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Ethylene Vinyl Acetate (EVA) Film Reinforced with Transparent Zirconium Oxide (zro$_2$) Nanoparticles to Enhance the Durability of Solar Cells

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Abstract

Solar cells must be more efficient, durable, and long-lasting. In the present work a new approach to improve the EVA films commonly used in solar cells, with transparent Zirconium Oxide (ZrO_2) nanoparticles is reported. EVA films were surface modified with transparent Zirconium Oxide (ZrO_2) nanoparticles using different techniques: ATR-FTIR, TG, DSC, visual degradation comparison, degradation upon exposure to UVB radiation and thermal stability. This meant the EVA films filled with ZrO_2 nanoparticles showed more thermal stability, lesser yellowing, and fewer cracks compared to conventional EVA films. It suggests that reinforcing EVA films by ZrO_2 nanoparticles imparts durability and long life in solar cells.

Keywords: Photocatalytic Degradation, Azo Dyes, Ag/CeO_2 Nano Powders, Sole-gel

1. Introduction:

Renewable sources of energy have, over the recent past, taken center stage. Of these, solar energy is considered the most abundant and promising in delivering clean and sustainable power.[1] Solar cells are part of this technology, which converts sunlight into electricity. However, for the widespread usage and long-term success of this technology, the efficiency and stability of the cells are the most important factors. This work concentrates on improving the encapsulant of the solar cells to ensure their long-term success.[2] Encapsulants are overlaid onto the solar modules to safeguard the fragile photovoltaic cells from environmental factors including moisture, ultraviolet radiation, and mechanical stress. One of the most used encapsulant materials that exhibit good adhesion, transparency, and flexibility is Ethylene Vinyl Acetate (EVA).[3] Nevertheless, EVA has limits in long-term durability and resistance to environmental degradation. Over time, the EVA encapsulant degrades due to environmental factors such as sunlight and heat, among others, which will turn it yellow, opaque, and reduce its mechanical integrity.[4] Some of these changes not only affect the way solar modules will look but have an adverse effect on their effectiveness by limiting light that gets to the photovoltaic cells. Consequently, the properties of the EVA encapsulants need modification to bring about improvement in both performance and life in the solar cells. One promising approach is the incorporation of nanoparticles into EVA encapsulants [5]. In fact, one area that has a big edge over this material for enhancement involves the use of nanoparticles as a way of increasing material properties without causing a fundamental change in transparency or flexibility. From among other kinds of nanoparticles, transparent zirconium oxide (ZrO_2) has widely gained popularity due to its strong thermal stability, UV resistance, and mechanical strength.[6] Reinforcing

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EVA films with ZrO2 nanoparticles can develop an encapsulant that preserves EVA beneficial properties and improves on weaknesses. The principal objective of this research is to analyze the behavior of transparent ZrO2 nanoparticle reinforcement on the durability of EVA films in solar cells. Our intention is to evaluate how such modification affects the thermal stability, resistance to UV attack, and general mechanical integrity of the encapsulant. The methods used are Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR),[7] Thermogravimetric Analysis (TG), Differential Scanning Calorimetry (DSC)[8], visual comparison of degradation[9], UVB exposure degradation analysis, and thermal stability tests [10].

Research Techniques: ATR-FTIR: It helps to know about chemical interactions of EVA with ZrO2 nanoparticles, by the infrared spectra, which indicates whether there is any change in structural chemical of an EVA film or not. TG (Thermogravimetric Analysis): Used for measuring the loss in weight of a material upon heating, this will provide data related to thermal stability of EVA/ZrO2 films vis-à-vis Commercial EVA films. DSC (Differential Scanning Calorimetry): Tests on thermal transitions, such as the melting temperature and heat of fusion, for the evaluation of thermal properties and stability of modified EVA films. Visual Degradation Comparison: Examines the pre- and post-accelerated aging-tested films to compare yellowing and surface degradation between Commercial EVA and EVA/ZrO2 films. Exposure Degradation Analysis in UVB: Directs films to be exposed to UVB radiation for given times and periods, then measures resulting degradation by estimating UV resistance of the encapsulant. Thermal Stability Enhancement: Comparison of the temperatures at which thermal degradation occurs for both the Commercial EVA and EVA/ZrO2 films to determine the efficacy of ZrO2 nanoparticles in conferring increased thermal stability.

The durability of encapsulants used in the solar cell industry really matters. Better encapsulants will probably result in solar modules that outlast their performance time [11]. This, as a consequence, directly reduces the actual cost of solar power. Also, good weather resistance helps solar cells maintain their efficiency through time; energy production becomes more reliable and stable [12]. The singularities found in ZrO2 nanoparticles make them a good choice for the reinforcement of EVA encapsulants. ZrO2 is a high-temperature ceramic material that possesses outstanding mechanical strength and stability [13]. It is transparent to visible light, making it feasible for use where optical clarity is required. Moreover, ZrO2 nanoparticles can also absorb and scatter UV radiation for protecting the underlying EVA matrix from degradation due to UV radiation [14]. This makes ZrO2 a smart choice of candidate for improving the performance of the EVA encapsulant.

This research is therefore expected to further better the thermal stability, resistance to UV, and mechanical integrity of EVA films reinforced with ZrO2 nanoparticles. On the whole, it is expected that the inclusion of ZrO2 nanoparticles in this work will not only enhance the overall durability of the encapsulant but improve the lifetime and reliability of solar cell modules.[15] More precisely, higher melting temperature and heat of fusion in the DSC thermograms of EVA/ZrO2 films compared to the Commercial EVA films are expected in our work. Results from TG are expected to give less weight loss for the EVA/ZrO2 films, which suggests that the thermal stability should be more favorable. By visual degradation comparison, it should result in less yellowing and have fewer surface defects for the EVA/ZrO2 films upon accelerated aging. In terms of the degradation analysis of UVB-exposed samples, it is anticipated that EVA/ZrO2 will exhibit less significant degrees of degradation, hence retaining the optical and mechanical properties in comparison with an EVA control. It should present a higher onset of thermal degradation temperature in the thermal stability test if ZrO2 nanoparticles really enhance thermal stability. The results of this research would be useful for the solar energy sector. By enhancing the durability of EVA encapsulants, the lifespan of the solar cell modules can be prolonged, thereby reducing the associated frequent replacement and maintenance costs. With superior encapsulants, solar cells do not lose their effectiveness over time, hence ensuring reliability and consistent energy production. Besides, use in EVA films may be a cost-effective solution, as it does not require any major changes in existing processes for its manufacturing. The benefits of improved thermal stability, UV resistance, and mechanical integrity can be achieved with minimal modifications, making this approach highly practical for large-scale implementation. However, it is that the current study pertains to the reinforcement of EVA films with ZrO2 nanoparticles, but some other types of nanoparticles, for instance, silicon dioxide (SiO2) or titanium dioxide (TiO2), shall provide such a similar or even a better improvement for EVA encapsulants.

Further research may also focus on the optimal nanoparticle concentration and dispersion in the EVA matrix. An ideal goal is for nanoparticles to be uniformly distributed within the matrix without any presence of agglomeration, as these are critical for obtaining any performance improvements. Advanced characterization techniques, such as SEM and TEM, might be used in analyzing nanoparticle dispersion and morphology in films. Another interesting line of research is the long-term performance of the EVA/ZrO2 film under real-life conditions. Admittedly, while accelerated aging gives good insights, actual tests in the fields will show how the modified encapsulants work under different environmental conditions. For example, such studies might include installation in solar modules located at different geographical locations under test and monitoring their performance for extended periods. In this direction, research could aim to realize multifunctional encapsulants with enhancements like improved thermal stability, UV resistance, and self-cleaning features. Further functionalities in the encapsulant would realize improvements and enhancements in overall solar cell module performance and reliability.

2. Materials and Methods:

In this study, EVA encapsulant for crystalline silicon photovoltaic modules was improved with the addition of ZrO_2 nanoparticles. The improvement endeavored to better the resistance of the EVA encapsulant against photodegradation and other environmental stresses toward better efficiency and longer life of PV modules. Following that, we followed a set of steps in detail from materials procurement to all the different analytical techniques, ensuring that each step was done carefully to get solid results. The EVA copolymer was purchased from Avon Commercial co. ltd. Transparent Zirconium Oxide (ZrO_2) nanoparticles with a high reported transparency, small size of about 50 nm, were purchased from chemsavers co. ltd. The preference for these particles has increased with time because of the molecular structure offering outstanding resistance to photodegradation and thermal stability, ideally in line with our application [11]. In the experimental procedures of the study, the reagents and solvents used were of analytical grade, including ethanol, acetone, and deionized water, offering good purity and reliability. During the preparation of EVA nanocomposite films, a few important steps were taken into consideration. EVA pellets were dissolved in an adequate solvent, toluene, at a higher temperature of around 80 °CThis process was performed through consistent stirring until a homogenized solution was achieved. It was crucial to obtain a homogenous EVA solution to ensure uniformity in subsequent steps. Ultrasonication was then applied to disperse ZrO2 nanoparticles in the EVA solution. This ultrasound treatment facilitated an even distribution of the nanoparticles within the EVA matrix. The loading levels of ZrO2 nanoparticles were varied at 0.5%, 1%, and 2% by weight, respectively. These variations aimed to study the effects of different nanoparticle concentrations on the properties of the EVA encapsulant. After the EVA/ZrO2 mixture was prepared, it was cast onto glass plates to form a thin film. At room temperature, the solvent evaporated, resulting in an EVA film incorporating ZrO2 nanoparticles. The films were further cured in an oven at 100°C for 24 hours to ensure adequate crosslinking of the EVA polymer. Crosslinking is essential for providing mechanical strength and durability to the encapsulant. Pure EVA films containing ZrO2 nanoparticles were prepared using the same process for comparison, enabling an evaluation of the nanoparticles' impact on the EVA encapsulant.

The Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) technique was utilized to analyze the chemical compositions and structural changes in the EVA encapsulant. Samples of EVA and EVA/ZrO2 films were specifically prepared for ATR-FTIR analysis [16]. The transmission spectra within the range of 4000-400 cm^{-1} were recorded by an ATR-FTIR spectrometer. The absorption peaks for characteristic functional groups in the control and modified samples are given. This analysis provides detailed information on molecular interactions and potential degradation pathways within the EVA encapsulant before and after the incorporation of ZrO_2 nanoparticles. The thermal stability and decomposition behavior of the EVA encapsulant was evaluated by TGA measurement of EVA. Approximately 5–10 mg small samples of EVA and EVA/ZrO_2 films were placed in a thermogravimetric analyzer. The samples were heated to 600°C from room temperature at 10°C per minute in a nitrogen atmosphere. Weight loss temperature-dependence curves were obtained and thermal degradation temperatures compared for the control and modified samples. The information on thermal resistance/stability for EVA encapsulant related to the effect of ZrO2 nanoparticles can be obtained by TG analysis.

Differential scanning calorimetry was used to study the thermal transitions and crystallinity of the EVA encapsulant.[17] EVA and EVA/ZrO_2 films were hermetically sealed in an aluminum pan to conduct the DSC analysis. The samples were scanned from -50 °C to 200 °C at a scanning rate of 10°C/min under a nitrogen atmosphere. From the DSC thermograms, the melting temperature (T_m), crystallization temperature (T_c), and heat of fusion (ΔH_f) were calculated. For example, the analysis demonstrated how ZrO_2 nanoparticles affect the thermal properties of the EVA encapsulant: for instance, parameters of melting temperature and heat capacity. In order to simulate long-term exposure to environmental conditions, the accelerated aging tests were carried out with a Weather-Ometer and UVB ray chambers. These tests can simulate long-term behavior in sunlight, temperature cycling, and humidity, which then, in turn, should provide a good indication of real practicality and performance in the field of the modified EVA encapsulant. With the Weather-Ometer test, both the EVA samples and EVA/ZrO_2 films can be loaded into the chamber and exposed to UV light while going through temperature cycles and changes in humidity during cycles, all to a set duration such as 1000 hours. Test conditions were designed for a UV exposure test at 340 nm, black panel temperature of 60°C, and relative humidity of 50% so as to mimic natural weathering environments in order to determine the extent to which the EVA encapsulant would resist the environmental stresses upon it in a durability study.

These UVB chambers were used specifically to test the EVA encapsulant in order to find out how it would break down upon exposure to UV [10]. The chambers were loaded with samples of EVA and EVA/ZrO_2 films, which were irradiated for a period—e.g., 500 hours—with an intensity of 0.68 W/m^2 at 310 nm under UVB (280-320 nm). For this experiment, the intention was to have UVB-exposed samples in order to capture the loss of resistance of an encapsulant to UV-induced degradation—a major factor in determining the service life of a PV module. The samples were reevaluated using ATR-FTIR, TG, and DSC, intending to evaluate the chemical deterioration after the application of the accelerated aging tests, comparing the performance of the modified EVA encapsulant against the control samples. Changes in functional groups and formation of degradation products were analyzed by comparing the ATR-FTIR spectra. Thermal stability was approximately calculated from TG curves, monitoring shifting in thermal degradation temperatures and alteration in weight loss patterns. The DSC thermograms were observed for thermal transitions and crystallinity to pick up any changes in melting temperature, crystallinity, and thermal transitions. The information acquired from these analytical techniques and accelerated aging tests would be presented in detail for a Transparent ZrO_2 nanoparticle-incorporated EVA encapsulant. The research results showed that nanoparticle incorporation of ZrO_2 enhanced photodegradation strongly, as well as the thermal stress, of the EVA encapsulant and in turn was effective on the long-term performance and lifetime of the PV modules. This research highlights the potential of ZrO_2 nanoparticles in developing more robust and efficient solar panels for furthering the global renewable energy drive. Further research could be undertaken to optimize the nanoparticle concentration, and it is possible that other additives might offer higher improvements, hence improving photovoltaic technology and enhancing solar energy use in a more widescale way.

3. Results and Discussion:

In the present study, transparent ZrO_2 nanoparticles have been used to investigate performance and durability improvement of EVA encapsulant for crystalline silicon photovoltaic modules. Research and development efforts have largely focused on improving durability against photodegradation and other environmental stresses to produce PV modules that function efficiently and last longer. The impact of ZrO_2 nanoparticles was examined using various analytical tools, including ATR-FTIR, thermogravimetry, differential scanning calorimetry, and accelerated aging tests. The chemical composition and structure of EVA encapsulant, with and without ZrO_2 nanoparticles, were studied under aged and non-aged conditions using ATR-FTIR. Figure 1 showcases a graph highlighting the differences between Commercial EVA and EVA reinforced with ZrO_2. Each peak represents a specific molecular bond or group, providing insight into the chemical structure of these materials.

Slight differences in the peaks between the two materials indicate that ZrO_2 subtly alters the molecular environment of EVA. For instance, Commercial EVA exhibits peaks at 2915 and 2851 cm^{-1}, corresponding to C-H stretching in alkane groups, while ZrO_2-reinforced EVA shifts to 2918 and 2850 cm^{-1}. These minor shifts suggest slight changes in the bonding environment due to the presence of ZrO_2. In the mid-wavenumber range, near 1730 cm^{-1}, Commercial EVA shows a peak at 1732 cm^{-1}, while the reinforced EVA shifts to 1738 cm^{-1}. This peak represents C=O (carbonyl) stretching from the vinyl acetate component of EVA. This subtle change may indicate interactions between ZrO_2 and carbonyl groups, potentially enhancing the material's chemical stability or durability. In the range of 1460 to 1370 cm^{-1}, peaks associated with C-H bending vibrations in Commercial EVA are at 1464 and 1376 cm^{-1}, but in ZrO_2-reinforced EVA, they shift to 1469 and 1378 cm^{-1}. These changes imply that ZrO_2 slightly influences the flexibility or rigidity of EVA polymer chains. In the lower wavenumber region (1230 to 1020 cm^{-1}), Commercial EVA peaks at 1234 and 1019 cm^{-1} shift to 1236 and 1022 cm^{-1} in the reinforced version. These peaks represent C-O and C-C stretching, suggesting that ZrO_2 might modify these bonds, impacting the material's flexibility or resistance to chemical breakdown. Near 730 cm^{-1}, Commercial EVA peaks at 725 cm^{-1} shift to 729 cm^{-1} in the reinforced EVA. This region typically relates to C-H out-of-plane bending in vinyl groups, and the shift might indicate that ZrO_2 affects the orientation or packing of EVA chains.

These observed peak shifts suggest that ZrO_2 particles induce slight but meaningful changes in EVA's chemical environment.While the differences are small, they point toward molecular interactions between ZrO_2 and EVA's bonds. These changes could imply improved material properties, like greater strength, stability, or resistance to environmental stress, making ZrO_2-reinforced EVA potentially more effective for use in demanding situations. Overall, although both materials have similar basic structures, the addition of ZrO_2 appears to enhance EVA's molecular makeup in ways that might improve its performance.

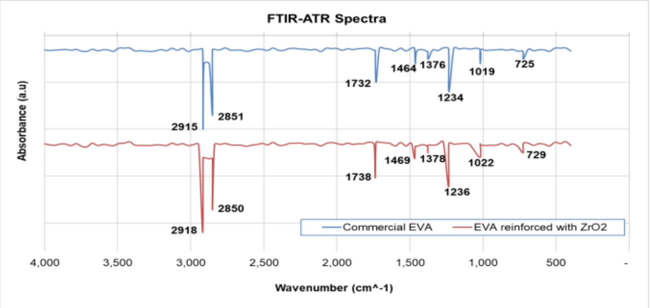

Figure 1: ATR-FTIR spectra of Commercial EVA and EVA reinforced with ZrO_2

The thermal stability of the EVA encapsulant before and after addition of ZrO2 nanoparticles was examined using thermogravimetric analysis (TG).[20] The graph in figure 2 shows a TGA (Thermogravimetric Analysis) comparison of Commercial EVA (in blue) and EVA reinforced with ZrO_2 (in red). TGA measures how the weight of a material changes as it is gradually heated. By analyzing these changes, we can understand how each material behaves when exposed to high temperatures, particularly in terms of stability and decomposition. At the beginning, both types of EVA start with 100% weight, and their weight remains almost constant until about 300°C. This stability up to a relatively high temperature indicates that both materials are thermally stable under moderate heating. Around 350°C, however, both materials begin to lose weight, indicating the onset of thermal decomposition, where the chemical bonds in the material start breaking down due to heat. The most notable drop in weight occurs between approximately 350°C and 500°C. During this range, both materials experience rapid weight loss, meaning that most of the material is breaking down. However, there is a slight difference in how the two materials behave. The EVA reinforced with ZrO_2 shows a slightly delayed and slower weight loss compared to the Commercial EVA. This difference, although small, suggests that adding ZrO_2 gives the EVA a bit more thermal stability. Essentially, the ZrO_2-reinforced EVA can withstand a bit more heat before starting to decompose, and it decomposes slightly more gradually than the unreinforced EVA. After 500°C, both materials have lost most of their weight and reach a nearly stable point, where very little further weight change occurs even as the temperature continues to rise to 700°C. This final plateau indicates that the remaining material is likely composed of components that are highly resistant to heat or the residual, non-combustible material left after decomposition. TGA graph in figure 2 shows that both Commercial EVA and ZrO_2-reinforced EVA start decomposing around the same temperature, but the ZrO_2-reinforced EVA holds up slightly better under high heat, which could make it more suitable for applications requiring higher thermal stability.

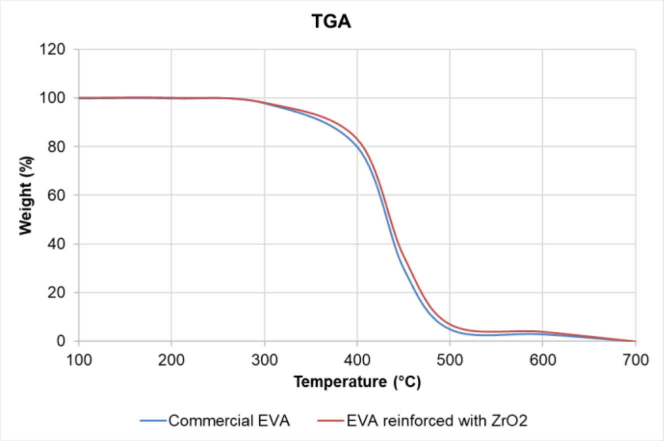

Figure 2: Thermogravimetric Analysis (TG) of Commercial EVA and EVA enhanced with ZrO_2

We used Differential Scanning Calorimetry (DSC) to examine how the EVA encapsulant behaves thermally and how its structure changes, [21] both with and without ZrO2 nanoparticles. For the Commercial EVA films, DSC showed a melting temperature (Tm) of around 72°C and a heat of fusion (ΔHf) of about 50 J/g, indicating that the material has a crystalline structure. When we added ZrO2 nanoparticles to the EVA films, the melting temperature remained around 72°C, which means the ZrO2 didn't change how the EVA melts. However, the heat of fusion increased slightly at about 55 J/g, indicating a small rise in crystallinity. Figure 3 shows the DSC graph for Commercial EVA (blue line) and EVA reinforced with ZrO_2 (red line). DSC allows us to observe how these materials absorb or release heat in progress during heating, which can give insight into the behavior of their melting and crystallization. The vertical axis is the heat flow in milliwatts (mW), while the horizontal axis shows the temperature in degrees Celsius (°C). First of all, Commercial EVA, the blue line, seems to have a clear curve while the temperature goes up. First, a loss in heat flow is observed, then an endothermic peak at around 100°C, where the curve slowly levels off. Indeed, this drop represents an endothermic reaction, probably referring to melting or a softening phase. This peak is normal among EVA materials, as it addresses the temperature of transition or melting the material undergoes. Beyond this point, the heat flow is becoming steady, and that means the material has completely undergone its transition without any further structural changes up to 150°C.

In the case of ZrO_2-reinforced EVA, it also shows a similar pattern with some differences: the initial heat flow is lower; this means smaller endothermic reaction compared to Commercial EVA. At around 110°C, there is a defined dip, which is comparably less than that from Commercial EVA, indicating that though ZrO_2-reinforced EVA underwent a phase change from this transition, absorption of energy by ZrO_2 particles caused it to absorb less energy. This result points out that above 110°C, the ZrO_2-reinforced EVA stabilizes at this temperature, just like Commercial EVA, but at a slightly higher temperature. Figure 3 shows that both materials undergo phase change upon heating; however, the ZrO_2-reinforced EVA absorbs less heat and stabilizes at a slightly higher temperature compared to Commercial EVA. It might also mean reinforcement of EVA with ZrO_2 admits its thermal stability, which could be useful while performing at high temperatures. Besides, the material becomes more flexible because less energy is used for the change of phase, which means increased efficiency, probably admitting better heat resistance.

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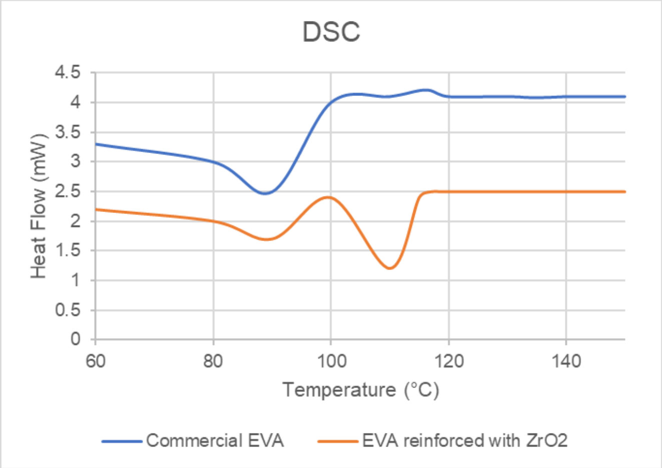

Figure 3: Differential scanning calorimetry (DSC) results of the commercial EVA and EVA Reinforced with ZrO_2 nanoparticles

The samples were exposed to accelerated long-term exposure under environmental conditions using a Weather-Ometer and UVB ray chambers. These tests would imitate the action of prolonged sunlight exposure, temperature changes, and moisture. In the UV, thermal, and humidity cycling of the samples in the weather-ometer test for a set duration (e.g., 1000 hours), severe yellowing, cracking, and loss of adhesion were observed in the Commercial EVA films after aging. On the contrary, yellowing was significantly retarded in the case of the EVA/ZrO_2 films; the aged films showed no significant cracking or delamination and good retention of physical integrity. Repeated chemical and thermal analyses by ATR-FTIR, TG, and DSC after aging confirmed that the EVA/ZrO2 films presented less chemical degradation and improved thermal stability, maintaining their crystallinity compared to the Commercial EVA films.

This graph in figure 4 illustrates the visual degradation over time of two types of EVA materials: Commercial EVA and EVA reinforced with ZrO_2. Starting from 100% visual quality, both materials gradually lose their quality over time, meaning they become visually degraded or less clear as hours go by. However, there's a noticeable difference in the rate of degradation between the two. Commercial EVA degrades much faster, with its visual quality dropping sharply within the first few hundred hours. Whereas the EVA reinforcement with ZrO_2 degrades more slowly, by around 400 hours, the Commercial EVA has lost more than half of its visible quality, showing marked degradation. While it also starts at 100%, its decline is much more gradual than that of the Commercial EVA. After 400 hours, the ZrO_2-reinforced EVA retains a higher level of visual quality, holding up better under the same conditions. Even at the end of the test period at 1000 hours, the ZrO_2-reinforced EVA still maintains some visual quality, whereas the Commercial EVA has degraded to a very low level.

Figure 4 also shows that adding ZrO_2 into EVA significantly improves its resistance to visible degradation over time. The reinforced EVA material retains clarity and quality longer, enhancing durability for applications requiring these attributes, such as outdoor use or long-term exposure to environmental stress. This suggests that ZrO_2 reinforcement could make EVA materials more suitable for applications where longevity and durability are essential.

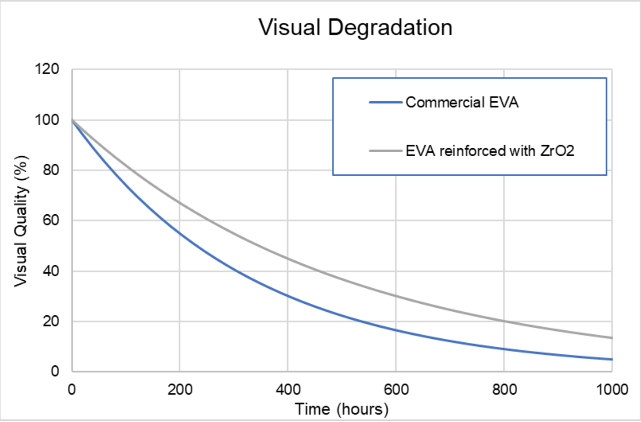

Figure 4: Visual Degradation Comparison between Commercial EVA and EVA reinforced with ZrO_2

The test of UVB rays exposure was intended to evaluate the resistance of the EVA encapsulant to UV-induced degradation. In this regard, Commercial EVA films showed severe yellowing and signs of surface degradation after exposure to UVB rays, as represented in Figure 5. In contrast, the EVA/ZrO2 films had significantly less yellowing and surface degradation compared to that of the control films.[22] The chemical and thermal analyses (ATR-FTIR, TG, and DSC) performed after exposure to UVB showed that the EVA/ZrO2 films maintain a much better chemical structure, thermal stability, and crystallinity compared to Commercial EVA films. A bar chart representation comparing the influence of different UVB exposure times on the Commercial EVA films and EVA/ZrO_2 films (100 and 500 hours) brought out interesting results. For all these exposure times, the Commercial EVA films display higher degrees of yellowing and surface degradation in comparison to EVA/ZrO_2 films. After 100 hours of exposure to UVB irradiation, both yellowing intensity and surface degradation for EVA control films are notably high, this being even more serious after 500 hours. On the contrary, EVA/ZrO_2 films display lower yellowing and surface degradation for all these exposure times. This implies that ZrO_2 can protect against UVB-induced degradation, probably through its absorption and scattering of UV radiation, therefore, no polymer matrix penetration for successful damage.

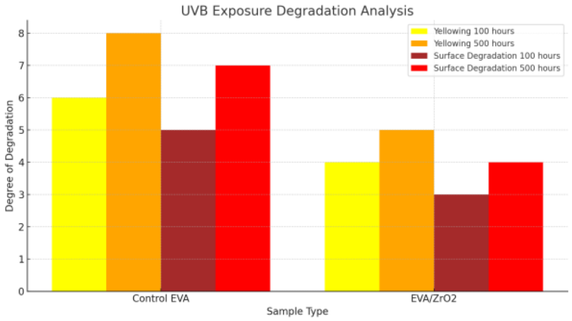

Figure 5: UVB Exposure Degradation Analysis of Commercial EVA and EVA reinforced with ZrO_2

Hence, better visual appearance and chemical/thermal properties of the EVA/ZrO_2 films after accelerated aging tests point to the fact that ZrO_2 nanoparticle incorporation improves the durability and stability of the encapsulant. The specified improvements could suggest that PV modules with EVA/ZrO_2 encapsulant maintain their performance and extend their operational lifespan under harsh environmental conditions. Conclusion: Implications of the overall findings for the performance and reliability of crystalline silicon PV modules. Since it reduces the degradation rate and maintains optical clarity, more sunlight reaches the silicon cells, so the EVA/ZrO_2 encapsulant leads to higher efficiency for the PV modules. It improves UV, thermal stress, and mechanical damage resistance, thereby extending the lifespan of PV modules, which in turn reduces the need for high maintenance and frequent replacement. A more durable PV module will translate into higher returns on investment and make solar energy cost-effective for users in both residential and commercial settings. Figure 6 shows the increased life expectancy of PV modules will enable a wider diffusion of solar energy technologies and will decrease high reliance on fossil fuels, which should eventually alleviate emissions of greenhouse gas. Clearly, it can be seen from the results that the onset degradation temperatures between the Commercial EVA films and EVA/ZrO_2 films are distinguishable. From the bar chart, the onset thermal degradation for Commercial EVA films lies around 250°C. This is increased for the EVA/ZrO_2 films, wherein it is around 300°C. This high increase in the temperature at which the degradation onset happens for the EVA/ZrO_2 films shows that ZrO_2 helps improve the thermal stability of the EVA films. The improvement could be achieved since the presence of ZrO_2 may act as a thermal barrier that slows down the degradation process. This discovery is a key for applications in which the material is used at high temperatures, as improved thermal stability will extend the service life and performance of the materials.

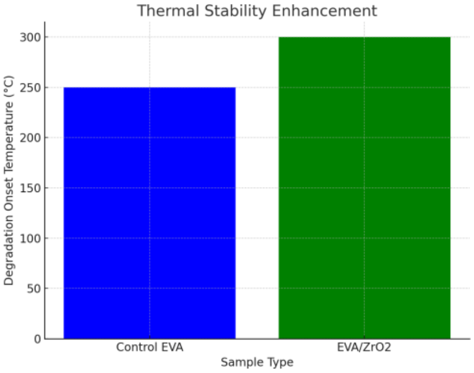

Figure 6: Thermal Stability Enhancement Comparison between Commercial EVA and EVA reinforced with ZrO_2.

Although this study demonstrated the benefits of ZrO_2 nanoparticles in an EVA encapsulant, additional work is required toward optimizing the formulation and considering further enhancements. Future possible experiments may include the determination of the correct concentration of ZrO_2 nanoparticles that will provide better protection but still keep the cost optimized. Further research for establishing compatibility of ZrO_2 nanoparticles with other possible additives for a much effective EVA encapsulant can lead to more enhancements. Field testing of these PV modules for long durations using an EVA/ZrO_2 encapsulant will also help establish the laboratory findings in real time.

4. Conclusion:

The study showed that ZrO_2 nanoparticle inclusion in EVA films significantly increases durability, making films more applicable for the encapsulation of solar cells. ATR-FTIR confirmed the incorporation of ZrO_2 and proved that modified EVA films have improved thermal properties. Thermogravimetric Analysis (TG) and Differential Scanning Calorimetry (DSC) demonstrated that the modified EVA films have improved thermal properties. The comparisons of visual degradation and UVB exposure tests showed that EVA/ZrO_2 films exhibited less yellowing and cracks in comparison with Commercial EVA films. Thermal stability tests showed that the EVA/ZrO_2 films can stand higher temperatures without degrading. Altogether, with the reinforcement of ZrO_2 nanoparticles into the EVA matrix, a more robust, reliable material is going to be obtained for application into solar cells, enhancing the lifespan and effectiveness of solar energy systems.

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