

THE RIGHT WAY TO CHARACTERIZE ADHESION OF POLYMERS IN PV MODULES

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ABSTRACT: It is widely accepted that adherence (which reports to what is measured when performing an adhesion test) of the encapsulant to the main substrates of the module plays a key role in the long term reliability of the PV module [1,2]. Consequently, adherence is commonly measured and used to assess or compare encapsulant compatibility with a given substrate. The most common procedures used in the PV field to characterize adhesion between a polymer film and a substrate are the so called peeling test, lap shear and compressive shear tests.

Here we use a compressive shear setup to characterize the adherence of Poly Vinyl Butyral (PVB) and Polyethylene-co-vinyl acetate (EVA) to glass before and after degradation in damp-heat (DH) conditions (85°C, 85%RH). The adherence metrics that can be derived from a Compressive Shear Test (CST) are presented and discussed. We show that a single metric is not sufficient to characterize adherence and that a set of at least two indicators including the peak shear stress and the viscous dissipation should be used. Using this set it is found that the interface PVB/Glass is more affected by the degradation than the EVA/Glass interface.

1 INTRODUCTION

Adherence tests usually consist of recording the force acting on the sample as a function of the applied displacement. From this data several indicators can be calculated that are intended to describe the adhesion between the polymer layer and the substrate. The most common ones are the mean force at which the delamination stably propagates divided by the sample width [N/m] for peel tests [3] and the peak force at joint failure divided by the sample surface expressed in [N/mm²] or [MPa] for lap shear [4] and compressive shear tests [5]. However the values provided by the experiments need to be taken carefully when describing an interfacial adhesion. Indeed, the joint response curves (force versus displacement) do not only contain information about the interface itself but on the whole joint system (encapsulant, substrates and interfaces). Thus the derived indicators cannot be dedicated to the description of an interfacial adhesion but rather to an apparent joint strength which is called adherence.

Here, we present adherence results for PVB and EVA on glass obtained with a compressive shear test procedure (fig.1). The main advantage of this procedure as compared to the other adherence tests is that the encapsulant layer is always subjected to pure shear strain and that no direct peel stresses are induced due to substrate bending (lap-shear) or direct encapsulant bending (peeling). This test procedure gives then a better reproducibility and makes the comparison of different encapsulation systems easier, when trying to assess the correct value of the interfacial energy.

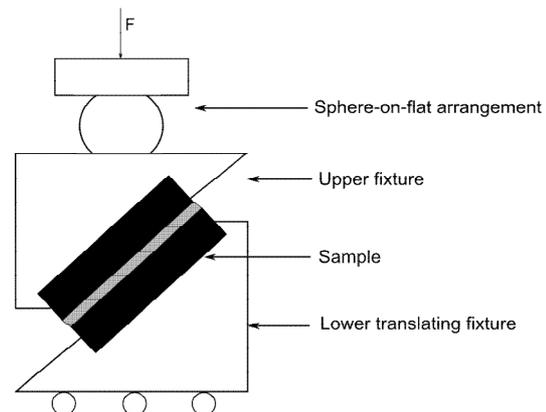


Figure 1 : Compressive shear test (CST) setup.

2 MOISTURE INGRESS AND DAMP-HEAT DEGRADATION

Moisture ingress in a square compressive shear sample (25x25mm) can be described solving Fick's second equation (1).

$$\frac{\partial c(\vec{x}, t)}{\partial t} = \nabla \cdot (D \nabla c(\vec{x}, t)) \quad (1)$$

As our CST samples are too small to be considered as an infinite media (i.e. the characteristic length of diffusion is not much smaller than the sample's size), the standard solution of the 2nd Fick law (1) expressed using the error function cannot be used. However, a Taylor series solution (2) as proposed by Crank [6] can be used, assuming a constant diffusion coefficient, a 2D diffusion (in the plane of the encapsulant) and assuming that the water concentration at the edge of the module is constant.

$$c_{x,t} = c_{sat} - \frac{16c_{sat}}{\pi^2} \cdot \sum_{i=0}^n \left(\frac{1}{2i+1} \cdot \text{Exp} \left[\frac{-D_{H2O} \cdot (2i+1)^2 \cdot \pi^2 \cdot t}{L_x^2} \right] \cdot \sin \left[\frac{(2i+1)\pi \cdot x}{L_x} \right] \right) - \sum_{i=0}^n \left(\frac{1}{2i+1} \cdot \text{Exp} \left[\frac{-D_{H2O} \cdot (2i+1)^2 \cdot \pi^2 \cdot t}{L_y^2} \right] \cdot \sin \left[\frac{(2i+1)\pi \cdot y}{L_y} \right] \right) \quad (2)$$

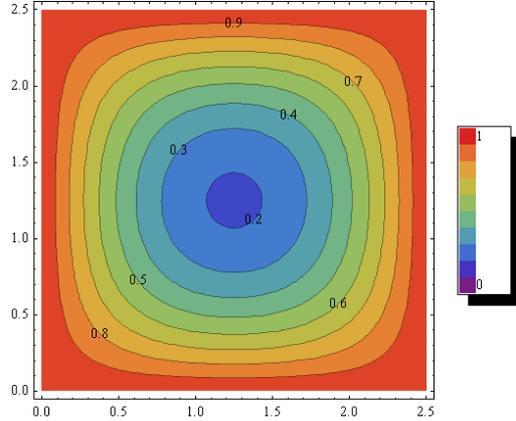


Figure 2 : Moisture ingress in a CST sample of 2.5x2.5cm expressed as the ratio between the water concentration and the water solubility in the encapsulant

Equation (2) is used to calculate the time needed for a standard EVA to reach 95% of its saturation concentration at the sample's center. The degradation time in damp-heat condition is then taken as the time needed to saturate an EVA sample plus an additional 30h which leads to a total duration of 70h.

3 ADHERENCE METRICS [7]

Several indicators can be derived from a CST response curve (force versus displacement). The most common one is the peak force density F_{max}/S calculated as the force recorded at failure normalized by the sample surface and expressed in [MPa]. It represents the maximum load level density that the encapsulation system can sustain before failing.

A more accurate metric would be the peak shear stress τ_{max} calculated as the shear force (applied force multiplied by the cosine of the angle of loading, in our case 45°) normalized by the delaminated area and expressed in [MPa] as well. The advantages of this metric as compared to the standard peak force density are twofold. First the peak shear stress only takes into account the shear force useful for the delamination. Second the normalization surface is taken as the real delaminated area allowing a more accurate description of the tests where partial delamination takes place.

In order to complete the sample behavior description, two others metrics can be used.

First, the equivalent shear strain at failure γ_{max} is calculated from the machine arm displacement under the assumption of homogeneous shear deformation using equation (3) where θ is the CST angle of loading, h_0 the initial encapsulant thickness and u_{max} the displacement at failure. It represents the maximum deformation the encapsulation systems can sustain before failing.

$$\gamma_{max} = \frac{2\cos(\theta)}{h_0} \cdot u_{max} \quad (3)$$

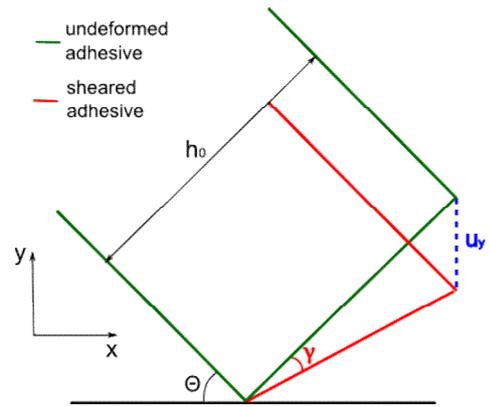


Figure 3 : Relation between the displacement u_y , the shear strain γ , the initial encapsulant thickness h_0 and the loading angle θ

Second, the viscous dissipation E^{el} is calculated as the integral of the shear stress τ versus equivalent shear strain γ curves. It is expressed in [mJ/mm³] and represents the energy density absorbed in the encapsulant deformation before failure.

4 RESULTS

Compressive shear tests were performed on 25x25mm samples including an encapsulant layer (PVB or EVA) laminated between two pieces of solar-grade glass. CST samples are obtained by diamond sawing from larger laminates. Half of the samples were aged in damp-heat conditions (85°C, 85%RH) for 70h. For every test condition 5 samples were tested with a good reproducibility (fig.4). The tests are performed at a constant shear rate of 0.2 [s-1].

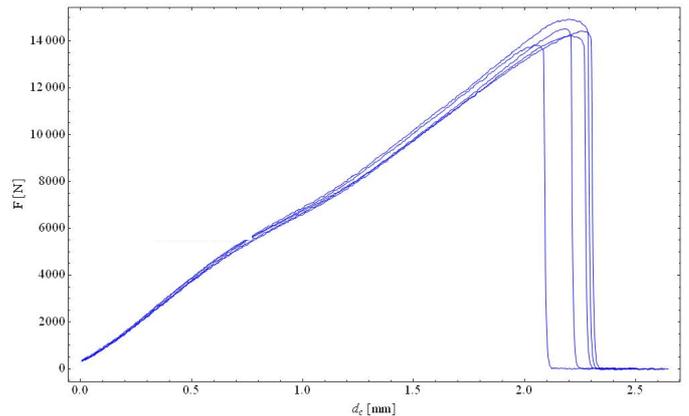


Figure 4 : Reproducibility of CST performed on Glass/PVB/Glass samples

Figure 5 presents typical CST response curves for PVB and EVA samples before (as laminated) and after DH degradation. The CST response curve before degradation for PVB is higher than for EVA for all the adherence indicators (see table 1). However, the evolution of those indicators through DH degradation is not the same for the two encapsulants.

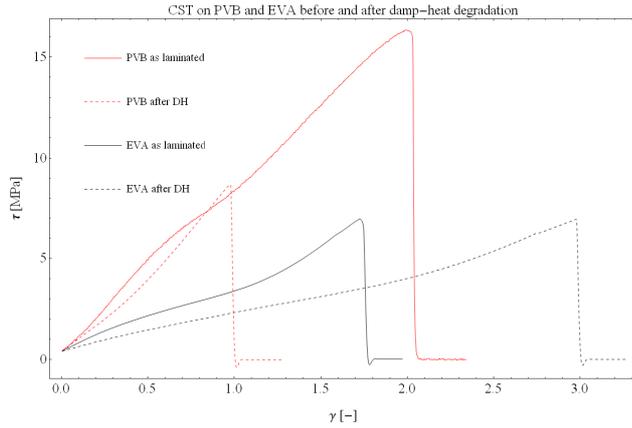


Figure 5 : CST response curves for PVB and EVA samples, before and after damp-heat.

While the peak shear stress is lowered by nearly a factor of two for the PVB (going from 16.2 to 7.9 [MPa]) it stays roughly constant at ~ 7 [MPa] for EVA. At the same time, the viscous dissipation is increased in the EVA case by a factor of two while it experiences a serious decrease by a factor of nearly 5.5 in the case of the PVB. The same trend is observed for the equivalent shear strain at failure which decreases for the PVB while it increases for the EVA.

It is clearly seen from fig.5 that the bulk response (shape of the curve before failure) of EVA is more affected by the degradation than for the PVB, indicating structural changes in the encapsulant. This results in a softer CST response for EVA after degradation characterized by an increase in the viscous dissipation. At the same time, as the peak shear stress stays constant, we may assume that the interface itself does not degrade too much and breaks once a critical stress level of ~ 7 [MPa] is reached. On the other hand, the bulk response of PVB is not as affected as the one of EVA while the peak shear stress is lowered. Therefore, it can be assumed that no extensive degradation of the PVB occurs in DH conditions while the interface glass/PVB is affected, failing then at a lower stress level.

These results clearly show that using only one metric to describe the adherence of an encapsulant on a glass substrate is inappropriate and doesn't allow a reliable comparison between different encapsulation schemes or between degraded and non-degraded conditions. It is proposed that a set of at least two metrics should be used to describe the adherence. First one is the viscous dissipation that represents the stored energy in the encapsulant deformation. Second one can be either the peak shear stress or the equivalent shear strain depending if the sample failure is seen to be force, respectively displacement, controlled.

Table 1 : Adherence metrics for PVB and EVA on glass

Condition	τ_{\max} [MPa]	γ_{\max} [-]	E^{el} [mJ/mm ³]
PVB before DH	16.2 ± 0.8	2.2 ± 0.1	18.7 ± 1.7
PVB after DH	7.9 ± 0.3	1 ± 0.02	3.56 ± 0.3
EVA before DH	7.1 ± 0.4	1.7 ± 0.1	5.5 ± 0.4
EVA after DH	6.3 ± 0.6	2.8 ± 0.15	9.4 ± 0.6

5 CONCLUSIONS

The Compressive Shear Test (CST) is a powerful and reliable tool to determine adherence of PV encapsulants on rigid substrates. Here we showed how CST can be applied to describe the adherence of standard encapsulation systems with an example of the effect of damp-heat on its degradation. The different metrics that can be used to describe the adherence were presented and discussed. It was shown that a single metric is not sufficient to characterize adherence and that a set of at least two indicators including the peak shear stress and the viscous dissipation should be used. Using this set of two metrics, it is shown that the interface PVB/Glass is more affected by the degradation than the EVA/Glass interface. However, as the initial adherence of PVB on glass is better than for EVA, this adherence drop is not seen to be critical.

6 ACKNOWLEDGEMENTS

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