

The Role of a Silane Coupling Agent in Common Photovoltaic Encapsulation Systems

Jinyang Song, Mengli Chen, Tongjian Lu*, Shuhui Dong

Liaoning University, Shenyang 110031, Liaoning Province, China

*Corresponding author: Tongjian Lu, 15674791828@163.com

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Abstract: Grafts of silane coupling agent EVA and POE were prepared by twin-screw melt extrusion method to obtain grafts EVA-g-KH171 and POE-g-KH171. The effect of silane coupling agent KH171 on the properties of two commonly used encapsulants in the photovoltaic field was investigated. The changes in the melt index of the grafts were tested by different dosages of silane coupling agents to explore further the effect of the changes in the melt index of the two grafting products, namely, EVA and POE, on the peeling strength. With the addition of the silane coupling agent, the melt index of the grafting product of EVA and POE increased. The peel strength test showed that the silane coupling agent KH171 had a more significant improvement in the adhesion of EVA and POE, proving the feasibility of its application in practical conditions.

Keywords: Silane coupling agent; Bonding agent; EVA; POE; Peel strength

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1. Introduction

The durability of photovoltaic (PV) modules has a decisive role in the life cycle of solar cells. Good encapsulation materials are the key to prolonging the service life of photovoltaic modules because of the harsh environment in which solar cells are used^[1-4]. Photovoltaic cell encapsulants should have good adhesion, low interfacial conductivity, and moisture permeability^[5].

In recent years, encapsulation materials for photovoltaic modules have made extensive use of synthetic polymers^[6-7]. Ethylene-vinyl acetate (EVA) is a copolymer of ethylene and vinyl acetate. It is a thermoplastic elastomer with high elasticity and toughness, which has a wide range of applications in the plastics industry and is commonly used as an encapsulation material for crystalline silicon solar cells^[8-9]. Poor performance in repairing PV modules is due to insufficiently prominent cross-linking chemistry of EVA during processing and low aging resistance of the film^[10]. The following EVA replacement encapsulants are commonly used in the industry: thermoplastic polyurethane, polyolefin encapsulants, polyvinyl butyral, and thermoplastic silicone rubber^[11-12]. Polyolefin-based encapsulation materials have good market prospects due to their significant encapsulation effect and generally lower prices.

Polyolefin elastomers (POE) are copolymers of ethylene and octene, and their crystalline properties are mainly affected by internal octyl content and spatial distribution^[13-14]. POE's aging resistance is better, cohesion is smaller, light transmittance is better, and adhesion is more long-lasting, so it is more adaptable to the common use of photovoltaic cells. Silane coupling agents have been studied to promote the adhesion of polyolefins within a certain dosage range^[15-16]. This article will further explore the effect of silane coupling agents on the material enhancement of EVA.

The focus of this study was on the modification of POE and EVA with silane coupling agent KH171, and the effect of KH171 on the peel strength of EVA and POE was tested to explore the enhancement of KH171 on the properties of two common photovoltaic encapsulation materials and design a feasible solution.

2. Experiment

2.1. Materials

The following raw materials were used in this study: vinyltrimethoxysilane (KH171); polyolefin elastomer (POE); 2,5-dimethyl-2,5-(di-tert-butylperoxy)hexane (DBPH), xylene, trichloroacetic acid-isopropanol, ethylene vinyl acetate copolymer (EVA), borosilicate glass plate with a thickness of 3.2 mm, and backsheets for testing adhesion.

2.2. Sample preparation

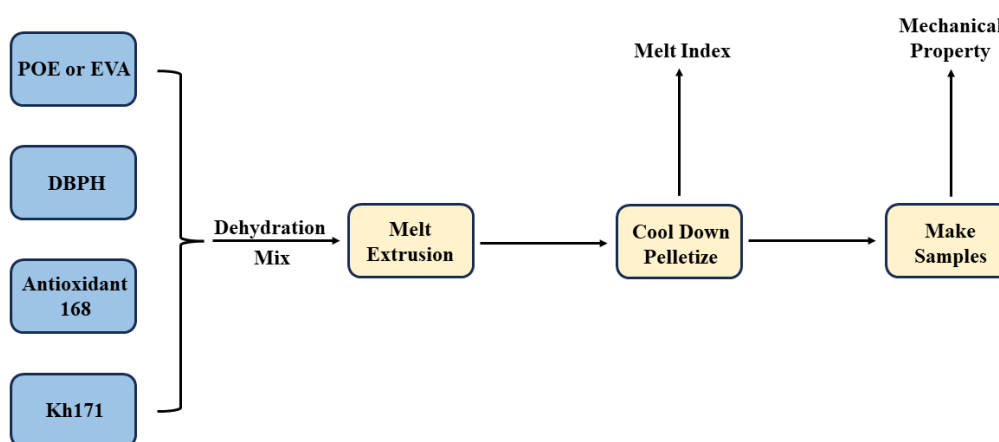
The silane coupling agents KH171, POE, DBPH, and others are combined following the proportion shown in **Table 1** and then mixed in a high-speed mixer to achieve uniform dispersion. The blended mixture is added to the twin-screw extruder in the melt extrusion. Then the mixture is pelletized in the pelletizing machine to obtain the POE-g-KH171. Twin-screw extruder temperature is set to: 170°C, 175 °C, 180°C, 190°C, 190°C, 180°C, 175°C, 170°C, head temperature of 170°C, melt pressure of 16 MPa, screw speed of 500 r/min, and feed speed of 110 r/min. The cooled granulation is dried in the oven for 4 hours at 130°C to produce the graft product of polyolefin elastomer POE POE-g-Kh171 following the same operation ratios in **Table 2**. The process to produce EVA graft product EVA-g-KH171 is shown in **Figure 1** below.

Table 1. POE and silane coupling agent

Serial number	Amount added/part			
	POE	KH-171	DBPH	Antioxidant168
L ₀ \K ₀ \T ₀ \Y ₀ \R ₀	100	1/2/3/4/5	0	0.2
L ₁ \K ₁ \T ₁ \Y ₁ \R ₁	100	1/2/3/4/5	0.05	0.2
L ₂ \K ₂ \T ₂ \Y ₂ \R ₂	100	1/2/3/4/5	0.1	0.2
L ₃ \K ₃ \T ₃ \Y ₃ \R ₃	100	1/2/3/4/5	0.15	0.2
L ₄ \K ₄ \T ₄ \Y ₄ \R ₄	100	1/2/3/4/5	0.2	0.2
L ₅ \K ₅ \T ₅ \Y ₅ \R ₅	100	1/2/3/4/5	0.25	0.2
L ₆ \K ₆ \T ₆ \Y ₆ \R	100	1/2/3/4/5	0.3	0.2

Table 2. EVA and silane coupling agent

Serial number	Amount added/part			
	EVA	KH-171	DBPH	Antioxidant168
L ₀ \K ₀ \T ₀ \Y ₀ \R ₀	100	1/2/3/4/5	0	0.2
L ₁ \K ₁ \T ₁ \Y ₁ \R ₁	100	1/2/3/4/5	0.05	0.2
L ₂ \K ₂ \T ₂ \Y ₂ \R ₂	100	1/2/3/4/5	0.1	0.2
L ₃ \K ₃ \T ₃ \Y ₃ \R ₃	100	1/2/3/4/5	0.15	0.2
L ₄ \K ₄ \T ₄ \Y ₄ \R ₄	100	1/2/3/4/5	0.2	0.2
L ₅ \K ₅ \T ₅ \Y ₅ \R ₅	100	1/2/3/4/5	0.25	0.2
L ₆ \K ₆ \T ₆ \Y ₆ \R	100	1/2/3/4/5	0.3	0.2

**Figure 1.** EVA graft product EVA-g-KH171 preparation process

2.3. Measurements

The obtained products were numbered according to the tables and the grafting rate of each grafted product was tested. The grafting rate was tested by titration as follows. 0.5 g of purified grafted polymer was accurately weighed and placed in a three-necked flask, 80 mL of xylene was added, the three-necked flask was heated in an electric heating jacket to dissolve the grafts completely, then refluxed for 30 min, 10 mL of trichloroacetic acid-isopropanol standard solution was added slowly. After refluxing for 1.5 h, heating was stopped, phenolphthalein was added as an indicator, potassium hydroxide-ethanol solution was titrated to the endpoint, and the determination was repeated three times to get the average value for the grafting rate. The grafting rate can be calculated according to the following formula:

$$G = \frac{(C_1V_1 - C_2V_2) \times M}{W \times 1000} \times 100\%$$

C_1 and V_1 denote the concentration of trichloroacetic acid-isopropanol solution (mol/L) and the volume used (mL) respectively; C_2 and V_2 denote the concentration of potassium hydroxide-ethanol solution (mol/L) and the volume consumed (mL) respectively; M refers to the molecular mass of KH171 (148 g/mol); and W denotes the weighted mass of the purified grafted polymer of the monomer (g).

The curing of the samples used for peel strength measurements was carried out on a vulcanizing machine (BFC-25T, Granite, China) with a clamping force of 25 MN and a plate unit pressure of 14 MPa. The curing

process in the pressurized vulcanizer was carried out at 140°C for 40 minutes. Peel strength measurements of the samples were performed using the American Standard Test Method (ASTM) D903-98 with a separation angle of approximately 180°, a separation rate of 152 mm/min, and a room temperature of 25°C [1]. The samples used for peel measurements were in a composite mode of polymer blends/PET backsheets. The cross-linking degree of the samples was measured using the Chinese GB/T36965-2018 Cross-linking Degree Test Method for Ethylene-Vinyl Acetate Copolymers for Photovoltaic Modules-Differential Scanning Calorimetry [1]. The samples used for melt index determination were measured according to the GB/T3682-2000 standard, the temperature was set at 190°C and the load was set at 2.16 kg. Three samples were taken as a group and the average value was obtained.

3. Results and discussion

After the infrared spectroscopy scanning measurement, the test results of the FT-IR of the test samples are as follows. It can be seen from **Figure 2** that the $C(CH_3)_3$ vibration peak at 1370 cm^{-1} and the $C=O$ vibration peak at 1740 cm^{-1} are the characteristic peaks belonging to EVA. For the silane coupling agent grafting of the pure EVA-g-KH171, the absorption peaks appeared at 1130 cm^{-1} as shown in **Figure 2**. This is caused by the Si-O-Si bond in the silane coupling agent successfully grafted onto the EVA, thus it can be proved that the Si-O-Si on the silane coupling agent successfully grafted onto the polymer chain of EVA, and the grafting reaction [1] was successful. The reaction mechanisms are shown in **Figure 3**.

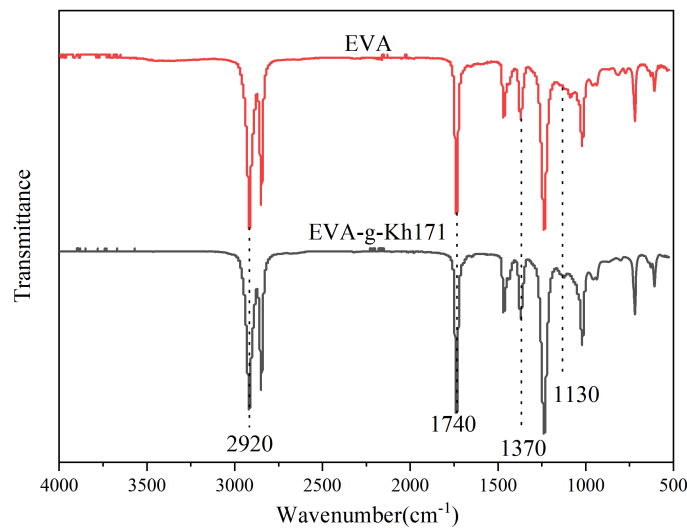


Figure 2. FTIR spectra of EVA and EVA-g-KH171

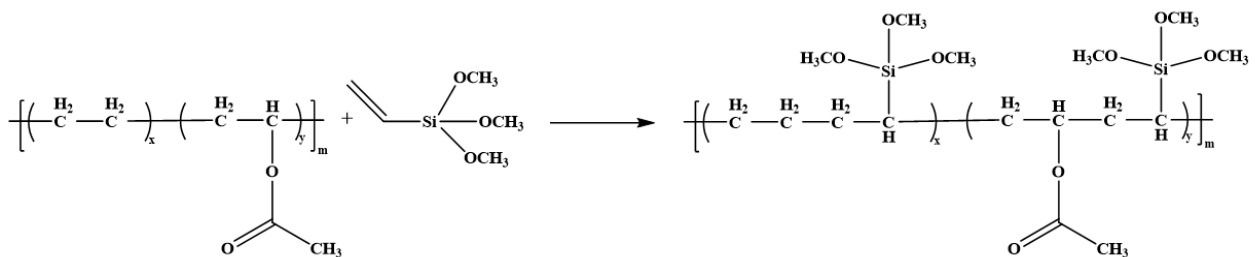


Figure 3. Reaction mechanism of EVA-g-KH171

The FT-IR spectra obtained from the test of the grafted product samples of POE are shown in **Figure 4**. The C=C vibrational peak at 2920 cm^{-1} and the C=C vibrational peak at 1470 cm^{-1} are the characteristic peaks belonging to POE. The pure POE-g-KH171 grafted with silane coupling agent can be seen in the strong absorption peaks that appeared at 1092 cm^{-1} in **Figure 4**. The absorption peak is caused by anti-symmetric stretching of the Si-O-Si bond, which can prove that the Si-O-Si on the silane coupling agent was successfully grafted onto the polymer chain of POE, and the silane coupling agent decomposed under the experimental conditions to generate free radicals, which can be crosslinked with the olefin polymers so that the bonding properties exhibited by the overall structure of olefin polymers were enhanced. The reaction mechanisms are shown in **Figure 5**.

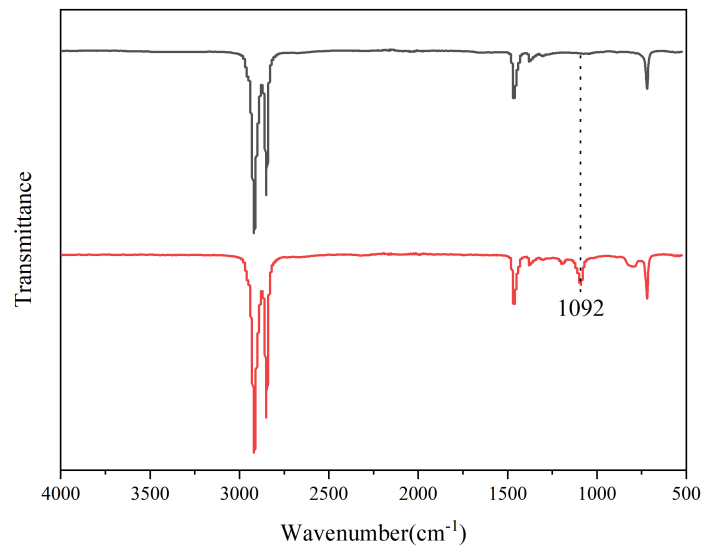


Figure 4. FTIR spectra of POE and POE-g-KH171

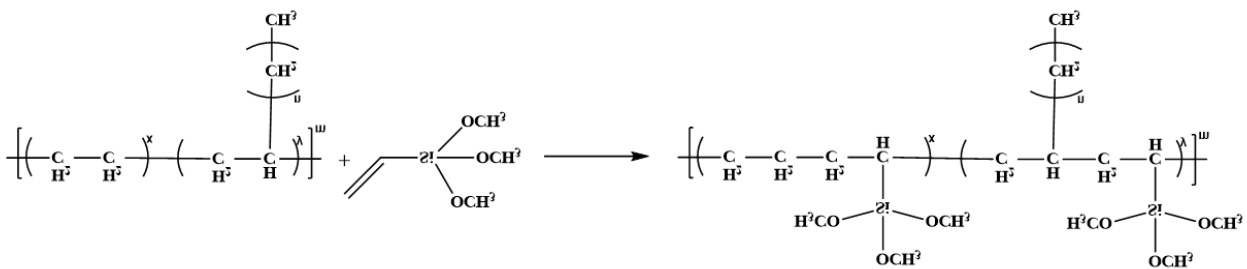


Figure 5. Reaction mechanism of POE-g-KH171

To further explore the factors affecting the peel strength, the grafting rate and grafting efficiency of each group of grafting products were tested. The grafting rate continued to increase with the increase of the silane coupling agent, but the growth rate gradually decreased and reached an optimum at the addition of four parts of the silane coupling agent. The structural stability of the lamellar structure inside the polyolefin partly rises with the addition of the functional groups of silane coupling agent when the system was not saturated with mPOE/mKh171 ratio of 100:4. As shown in **Figure 6**, the melt index growth rate increase with the increase in the amount of silane coupling agent due to the internal coupling reaction and other side reactions, but the stability gain is gradually reduced.

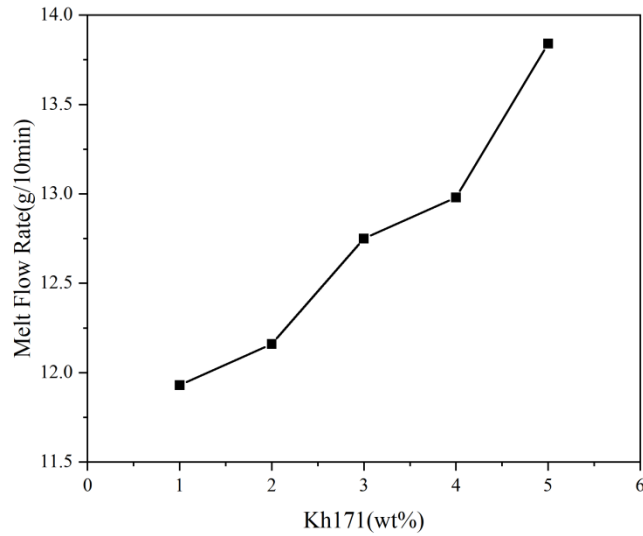


Figure 6. Melt index of KH171 and POE-g-KH171

The melt index of EVA in **Figure 7** indicates that the grafting rate is positively correlated with the amount of silane coupling agent added, and the grafting efficiency gradually decreases with the gradual increase in the amount of silane coupling agent added. When the input ratio mEVA/mDBPH/mKh171 is 100:0.3:3, the growth rate of the melt index gradually slows down, which is the optimal input ratio.

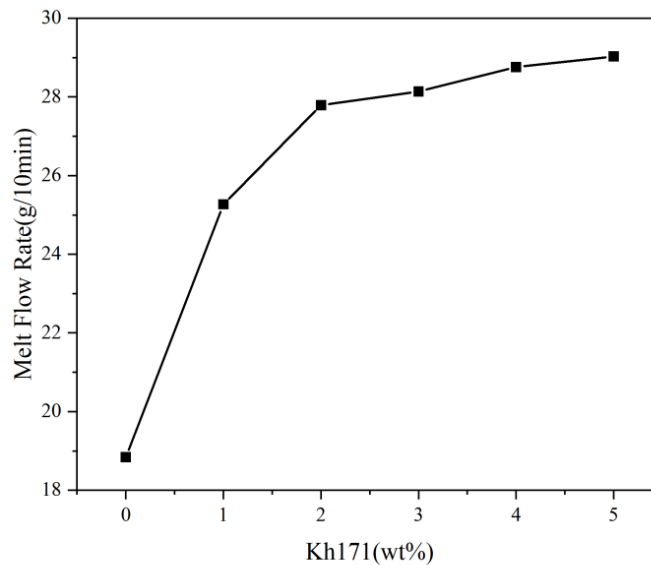


Figure 7. Melt index of Kh171 and EVA-g-KH171

As shown in **Figure 8**, when the melt index of the POE graft product is higher, the molecular mobility is larger and the peel strength is relatively poor. This makes the adhesive unevenly bonded when used, which is not favorable for two-phase bonding and makes the adhesion lower. In comparison with the peel strength before adding silane coupling agent KH171, it can be obtained that POE-g-KH171 has the highest peel strength when the melt index is 12.68 g/10min.

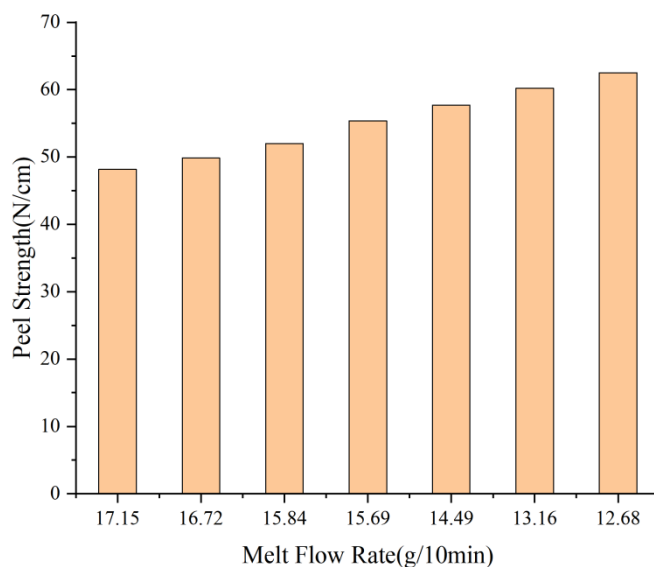


Figure 8. Melt index and peel strength of POE-g-KH171

As shown in **Figure 9**, the peel strength of EVA with the addition of the silane coupling agent, increased the polarity of the internal structure of EVA, so that the peel strength of EVA has a significant enhancement. The mEVA/mKh171 ratio at 100:3 has the best adhesion performance among the EVA graft product.

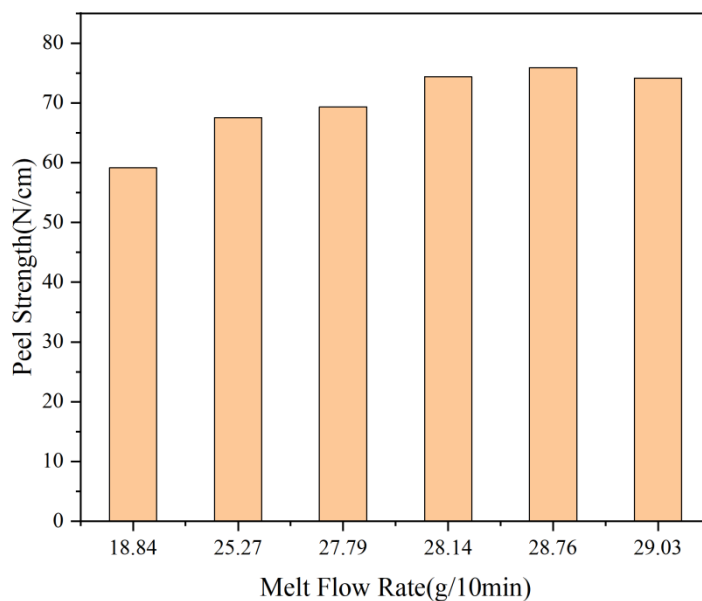


Figure 9. Melt index and peel strength of EVA-g-KH171

4. Conclusion

In this study, vinyltrimethoxysilane (KH171) was grafted onto polyolefin elastomer (POE) and ethylene vinyl acetate copolymer (EVA), respectively, and the grafting effect was enhanced by the use of 2,5-dimethyl-2,5-(di-tert-butylperoxy)hexane (DBPH). According to the FTIR spectra, it was found that KH171 was successfully grafted onto POE and EVA. Further validation concluded that when the mPOE/mDBPH/mKH171 ratio was

at 100:0.25:4, the melt index was 12.68 g/10min and the peel strength was 62.51 N/cm. When the mEVA/mDBPH/mKh171 ratio was at 100:0.3:3, the melt index was 28.14 g/10min and the peel strength was 74.37 N/cm. This shows that the material and nature enhancement at the optimal ratio is feasible and has future prospects as encapsulation material.

Disclosure statement

The authors declare no conflict of interest.

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