glass fiber of 220 g/m^2 in a $[0/90]_s$ configuration and an epoxy L/hardener EPH 161 in a wet lay-up processing, yielding a skin final thickness of 0.7–0.8 mm with a fiber mass ratio of 0.65. Three different sandwich adhesives are studied and compared to the reference condition processed in vacuum bag with an epoxy adhesive (epoxy L / hardener EPH 161): (i) ethylene vinyl acetate (EVA, S88 Bridgestone), (ii) ionomer (SentryGlas, Kuraray Europe GmbH) and (iii) a polyolefin (PO) developed internally. Two sandwich cores are studied: one aramid honeycomb (Nomex paper® Coremaster C2, Schutz Composite) and an aluminum honeycomb (ECM 4.8-77 3003, Euro-Composites® S.A.).

Table 1
Maximum operating temperatures for a glass-backsheet module on a sunny, cloudless day located in northern Italy (Ispra) in three different configurations: (i) open rack fixation, (ii) building applied PV (BAPV) and (iii) building integrated PV (BIPV) without air circulation (as reported by Ref. [14]).

Mounting configuration	OT on a sunny, cloudless day (°C)
Open-rack	64
BAPV	72
BIPV	86

Table 2
Summary of materials and processing conditions used for the production of lightweight PV modules. *s* and *d* stand for one and two-step lamination processes, respectively.

	Materials		Processing Conditions	
	Honeycomb Core	*Adhesive*	*Vacuum bag*	*Lamination*
Reference	Aramid	Epoxy	24 h	–
Condition 1		EVA	–	*d* 11′ + 11′
Condition 2		Ionomer	–	*d* 11′ + 11′
Condition 3		PO	–	*d* 26′ + 26′
Condition 4	Aluminum	PO	–	*s* 26’

The modules frontsheet is composed of conventional crystalline silicon solar cells (Al-BSF c-Si from Bosch) with three busbars encapsulated in EVA and covered by an ethylene tetrafluoro-ethylene layer (ETFE 100 µm, Saint-Gobain).

2.2. Module manufacturing process

The lightweight PV module manufacturing process depends on the respective choices of sandwich adhesive and core. A detailed explanation of all manufacturing methods considered is presented in Appendix A1. Table 2 summarizes the manufacturing processes and corresponding processing time for each configuration.

2.3. Characterization methods

2.3.1. Adhesive layer characterization

The characterization of the sandwich adhesive layer is performed using differential scanning calorimeter analysis (DSC) and dynamic moving-die rheometer (D-MDR). DSC allows to derive the glass transition temperature, T_g and melting temperature, T_m [16,17]. The measurement is performed on a Mettler Toledo DSC1 system operating in a single run mode. Adhesive discs of about 5–10 mg are inserted into a standard crucible which is closed with a manually perforated lid. The thermograms are recorded under constant nitrogen flow from −20 to 225 °C at a rate of 10 °C/min, held at 225 °C for 1 min and then cooled down to −20 °C at a cooling rate of 10 °C/min [18,19]. The rheology measurements are performed using a MDR 3000 Professional, by Montech Werkstoff-prüfmaschinen GmbH and a cone-cone geometry: the lower plate is stationary, while the upper plate oscillates at a small angle (typically 0.5°) and at a frequency of 1 Hz. During this measurement, the torque and the phase shift oscillation are continuously recorded. From this data, the shear storage modulus G' [Pa] and the dynamic viscosity η' [Pa s] are obtained [20]. The rheology measurements are performed from 30 °C up to 170 °C.

2.3.2. Sandwich mechanical characterization

The bending stiffness, D [N·m^2] and the yield load, P_y [N] of the composite sandwich structures are characterized using four-point bending tests (see Appendix A2). Samples are manufactured according to Table 2. Tests are performed at room temperature using a Walter + Bai AG EC80-MS mechanical testing instrument in displacement control at a rate of 20 µm/s. The bending stiffness and yield load of composite sandwich structures aged in thermal cycling (TC, 200 cycles from −40 °C to 85 °C) and damp-heat (DH, 1000 h, 85 °C, 85%RH) have been quantified as well (specimens are measured 24 h after removal from the aging test). Four-point bending tests are also performed at 80 °C using a climatic chamber directly on the tensile testing equipment with a temperature resolution of ± 0.1 °C. The goal of this test is to access the bending stiffness at a real operating temperature that a BIPV modules might reach. Tests are performed using a 50 kN load cell. Specimens are kept at constant test temperature for at least 30 min before the test starts.