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Investigation note

Evaluation of HNBR as a substitute polymeric material for encapsulations in silicon photovoltaic panels

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Abstract

Currently, the use of renewable energies, specifically photovoltaic energy, has experienced almost exponential growth due to the increasingly intense energy demand in the world. This has led the photovoltaic industry to focus its efforts on the efficiency of photovoltaic generators. An area of study of great interest is the substitution of materials currently used either as encapsulants or insulators for the manufacture of silicon photovoltaic modules. In this work, polymeric coating tests for photovoltaic cells were carried out using hydrogenated nitrile butadiene rubber to study the feasibility of its use as a photovoltaic encapsulant. Polymer membranes were prepared by pressing under different conditions to obtain the desired optimal adhesion and transparency properties. Finally, tests of electrical variables were performed under standard laboratory conditions (25 °C, 1 000 W m^{-2}, 1.5 air masses). The results of the measurements validate the use of hydrogenated nitrile butadiene as an encapsulating polymer for photovoltaic modules, since this material shows a greater thermal stability of more than 100 °C compared to conventional encapsulants, such as ethylene vinyl acetate, without affecting the passage of electrical current through the material, which makes it a more stable and durable option with potential application in larger-scale solar cells.

Keywords:

HNBR, rubbers, silicon, solar energy, solar panels.

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Photovoltaic panels are exposed to a variety of harsh environmental conditions that affect their performance and durability. Among the most critical factors that can impair their operation are prolonged exposure to ultraviolet (UV) radiation, extreme temperature variations, humidity, and the presence of atmospheric pollutants. These elements can lead to premature degradation of encapsulating materials, affecting both the mechanical stability and energy conversion efficiency of the photovoltaic module (Ossa-Arango, 2017).

To address the aforementioned problem, polymeric encapsulants play an essential role in the protection of solar cells, as they prevent the infiltration of oxygen and moisture, minimize the effects of UV radiation, and contribute to thermal dissipation within the module. The choice of encapsulation material in photovoltaic modules is crucial to ensure both energy efficiency and system durability.

Currently, EVA is the most widely used encapsulating material due to its low cost, adequate optical properties, and adhesive capacity (Säckl *et al*., 2024). Nevertheless, its susceptibility to yellowing, thermal degradation, and loss of mechanical properties over time have generated the need to explore new materials with better resistance and durability characteristics.

However, studies have pointed out that under adverse environmental conditions, such as high temperatures, high humidity, and high ultraviolet irradiance, typical environmental factors in various regions of the country, EVA is susceptible to yellowing, thermal degradation, and loss of mechanical properties over time, affecting the efficiency and useful life of photovoltaic modules (Agroui and Collins, 2003). This has generated the need to explore new materials with better characteristics of resistance and durability.

In this sense, hydrogenated nitrile butadiene rubber (HNBR) emerges as a promising alternative due to its remarkable thermal and chemical stability, its high resistance to UV radiation, and its adhesion capacity. This elastomer has been widely used in industrial sectors, such as the automotive and aerospace sectors, where high resistance to heat, solvents, and oxidation is required. Despite its considerably higher cost than EVA, its behavior in high-performance applications suggests that it could play a key role in improving photovoltaic cell encapsulants, extending their lifespan, and reducing the adverse effects of environmental degradation (Pazur, 2005).

Recent studies have shown that advanced polymer materials can significantly contribute to the optimization of the energy efficiency of photovoltaic modules. Encapsulants not only protect solar cells from environmental factors but also influence light transmission and heat dissipation, which directly impacts the overall performance of the system. An encapsulant with higher thermal and chemical stability can minimize efficiency loss over time and improve module performance in adverse climatic conditions.

Mexico has enormous potential in solar energy, with approximately 70% of its territory receiving irradiation of more than 4.5 kW h m^{-2} day^{-1}, making it a very sunny country. This implies that, using current photovoltaic technology, a 25 km^2 solar power plant anywhere in the state of Chihuahua or the Sonoran Desert (occupying 0.01% of Mexico's territory) could provide all the electricity demanded by the country (Juárez and Urdiales, 2022).

As for the use of solar panels in the agricultural sector, agrivoltaics, also known as agrophotovoltaics or agrisolar, is a technique that combines solar energy production with agriculture. This practice allows for the dual use of land for power generation and plant cultivation, offering benefits such as reduced water evaporation and crop protection against adverse climate conditions (Ordaz, 2022).

Although the adoption of agrivoltaic systems in Mexico is still incipient, areas with high potential for their implementation have been identified. For example, states such as Baja California, Yucatán, and Chihuahua present favorable conditions for the development of projects that integrate solar energy generation with agricultural activities (Gaona-Ponce *et al*., 2021). These systems could benefit rural regions, where agriculture is the main economic activity and access to electricity is still limited.

The general objective of this research is to evaluate the performance of hydrogenated nitrile butadiene rubber (HNBR) as an encapsulating material in silicon photovoltaic panels, analyzing its thermal and mechanical stability and its resistance to environmental degradation. It was studied to

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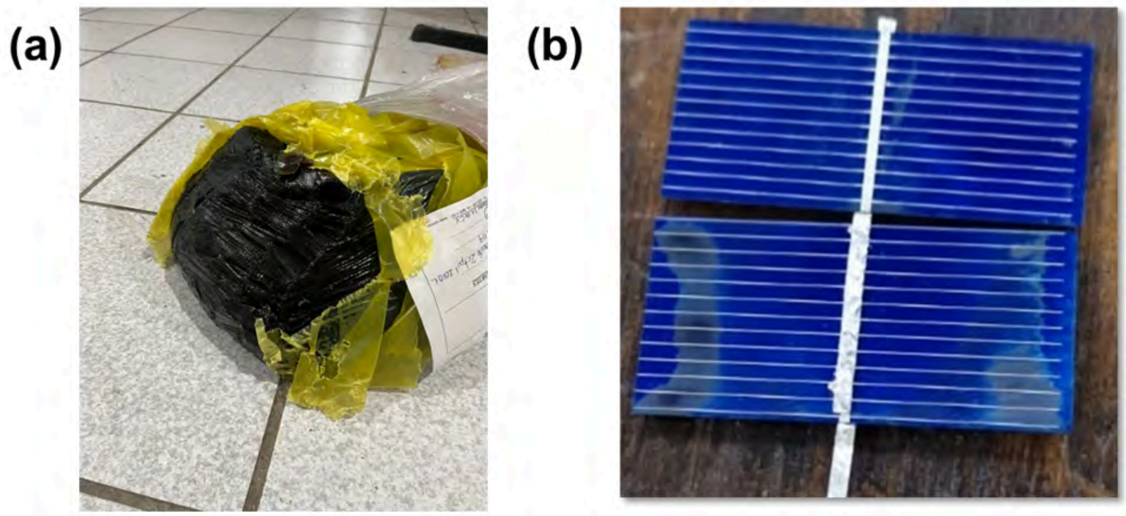
determine its feasibility as a substitute in photovoltaic applications, exploring its ability to improve the durability and efficiency of solar modules compared to conventional encapsulating materials.

The HNBR used here, commercially designated as Zetpol 2010 L, was obtained from the supplier Suministro de Especialidades SA de CV (Figure 1a). Commercial EVA, branded as Zanchen, was employed and obtained from the supplier Guangzhou Zanchen New Material Technology Co., Ltd. Monocrystalline silicon photovoltaic cells with an efficiency of 17% (Figure 1b) were used under standardized test conditions, ensuring an accurate comparison between the different configurations and types of encapsulant.

Figure 1. Photographs of commercial HNBR (a) and monocrystalline silicon cells (b)



Methodology. HNBR membranes were manufactured using a pressing process, controlling variables such as temperature and processing time to obtain a uniform film with a thickness of 0.6 mm. This value was chosen to maintain comparability with commercial EVA and to evaluate its behavior under similar conditions. HNBR membranes were fabricated in a Rositek manual press by applying a heat treatment at 175 °C without pressure for 2 min, then a pressure of 2 t at 218 °C for 4 min and finally, a cooling time of 2 min.

The thermal properties of HNBR were analyzed through differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The DSC analysis was performed with a TA Instruments Q-100 differential scanning calorimeter in a temperature range of -80 °C to 150 °C, and the TGA was performed on a TA Instruments Q-500 equipment; likewise, tests were performed at temperatures from room temperature to 800 °C. Both analyses were performed in a nitrogen atmosphere at a heating rate of 10 °C min.

These tests allowed us to evaluate its structural behavior in the face of temperature changes and determine its glass transition temperature (Tg), as well as the degradation of its polymeric structure under high temperature conditions. The application and fixation of the HNBR membranes in the cells was carried out by applying heat in a Workshore drying oven, model 2608, at a temperature of 170 °C and a drying belt speed of 100 rpm, which were the optimal conditions for the application of the encapsulant.

The mechanical and adhesion properties of HNBR and EVA were compared, obtaining five cells that were used as a model to carry out their electrical characterization. The electrical measurements consisted of readings of the voltage and current generated by the same cell, using a load with a resistance of 1 Ω with the capacity to dissipate 5 W of power; this was done under different environmental conditions of solar lighting to be able to evaluate the impact of the encapsulant on the electrical performance of the module. The output power of the cell used was 3.5 W under standard test conditions.

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A LabVIEW-based data acquisition system was used, which allowed us to record the variations in the electrical performance of the modules encapsulated with HNBR compared to those encapsulated with EVA. This technique facilitated the collection of data in real time, allowing a detailed analysis of the material's impact on the efficiency of the photovoltaic panel.

The data obtained in these tests allowed us to make a quantitative comparison between the performance of HNBR and EVA, determining the viability of HNBR as an alternative material for encapsulants in photovoltaic panels. Finally, the methodology followed throughout this work is schematically summarized (Figure 2).

Figure 2. Schematic representation of the methodology carried out.

Thermal properties of HNBR

Figure 3 shows the thermal characterization of the HNBR. Figure 3a presents the TGA curve, which indicates that HNBR begins its thermal degradation at temperatures above 450 °C. To obtain more precise information on thermal degradation, the weight loss derivative is represented (Figure 3b), where it was observed that the peak of greatest decomposition, in which the maximum percentage of weight loss is recorded, occurs at approximately 450 °C.

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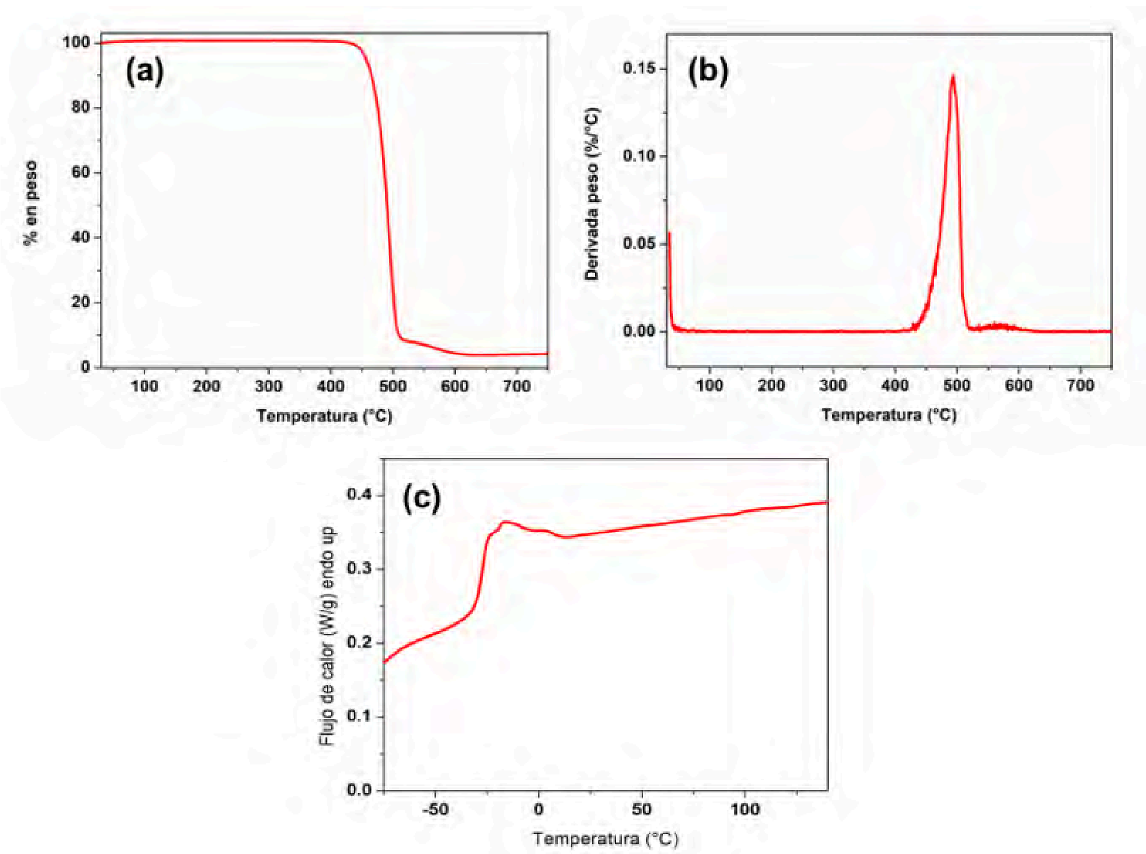
Figure 3. Thermal analysis of HNBR: a) TGA curve; b) weight loss derivative and c) DSC curve.



Finally, the DSC curve is presented (Figure 3c). This curve demonstrates the amorphous nature of the rubber and that it has a glass transition temperature of -26 °C. This value indicates that the material retains its flexibility even at low temperatures, making it ideal for applications in adverse climatic environments. Properties such as its Tg and thermal stability make HNBR a viable option for coatings on photovoltaic cells, where thermal stability and mechanical strength are essential.

This behavior shows a significantly higher thermal stability compared to EVA, which, according to the literature, begins to degrade at a temperature around 300 °C (Genesca, 2014). In contrast, the data presented show that HNBR presents a stability above 450 °C. This property makes HNBR a highly heat-resistant material, an alternative to EVA in applications where greater durability and thermal stability are required, such as in polymeric coatings for photovoltaic cells.

Thermal stability is essential, as the efficiency of solar panels decreases with increasing temperature. It has been observed that each 1 °C increase in ambient temperature can reduce the efficiency of the cell by between 0.25% and 0.5%, depending on the material used. An encapsulant with higher thermal resistance, such as HNBR, could mitigate this adverse effect (Espinosa-Ramírez *et al*., 2023).

In addition to thermal stability, resistance to moisture and UV radiation are critical factors in the durability of photovoltaic modules. Prolonged exposure to moisture can cause corrosion and delamination, while UV radiation can degrade the encapsulant, reducing optical transmission and therefore module efficiency.

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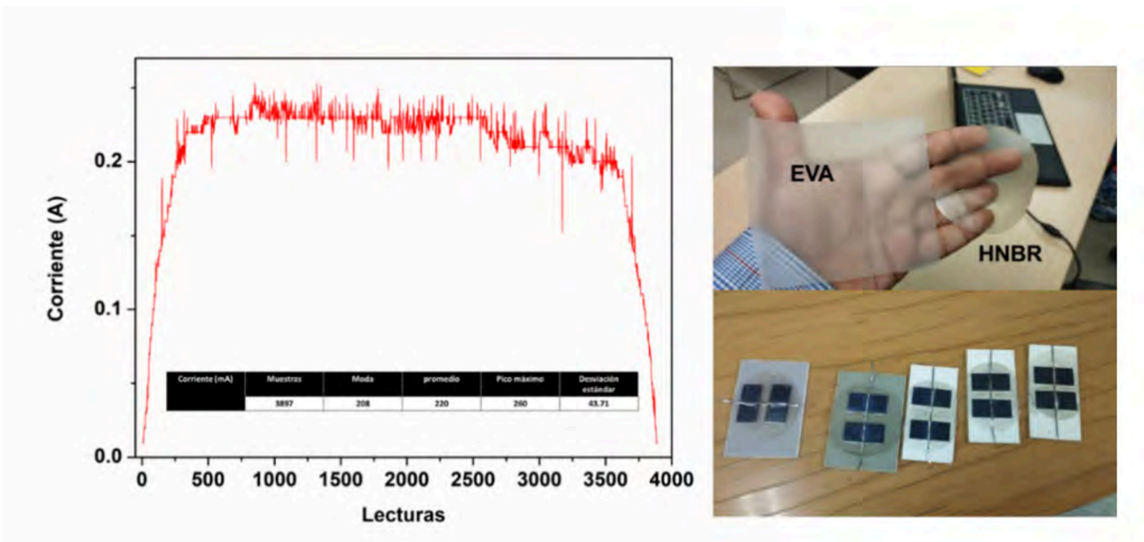
Although EVA offers certain advantages, its susceptibility to these factors limits its long-term performance (Säckl *et al*., 2024). HNBR, on the other hand, is reported to have greater resistance to moisture and UV degradation, which could translate into a longer lifespan and maintenance of energy efficiency (Agroui *et al*., 2016).

Tests on photovoltaic cells

The results of the measurements of the photovoltaic modules under real conditions are presented based on a total of 3987 measurements, where the cell generated an average current of 220 mA, with peaks of 260 mA and a mode of 208 mA in the measurements (Figure 4). These results suggest that the current passage through the HNBR polymer is comparable to that of other materials commonly used in industry, such as EVA, the values of which range from 210 to 240 mA (Badiee *et al*., 2016).

Figure 4. Current measurements in photovoltaic cells (left) and photographs of the transparency of the encapsulants and manufactured cells (right).



Data collected with the LabVIEW system indicated that modules encapsulated with HNBR maintained stable power output over time, even after being kept outdoors for a year. This suggests that HNBR not only improved the durability of the encapsulant but also allows optimal electrical performance to be maintained.

The ability of HNBR to maintain adequate performance in power generation suggests its viability as a polymer coating in photovoltaic applications. This performance, aligned with the modeling results, reinforces the idea that HNBR not only protects cells but also optimizes their operation by providing a level of transparency similar to that of materials already established in the market.

For this, Figure 5 shows photographs of the cells prepared with HNBR and EVA. It can also be observed that the level of transparency between HNBR and EVA is very similar, and the transparency of HNBR is even greater (Figure 5). This similarity suggested an equivalent optical behavior, supported by the generation efficiency observed in the cells and the direct comparison of the prototypes evaluated.

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Figure 5. Photographs of the photovoltaic cells with EVA and HNBR.

Conclusions

The results obtained in this study demonstrated that HNBR is a viable and highly competitive material as an encapsulant for silicon photovoltaic cells. Compared to EVA, HNBR exhibited superior thermal stability, with degradation temperatures exceeding 450 °C compared to 300 °C for EVA. In addition, electrical tests showed slightly higher performance of HNBR over EVA, which translates into a potential improvement in operational efficiency under standard conditions.

On the other hand, HNBR presented an optical transparency comparable to that of EVA and retained its physical-chemical properties after one year of environmental exposure, which confirmed its resistance to aging. These characteristics position this material as an alternative to replace EVA in demanding photovoltaic applications, with the potential to extend the life of the modules and optimize their performance in severe environmental conditions.

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