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# Adhesion Testing for Photovoltaic Laminates

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## Abstract

An adhesion test allowing for the realistic assessment of adhesion needs for PV modules has been developed. The difference is that the test is conducted in-situ during ageing experiments. Weights were attached to the backsheet of tested PV mini-modules in order to test stability of lamination and adhesion. All samples were tested at standard test conditions of module temperature of 85°C and 85% relative humidity. It is shown that appropriately laminated samples were able to withstand the force of 20g/cm for 1000 hours.

## Introduction

The reliability and durability of PV modules is key for the financial success of PV systems. PV modules rely on packaging materials to provide them reliability and durability to maintain long and useful energy generation under different operating environments. Typical module packaging materials include a front glass layer, two layers of EVA, and a layer of backsheet, which are laminated and framed to form a PV module. In order to estimate the PV module's lifetime, modules are subjected to various stress tests and test to fail. Different degradation mechanisms can be identified that may lead to premature or wear out failures of PV modules. This paper investigates the delamination issue of packaging material, which is one of the observed failure modes of fielded PV modules.

Delamination may cause faster moisture ingress into module, subsequent corrosion of solar cell, cell fingers, busbars and interconnects, leading to power losses. Delamination is also a major safety risk. However, up to now, there is no definition of how to test adhesion and how much adhesion is required for modules in any of the international standards. In the PV community, the peel test is widely used to characterise interfacial adhesions between glass and EVA or EVA and backsheet. The peel test normally is carried out under room condition before and after ageing experiments.

The temperature of PV modules is normally influenced by ambient temperature, irradiance, and wind-speed. At different sites with different climatic conditions, module temperature can easily reach 65 – 85°C. This can be verified using empirical models, e.g. [1] for rack-mounted modules in the field. Higher temperatures are expected for roof-mounted modules. Furthermore, under certain circumstance, the moisture absorbed by modules and the mechanical loading applied on backsheet, e.g. the weight of junction box and not well wired cable, may be presented at elevated temperature, too.

In order to test the robustness of module packaging and investigate the potential delamination due to the multiple stresses, a gravity test is implemented by attaching a weight to the module's backsheet during the damp-heat test. The module is mounted at 45 degree angle which changes the weight of e.g. a junction box from a shear force to a peel force. The time to delamination is recorded, i.e. time to failure. This gives a better assessment of the realistic adhesion requirements to test the adhesions between different layers of material under module operation condition, which in this work is 85°C and 85% relative humidity (RH). The elevated stress level may not be seen by modules during operation, but it is the common stress level applied. The weight attached to the module backsheet ranges from 20g/cm to 1kg/cm in order to identify the response to a range of conditions. The stress levels would represent something like 'normal' junction box weight to potentially some item being caught on connecting wires. Mini-modules laminated with different curing temperatures between 125°C and 150°C were used for the gravity test to obtain a range of adhesion. The curing temperature has a direct impact on crosslinking of EVA and thus the structure of EVA. The adhesion itself is normally carried out by thermally activated adhesion promoters. While the state of this is not measured directly, the gel content is still a secondary indicator as both depend strongly on the thermal history of the

lamination. Consequently, observed failures were both interfacial and cohesive.

### Experimental Setup

The samples used in this test are mini-modules that were laminated at CREST. Their size is 12.5cm by 20cm with a glass-EVA-solar cell-EVA-backsheet structure. No frames or sealants are used. All the materials are commercially available from PV industry. The glass front layer is 3.9mm thick float glass. Standard 460 $\mu$ m fast cure EVA is used as encapsulant. The backsheet is a tri-layer insulating polymer consisting PET/PET/primer layer. The solar cells used are 1.8W multi c-Si cells. These mini-modules were prepared under different lamination temperatures at 125°C, 135°C, 140°C, 145°C and 150°C with constant curing time of 10 minutes. These samples are referred to in the following as L125, L135, L140, L145 and L150, respectively. The backsheet of each mini-module was prepared 5cm longer than the module's length to enable easy attachment of a weight. The actual weight was connected at the top part of the backsheet (see Figure 1), which applied a mixture of peel and shear force by its gravity. Different weights of 250g, 500g and 1kg were used. For some samples, the top part of backsheet was cut into narrow strips of 1cm or 2cm wide for testing (see Figure 2). This initial cut significantly increased the force per unit width, which was expected to lead to different failures. All the samples were mounted on a testing frame as show in Figure 3 and this setup was then placed in an environmental chamber operating at 85°C/85%RH. All samples were subjected to test to fail, i.e. tested until delamination occurred. The time when the delamination occurred was recorded for each sample and used as an indicator of the quality of module packaging.

The results were compared to conventional peel tests performed at room condition, where the curing temperature has a significant impact on interfacial adhesion [3]. This test is to investigate the adhesion failures at the weakest interface of packaging materials under stressed condition. The melting point of EVA is around 60°C, which means the EVA may be in different phases under room condition and 85°C, increasing the likelihood of cohesive failure. This also affects adhesion between different layers of backsheet as well.



Figure 1: Samples with weight hung from the top part of backsheet.

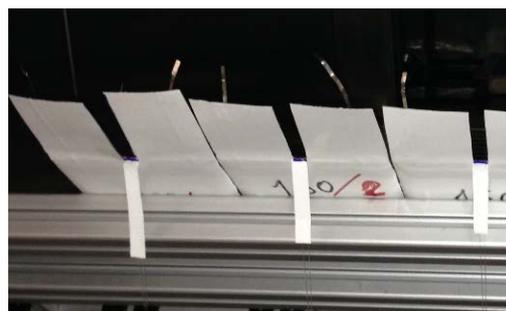


Figure 2: Samples with narrow strips for gravity test.

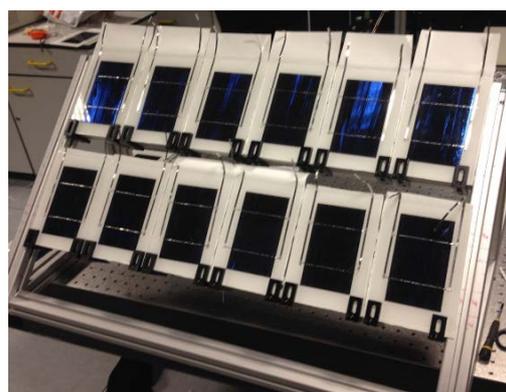


Figure 3: Testing frame for gravity test

### Observed Failure Categories

The mini-modules were prepared under different lamination temperature, the initial EVA crosslinking state, adhesion at glass/EVA and EVA/backsheet interfaces were different. With the stress test at temperature of 85°C, EVA with lower curing rates continues curing. Thus, the weakest interface of the packaging material could change with time, which led to different failure modes. Depending on the weight applied to backsheet, different failure modes were observed.

Figure 4 shows the observed four different types of failures of module packaging during the gravity test. Type A failure is delamination of backsheet sub-layers. This was observed for samples with weight

hung from narrow strips only. Type B failure is delamination at the interface between glass and EVA. Type C failure is delamination at the interface between EVA and backsheet. Type D failure is a mix of Type A and Type B that delamination occurred at multiple layers including backsheet sub-layer and between EVA and glass.

All samples tested delaminated eventually. The observed delamination categories are summarised in Table I in dependence of the lamination temperature and weight per centimetre.

Table I: Summary of failure categories

	20 g/cm	40 g/cm	80 g/cm	500 g/cm	1000 g/cm
L125	C	C	C		C
L135	A	A	B	AB	AB
L140			B	A	A
L145	A	AB	B		A
L150	A	A	B	AB	AB

L125 samples suffered from Type C delamination for all weights, i.e. weights between 20g/cm and 1000g/cm. This is due to the low curing temperature leading to low mutual diffusion of EVA and the EVA compatible material in the inner side of backsheet. Most likely, the 10 minutes curing time could not achieve enough diffusion to provide adhesion strength between EVA and backsheet higher than that between glass and EVA. Therefore, the weakest interface was between EVA and backsheet. The early failure (within 2 hours) was due the elevated stress condition, which also caused creep deformation of EVA. Adhesion could not even cope with a low weight of 20g/cm. For L135 samples and higher, the EVA and EVA compatible material in the inner side of backsheet was well crosslinked and no Type C delamination was observed. The weakest interface shifted from EVA/backsheet interface to glass/EVA interface or backsheet sub-layers with the increasing lamination temperature.

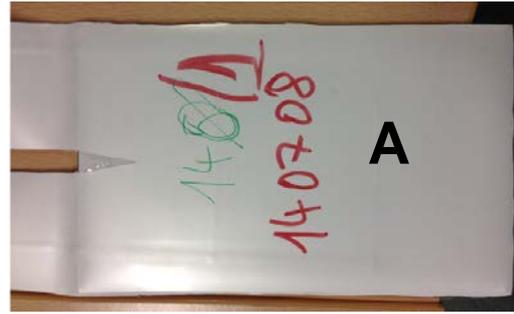


Figure 4: Different types of failures of module packaging during the gravity test.

Type B failure was seen by L135 to L150 samples tested with a weight of 80g/cm. Failure occurred rapidly (within 8 hours) with the extra weight. This indicates that, under these lamination conditions, the adhesion between glass and EVA was lower than that between EVA and backsheet. The backsheet inter-layer adhesions outstripped the adhesion at glass/EVA interface. The quick delamination did not allow enough time for further curing of EVA during the damp-heat test.

When applying a lighter weight of 20g/cm or 40g/cm, L135-L150 samples presented

Type A failure, i.e. at the backsheet sub-layer. The lower weights applied to the sample backsheet allowed a relative long period of time (up to ~1600 hours) before delamination happened. During this time, the samples which were not fully cured can continue curing. Thus, the adhesion between glass and EVA might surpass the adhesion between backsheet sub-layers, which shifted the delamination from Type B to Type A. Another factor might be that adhesion between backsheet sub-layers degraded faster than the adhesion at other interfaces. This is quite likely as the DH condition tests the effect of humidity ingress through the backsheet and the interfaces in the backsheet would see higher humidity levels.

The samples with a weight of 500g/cm or 1000g/cm as shown in Table I were the samples with narrow strips of backsheet for testing. They all experienced fast delamination within 2 hours, which means the adhesion could not cope with the weights. These forces are also not experienced for prolonged periods in the field, and thus this might be over testing the samples. However, the initial cut of backsheet led to different failures. The L135 and L150 samples presented a mix of Type A and Type B failures, which indicate that the adhesion at backsheet sub-layers and the adhesion at glass/EVA interface were comparable. The L140 and L145 samples, which are around the recommended optimum lamination temperature, saw Type A failure only. This suggests that the adhesion at the interface between glass and EVA was improved and better than that at backsheet sub-layers.

It was also found that all of the delaminated samples could cope with the weights applied to them and no obvious delamination was further observed when storing at room temperature.

### Delamination Time and Applied Weights

The observed delamination time for the L125-L150 samples is summarised against the applied weight in Table II. With the increasing weight, the delamination time decreases, as one could expect. The L140 and L145 samples withstand the applied forces for longer.

The weight of 20g/cm is similar to a junction box of PV module (around 200g,

10cm wide). The results presented would be the most relevant to normal field operation. Any additional loading may cause severe delamination relatively quickly but could also be seen as abnormal operation.

Table II: Summary of delamination time (hours)

	20 g/cm	40 g/cm	80 g/cm	500 g/cm	1000 g/cm
L125	2	2	2±1		1
L135	1000 ±100	175 ±25	4	2	2
L140			8±2	2	2
L145	1630 ±50	300 ±60	2		2
L150	800 ±50	25±5	3	2	2

### Conclusions

Gravity adhesion tests were performed at stress conditions at 85°C/85%RH. Delamination occurred at different interfaces and a correlation with lamination conditions could be found. To evaluate ability to withstand natural forces, it is suggested to use 20g/cm, i.e. in the presented test a force of 250g on a 12.5cm wide strip. Taking the conventional wisdom that 1000 hours exposure to damp heat condition causes changes within the packaging similar to 20 years operation in the field would indicate that appropriate adhesion for the package would be to withstand 20g/cm for 1000 hours, which is shown to be applicable for appropriately laminated samples.

### References

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