Effect of Encapsulation Modulus on the Response of PV Modules to Mechanical Stress

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ABSTRACT: The crystalline silicon photovoltaic (PV) module is a laminate assembly composed of materials with widely varying mechanical and thermal properties. The properties of these materials are important factors influencing the performance and reliability of modules following exposure to external mechanical stress. In particular, a key role of encapsulation is to protect the solar cells from external stresses, yet some encapsulant mechanical properties can vary with temperature. Since current mechanical loading tests for certification of PV modules are performed at room temperature, these tests may not adequately simulate or accelerate in-field mechanical stresses and failures. This work examines the impact on module performance and cell integrity of dynamic and static load testing at both high and low temperature using a custom-built mechanical testing rig capable of operating inside a climate chamber. Two different encapsulation materials were compared: a standard EVA thermosetting film and a silicone. The loading conditions were based on relevant qualification test standards and test modules were characterized for performance and damage using a solar simulator and electroluminescence imaging. Testing revealed significant differences in the ability of the encapsulant to protect the solar cells from damage due to mechanical loading at various temperatures, with the encapsulant modulus being a critical factor.

INTRODUCTION

In order to achieve optimum performance, the encapsulant material used in the production of photovoltaic modules must satisfy several different requirements, which include: high optical transmittance of incident light, good dielectric properties (electrically insulating), mechanical compliance to protect the solar cells from external mechanical loads and stresses induced by differences in thermal expansion coefficients, good adhesion to both glass and silicon solar cells, and sufficiently robust to withstand 20 – 30 years in the field. Since the 1980's, the encapsulant used in nearly all solar modules has been the copolymer ethylene vinyl acetate (EVA) [1-3]. EVA, as used in the solar industry, is a thermoplastic elastomer that is formulated with a curing agent, UV absorbers, as well as photo- and thermo-antioxidants. Although EVA encapsulation meets the overall stringent material property requirements at an attractive price, there a couple of areas for improvement. For example, the use of UV absorbers to prevent premature degradation of the EVA blocks part of the incident solar irradiation from reaching the solar cell and being converted into electricity. This results in a reduction of the short-circuit current of between 0.5% - 1.5% (relative) [4-6], reducing the efficiency of the module. Additionally, though the EVA is rubbery and compliant over a relatively wide temperature range, the modulus of the EVA increases by nearly two orders of magnitude over a span of fifty degrees between ambient and -25 °C. This stiffening of the material at sub-freezing temperatures could have implications for module stability and reliability in cold weather operation and under snow loads [7-8]. This study is concerned with exploring the behavior of test PV modules made with two different encapsulant materials, EVA and silicone, under load at various temperatures.

EXPERIMENTAL METHODS

In order to investigate the effects of mechanical loading on PV modules at different temperatures, a mechanical test stand was designed and built to fit inside a climate chamber. The test stand is comprised of an aluminum profile frame and uses an elastomeric bladder affixed to a rigid aluminum plate to transmit a load to the module under test (Figure 1). By lowering the bladder in contact with the test specimen and pressurizing it with compressed air, a uniform load in the range 2,400 Pa to 10,000 Pa could be applied to the module under test. The test rig was designed to accept test PV modules up to 550 mm x 550 mm in dimension in order to fit inside the climate chamber. Additionally, the test module could be mounted on one of several available mounting options, including a full frame or various point loads. Underneath the test module a displacement transducer (LVDT) is affixed to the structure to measure the deflection of the test module under load. The location of the displacement transducer can easily be positioned anywhere across the module, though it is typically mounted in the center to measure maximum displacement. Furthermore, the test stand can apply both static loads, as well as dynamic (cyclic) loads at a frequency of up to about 1 Hz.

A series of test PV modules were prepared using two different encapsulants: an industry standard EVA and a Dow Corning silicone. The test modules were comprised of two 3-cell strings using 156 mm multi-crystalline solar cells, a PET backsheet, and with front side glass dimensions of 550 mm x 405 mm and 3.2 mm thickness. In addition, two sets of test modules were prepared with cells of different thicknesses, 160 μm and 200 μm. The test modules were laminated using the encapsulant manufacturer's recommended procedures and full I-V characteristics were measured using a Pasan SunSim 3b flash solar simulator according to IEC 60904-9. Electroluminescence images were also obtained using a Xenics XEVA-1151 InGaAs camera. Test modules were subsequently subjected to a number of different static and dynamic loading profiles at various temperatures, as summarized in Table 1. The modules were again characterized after each loading test to identify changes in performance and to look for crack formation.

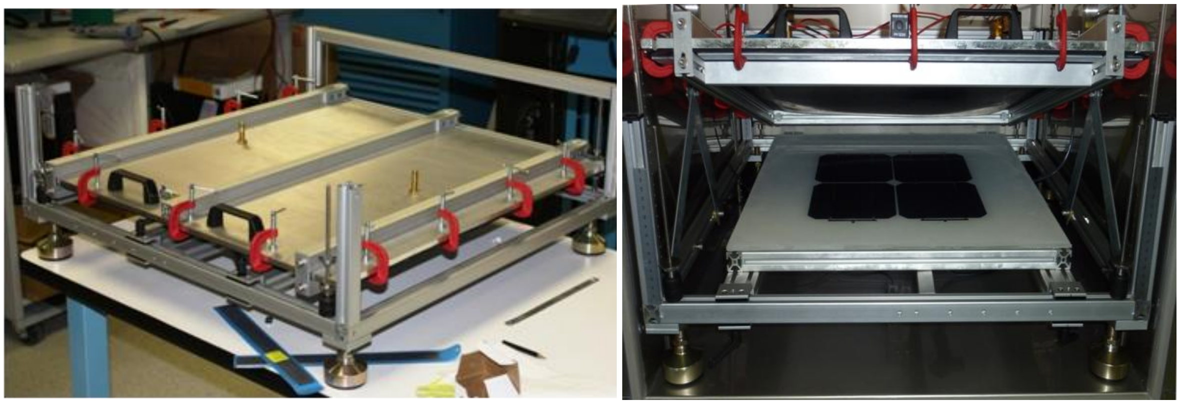

Figure 1. Custom built mechanical test stand for load testing of test PV modules inside a climate chamber. The image on the right shows a test module inside the stand with the rubber bladder seen above, attached to the top plate.

Encapsulant	Temperature	Load	Notes
Silicone EVA	-30 °C ambient 85 °C	Static: 1 hr @ 2400 Pa 1 hr @ 5400 Pa 1 hr @ 7000 Pa Dynamic (0.5 Hz): 10 000 cycles @ 5400 Pa	Static loading was performed in sequence on a single module, with characterization performed after each load cycle. Total of 24 modules were tested (3 temperatures, 2 encapsulant materials, 2 cell thicknesses, static & dynamic load).

Table 1. List of mechanical load testing parameters. Due to instrumentation error, test modules with 160 µm cells under dynamic loading were exposed to a maximum load of 4700 Pa. Test modules with 200 µm cells were loaded to 5400 Pa.

RESULTS AND DISCUSSION

In general, each of the modules tested passed the standard qualification requirement of no more than 5% power decrease after testing (Figure 3 and Figure 4). Furthermore, there was no significant change in any of the other electrical performance parameters in the tested modules. However, the electroluminescence images indicate considerable differences between silicone and EVA encapsulated modules, specifically at sub-ambient temperatures (Table 2). In particular, the cells in EVA modules were found to be substantially more cracked than those in the silicone modules, especially under dynamic loading. Furthermore, even at ambient temperature under a standard static load with 160 µm cells, no crack formation was observed in the silicone test module, whereas cracks did appear in the EVA test module (Figure 2). An analysis of the crack behavior, by tracking the number and severity (length) of the cracks, indicated that the cells in test modules with EVA encapsulant suffer increasing amounts of damage during the loading tests (Figure 5). It is also worth mentioning that the thinner cells were more susceptible to damage than the thicker cells, as evidenced by less cell damage occurring in the test modules prepared with 200 µm cells, as compared to those prepared with 160 µm cells (Figure 6).

160 µm Cells	TEST TEMPERATURE	CRACK DEVELOPMENT	
		EVA	Silicone
STATIC LOAD (5400 Pa)	-30 °C	Yes	No
	25 °C	Yes	No
	85 °C	No	No
DYNAMIC LOAD	-30 °C	Yes	No
	25 °C	Yes	No
	85 °C	No	No

200 µm Cells	TEST TEMPERATURE	CRACK DEVELOPMENT	
		EVA	Silicone
STATIC LOAD (7000 Pa)	-30 °C	Yes	No
	25 °C	Yes	No
	85 °C	No	No
DYNAMIC LOAD	-30 °C	Yes	No
	25 °C	No	No
	85 °C	No	No

Table 2. Summary of electroluminescence analysis on statically and dynamically loaded PV test modules with 160 µm (top) and 200 µm (bottom) cells.

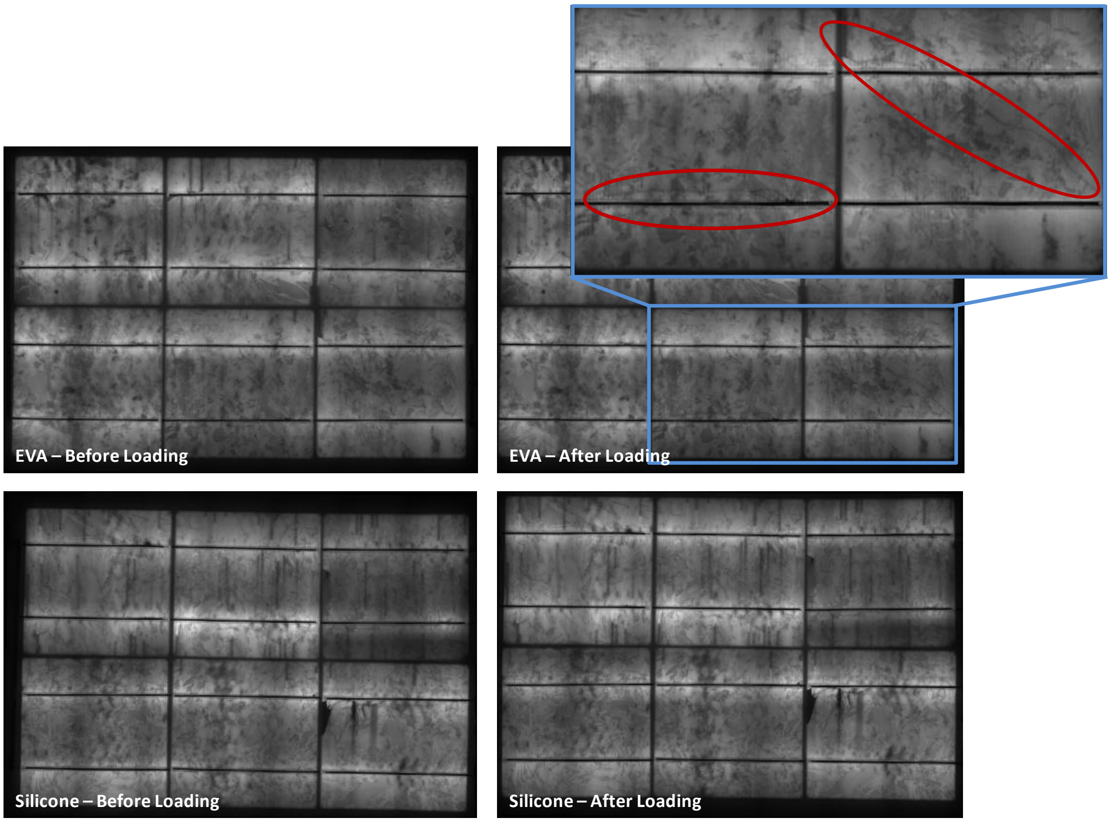

Figure 2. Electroluminescence images of modules after static loading to 5,400 Pa for 1 hour at ambient temperature. Cracks were observed to form in the module with EVA encapsulant, whereas no new cracks were seen in the module with silicone encapsulant.

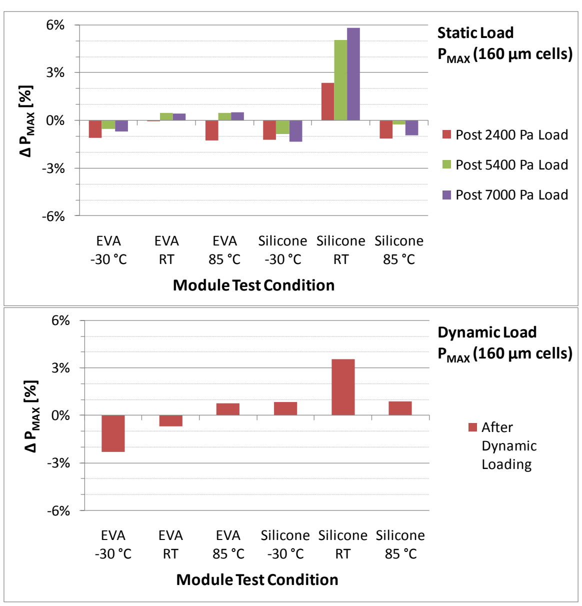

Figure 3. Change in maximum power output of test modules made with 160 µm cells after static (top) and dynamic (bottom) loading. The percent change is relative to the unloaded module.

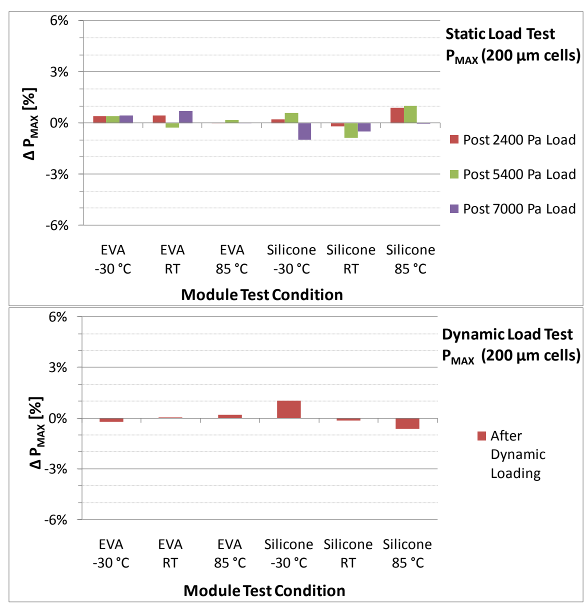

Figure 4. Change in maximum power output of test modules made with 200 µm cells after static (top) and dynamic (bottom) loading. The percent change is relative to the unloaded module.

The observed cracking behavior is consistent with the mechanical properties of the two different encapsulants over the temperature range explored in this study. The EVA encapsulant exhibits a glass transition in the range between -20 °C to -30 °C, and at -30 °C the modulus of EVA is about two orders of magnitude higher than at ambient temperature (Figure 7). This leads to a much greater probability of cell fracture at low temperatures, since more stress is transferred to the cells through the stiffer encapsulant [9]. The silicone encapsulant, on the other hand, has no thermal transitions in the standard PV module operating range of -40 °C to 85 °C, retaining its flexibility at sub-ambient temperatures (Figure 7). This allows the more compliant, lower modulus silicone encapsulant to absorb more of the loading force and thereby transmit less stress to the solar cells.

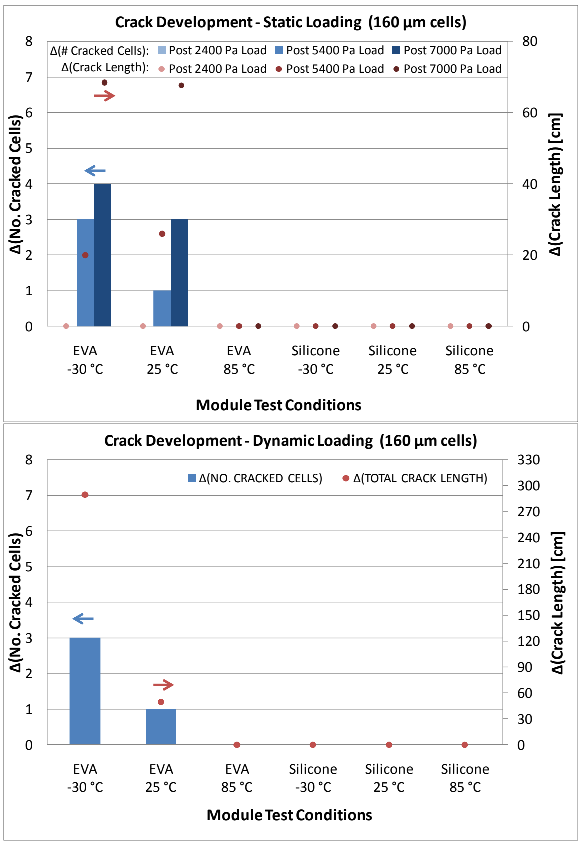

Figure 5. Crack development under loading for test modules with 160 µm cells: static loading (top), dynamic loading (bottom). The figures represent the change in the number of cracked cells (left axis), as well as the change in the total crack length (right axis) as a result of a given loading condition. Note that the large total crack length for the EVA module loaded dynamically at -30 °C is a result of the test module slipping off the test frame during loading, subjecting the module to very large deflections.

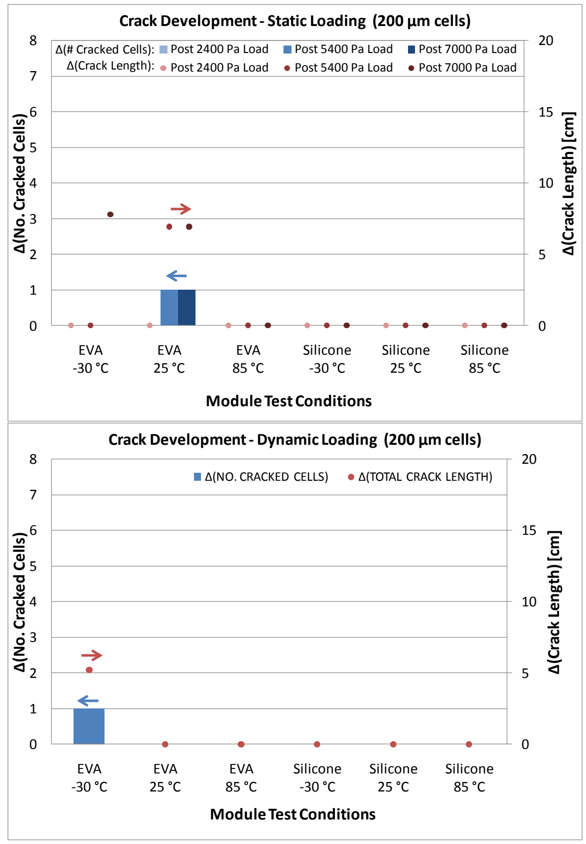

Figure 6. Crack development under loading for test modules with 200 µm cells: static loading (top), dynamic loading (bottom). The figures represent the change in the number of cracked cells (left axis), as well as the change in the total crack length (right axis) as a result of a given loading condition. Note that the severity of the cracking is much lower than that for the thinner cells (compare scale to Figure 5). The EVA module loaded statically at -30 °C already had a crack prior to loading, which was enlarged after one hour at 7000 Pa.

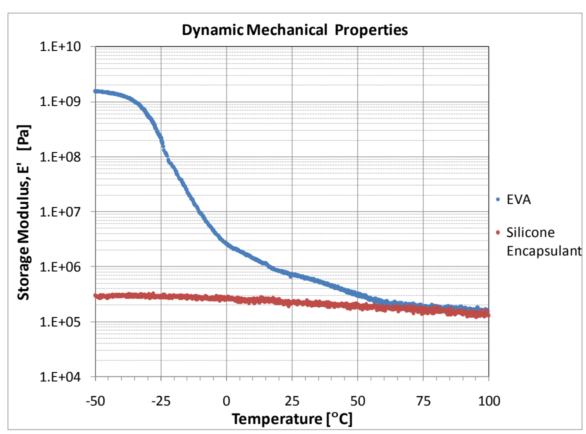

Figure 7. Storage modulus of silicone and EVA encapsulant measured using DMA in tension mode.

CONCLUSION

The results of this study clearly indicate the importance of taking temperature into account when investigating the response to mechanical loading of PV modules. In particular, EVA materials currently used as encapsulation in PV modules are known to have a glass transition in the operating temperature range, which has a significant impact on the mechanical properties of the encapsulant. As a result, the modulus of EVA increases by over an order of magnitude between ambient and -30 °C, making the encapsulation material much stiffer at lower temperatures. This large change in mechanical properties has been shown here to adversely affect the integrity of solar cells encapsulated in EVA as compared to those encapsulated with silicones, which have a lower and more stable cured modulus over the temperature range of the test. It is worthwhile to point out that although the I-V characteristics and power output are not greatly affected as a result of the loading test, subjecting modules with cracked cells to environmental stresses, such as thermal cycling, does lead to increased power loss as compared to modules with undamaged cells [10-11]. In addition, the silicone encapsulant has been shown to be more effective at protecting thinner, more fragile cells, from the effects of mechanical loading.

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