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REGULAR ARTICLE

Structural and Electrical Characterization of Different Grades of Polyolefin Encapsulants

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Encapsulant materials play a crucial role in the performance, durability, and reliability of silicon-based photovoltaic (PV) modules. They protect solar cells from environmental exposure, provide electrical insulation, and enhance mechanical stability. High optical transparency of encapsulants is essential for efficient light transmission and, consequently, for maximizing the energy output of PV modules. In addition, encapsulants should exhibit excellent UV resistance, thermal stability, and chemical resistance to ensure the long-term reliability of solar panels.

In this study, polyolefin polymer encapsulant films were obtained from two different companies, referred to as Company-1 and Company-2. The objective of this work is to investigate and compare their structural, thermal, optical, and electrical properties. The structural and optical characteristics were analyzed using Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, thermogravimetric analysis (TGA), and UV–visible spectroscopy. The electrical properties were evaluated using a broadband dielectric spectrometer. The investigated electrical parameters include dielectric constant (permittivity), electric modulus, and volume resistivity.

Keywords: Photovoltaics, Encapsulant materials, Electrical properties of encapsunats, Thermal properties of encapsulants.

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1. INTRODUCTION

The The rapid growth of the photovoltaic (PV) industry has increased the demand for advanced materials that can improve the performance, durability, and cost-effectiveness of solar modules [1]. Among these materials, polyolefins have become important components in silicon-based PV modules, particularly as encapsulant materials. The encapsulant plays a vital role in protecting solar cells from environmental degradation and mechanical damage while providing electrical insulation [2].

Polyolefins are a versatile class of polymers derived from simple olefins (alkenes), such as polyethylene (PE) and polypropylene (PP). They are promising materials for PV encapsulation because of their low cost, easy processing, chemical resistance, mechanical strength, optical properties, and good electrical insulation [3, 4]. Polyolefins are widely used in various fields, including the solar, electrical and electronics, automotive, packaging, construction, and healthcare industries [5].

Several polymeric materials are used as encapsulants in solar cells. These include polyolefin elastomers (POEs), ethylene-vinyl acetate (EVA), silicone resins, polyvinyl butyral (PVB), ionomers, and thermoplastic polyolefins (TPO) [6]. These materials protect solar cells from moisture ingress, mechanical stress, and UV-induced degradation while maintaining electrical insulation.

EVA has been widely used as an encapsulation material for more than three decades because of its low cost, flexibility, and good optical transmittance. However, EVA-based encapsulants have some limitations. During the cross-linking process, EVA can generate volatile organic compounds (VOCs) and acidic degradation products. These products can accelerate the degradation of the encapsulant and other module components during long-term outdoor operation, thereby affecting the performance and service life of PV modules [7, 8].

Recent advances in polymer science have led to the development of new polyolefin-based encapsulants that address some of the limitations of conventional materials. Cross-linked polyolefins can provide improved thermal and UV stability. Specialized additives can also enhance their optical properties and long-term durability. These developments can help extend the operational lifetime of PV modules, reduce the levelized cost of electricity (LCOE), and improve the sustainability of solar energy systems [9-11].

The electrical properties of encapsulants are particularly important for the reliable operation of PV modules. Encapsulation materials should have high dielectric strength to prevent electrical breakdown and provide effective insulation. Polyolefins generally exhibit good dielectric properties, which help them withstand high electric fields and maintain electrical isolation between the different components of a PV module. In addition, high volume resistivity is important for minimizing leakage currents and maintaining the electrical integrity of the module [12-14].

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The dielectric constant is another important parameter for evaluating encapsulant materials. It describes the ability of a material to store electrical energy when exposed to an electric field. A suitable dielectric constant helps maintain effective electrical insulation and influences the electric-field distribution within the PV module. Polyolefins generally exhibit stable dielectric properties, making them attractive candidates for encapsulation applications [15, 16].

The dielectric properties of encapsulants can also influence the electric-field distribution within silicon-based PV modules. Significant variations in dielectric constant may result in non-uniform electric fields and localized electrical stress. Such effects can contribute to localized heating and degradation of solar cells and other module components. Therefore, stable dielectric properties over a wide range of temperatures and environmental conditions are important for maintaining module reliability [17].

In addition, the dielectric properties of encapsulants can influence their response to high-frequency electrical signals and noise. Materials with low dielectric loss can reduce energy dissipation and heat generation. This property is beneficial for improving the electrical reliability and long-term stability of PV modules [18].

The electrical properties of polyolefins are also related to their performance under thermal stress. PV modules operate under varying temperatures and climatic conditions. Therefore, the ability of an encapsulant to maintain its dielectric properties and high resistivity during thermal exposure is essential for long-term module reliability. Overall, the excellent insulating properties, high resistivity, and stable dielectric behavior of polyolefins make them promising encapsulant materials for silicon-based photovoltaic systems [20].

In this research paper, we investigate the structural and electrical properties of polyolefins used as encapsulant materials in silicon-based photovoltaic (PV) modules. The structural properties are analyzed using FTIR, Raman, TGA, and UV–visible spectroscopy. The electrical properties are evaluated in terms of dielectric constant, volume resistivity, and electric modulus. We also discuss the importance of electrical properties as key parameters for assessing the quality and reliability of polyolefin encapsulant materials.

2. CHARACTERIZATION

A Fourier transform infrared (FTIR) spectra of the POEs were recorded using a Shimadzu FTIR-8400S spectrophotometer in the wavenumber range of 4000-500 cm^{-1}. Raman spectroscopy was performed at room temperature using a Jobin-Yvon, France Ramnor HG-2S spectrometer with a 514 nm laser to investigate the crystallinity and molecular structure of the POEs. The laser beam was focused on the samples using a microscope with a 50× objective. Raman spectra were recorded in the wavenumber range of 500-3500 cm^{-1}.

Thermogravimetric analysis (TGA) of the POEs was carried out using an SDTA 851 Mettler-Toledo system. The measurements were performed at a heating rate of 20 °C min^{-1} under a nitrogen flow rate of 40 mL min^{-1}. UV–visible transmittance spectra were recorded using a Shimadzu UV-2401 spectrophotometer in the wavelength range of 200-850 nm.

The electrical properties, including dielectric constant, electric modulus, and volume resistivity, were measured using a broadband dielectric spectrometer (Novo Control Technologies, Germany, Concept 80). The measurements were performed at 57 Hz over a temperature range of −30 to 100 °C. Frequency-dependent measurements were also carried out at room temperature over the frequency range of 1 Hz to 10^5 Hz.

3. RESULTS AND DISCUSSION

Two different grades of POEs were characterized by Fourier-transform infrared spectroscopy (FTIR) to identify their functional groups and chemical bonds. It was observed that both the POEs were made by the same polymeric material because the peaks positions are observed at same locations in both grades as shown in Fig. 1(a). Peaks at 2915 and 2848 cm^{-1} are observed due to C-H stretching, while peaks at 1465 and 730 cm^{-1} are found due to C-H bending. Peaks at 1375 and 1450 cm^{-1} are seen due to CH_3 group. Peak at 1710 cm^{-1} is observed due to C = O group [21].

Raman spectra of two different grades of POEs were recorded to identify their functional groups and molecular vibrations. Both samples showed peaks at 2883 and 2850 cm^{-1}, which are assigned to C–H stretching vibrations. These bands are commonly observed in polyethylene (PE) and polypropylene (PP). Additional peaks were observed at 1060 and 1132 cm^{-1} in both samples. These peaks can be attributed to C–C stretching vibrations and are commonly associated with polyethylene-based structures. A peak at 1375 cm^{-1} was assigned to CH_3 bending vibrations. Another peak at 1420 cm^{-1} was associated with vibrations from crystalline regions [22, 23]. The similar peak positions and spectral features of both samples suggest that they have similar polymeric compositions and molecular structures.

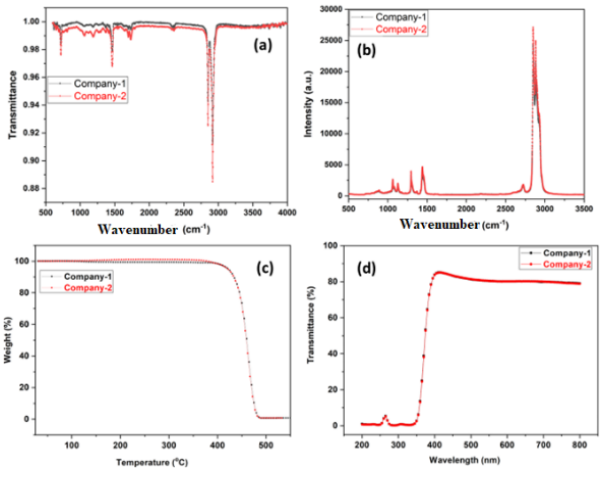


Fig. 1 – (a) FTIR spectra, (b) Raman spectra, (c) TGA curves, and (d) UV–visible transmittance spectra of POE samples from Company 1 and Company 2

Thermogravimetric analysis (TGA) was performed to evaluate the thermal stability and degradation behavior of the POE polymer sheets. TGA provides useful information about the thermal stability, composition, and possible presence of additives in polymeric materials. Both sam-

ples remained thermally stable up to approximately 400 °C. The TGA curves showed similar thermal behavior for both samples. Both samples began to undergo significant degradation at around 450 °C [21]. These results indicate that the two POE samples have comparable thermal stability and degradation characteristics.

UV–visible spectroscopy was used to evaluate the optical transmittance of the POE samples. Transmittance represents the fraction of incident light that passes through a material. Both samples showed similar transmittance values of approximately 82 %. The transmittance was about 83 % in the wavelength range of 400-425 nm and remained nearly constant at around 82 % at higher wavelengths. A sharp decrease in transmittance was observed in the UV region (200-350 nm), which may be associated with UV-absorbing additives or chromophores present in the POEs. A peak was observed at approximately 265 nm, which may be related to UV stabilizers or antioxidants in the POE samples.

The overall transmittance of both samples was nearly identical. Therefore, the structural and optical characterizations discussed above could not clearly distinguish the quality or grade of the POE samples. The two grades showed similar structural and optical characteristics. Hence, additional characterization techniques are required to effectively differentiate between different grades of POEs and evaluate their quality [24, 25].

The dielectric constant of the two POE samples was different but remained nearly constant with frequency, as shown in Fig. 2(a). The dielectric constant values for Company 1 and Company 2 were 2.06 and 2.08, respectively. A lower dielectric constant is generally desirable for electrical insulation because it can reduce dielectric losses. In solar modules, stable dielectric properties are important for providing reliable electrical insulation and protecting solar cells under varying operating conditions [26].

The dielectric constant also remained nearly constant with temperature up to approximately 40 °C. Above 40 °C, it increased significantly with increasing temperature, as shown in Fig. 2(b). This increase may be related to enhanced molecular motion, increased polarizability, and changes in the degree of crystallinity of the polymer. The temperature dependence of the dielectric constant is important for evaluating the suitability of POEs for electrical insulation and PV module encapsulation [27].

The electric modulus is inversely related to the dielectric response of the material. Both POE samples showed similar trends with frequency and temperature, but in the opposite direction to the dielectric constant, as shown in Fig. 2(c) and (d) [28]. These results indicate that the dielectric response and electrical relaxation behavior of the two POE samples are closely related.

The volume resistivity of both POE samples decreased with increasing frequency and temperature, as shown in Fig. 3(a) and (b). This behavior can be attributed to the increased mobility of charge carriers at higher temperatures and the frequency-dependent electrical response of the polymer. The temperature and frequency dependence of volume resistivity is important for evaluating the electrical insulation performance of POEs in applications such as cable insulation, electronic encapsulation, and PV module encapsulation [29, 30].

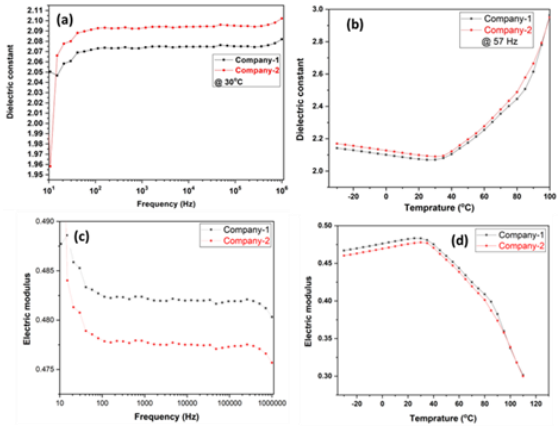


Fig. 2 – (a) Dielectric constant vs frequency, (b) Dielectric data vs temperature, (c) Electric modulus vs frequency and (d) Electric modulus vs temperature of POE (Company-1 & Company-2)

The volume resistivity of the Company 1 sample was higher than that of the Company 2 sample. Higher volume resistivity indicates better resistance to leakage current and better electrical insulation. The electrical measurements therefore show a clear difference between the two POE grades. Among the two samples, the POE from Company 1 exhibited better electrical insulation properties than that from Company 2. These results demonstrate that electrical characterization is an important tool for differentiating POE grades and evaluating their suitability for PV module encapsulation.

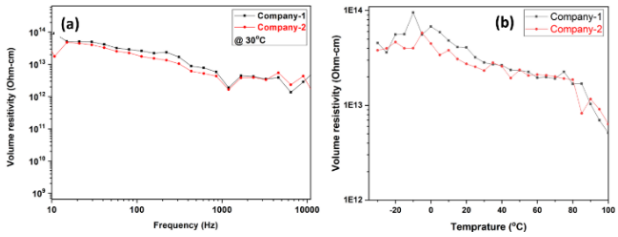


Fig. 3 – (a) Volume resistivity vs frequency, (b) Volume resistivity vs temperature of POE (Company-1 & Company-2)

4. CONCLUSION

The FTIR and Raman analyses showed that both POE films have similar structural properties. Both films also exhibited high optical transmittance and good thermal stability, which are important for PV module durability and performance.

The electrical properties, including dielectric constant, volume resistivity, and electric modulus, were also investigated. Both films showed good electrical insulation properties. However, the Company 1 POE exhibited higher volume resistivity and better overall electrical performance than the Company 2 POE. Therefore, the Company 1 film is more suitable for silicon-based PV module encapsulation.

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Структурна та електрична характеристика різних марок поліолефінових герметизуючих матеріалів

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Герметичні матеріали відіграють вирішальну роль у продуктивності, довговічності та надійності фотоелектричних (ФЕ) модулів на основі кремнію. Вони захищають сонячні елементи від впливу навколишнього середовища, забезпечують електричну ізоляцію та підвищують механічну стабільність. Висока оптична прозорість герметиків є важливою для ефективного пропускання світла та, як наслідок, для максимізації вироблення енергії ФЕ модулями. Крім того, герметики повинні мати відмінну стійкість до ультрафіолетового випромінювання, термостабільність та хімічну стійкість, щоб забезпечити довгострокову надійність сонячних панелей.

У цьому дослідженні було використано поліолефінові полімерні плівки для герметизації, отримані від двох різних компаній, позначених як «Компанія-1» та «Компанія-2». Мета цієї роботи – дослідити та порівняти їхні структурні, термічні, оптичні й електричні властивості. Структурні та оптичні характеристики аналізували за допомогою інфрачервоної спектроскопії з перетворенням Фур'є (FTIR-спектроскопії), раманівської спектроскопії, термогравіметричного аналізу (ТГА) та спектроскопії в ультрафіолетовій і видимій областях. Електричні властивості оцінювали за допомогою широкосмугового діелектричного спектрометра. До досліджуваних електричних параметрів належать діелектрична проникність, електричний модуль та питомий об'ємний електричний опір.

Ключові слова: Фотоелектрика, Герметизуючі матеріали, Електричні властивості герметизуючих матеріалів, Теплові властивості герметизуючих матеріалів.