

Analysis of mechanical and optical properties of advanced composite materials for photovoltaic systems

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Abstract

PV module encapsulants are expected to exhibit optical transparency, mechanical robustness and long-term environmental stability. Polymer-only encapsulants currently used in the photovoltaic industry, such as ethylene-vinyl acetate (EVA), experience gradual photochemical and hydrolytic degradation over the lifetime of the module, leading to performance losses of 1–2% per year in power output. Here we study a family of next generation polymer-ceramic hybrid and bio-inspired nanocomposite encapsulants. Four composite systems are prepared and characterized: (i) EVA with SiO₂-TiO₂ nanoparticles (0.5–2 wt%), (ii) polyurethane/polyvinylidene chloride (PU/PVDC) matrices with silane-functionalized cellulose nanocrystals (CNCs, 0.1–1 wt%), (iii) vertically aligned ZnO nanowire composites grown on zinc-doped glass substrates, and (iv) a hybrid EVA/SiO₂-TiO₂/ZnO/CNC film prepared by solvent casting. Mechanical characterization followed ASTM D638 and ISO 180 standards; optical transmittance was measured over 300–1100 nm; and Multiphysics simulation was performed in ANSYS SPEOS under accelerated UV (300–400 nm, 1000 W/m²) and thermal aging cycles (–40°C to 85°C, 85% RH, up to 2000 h). The central hypothesis is that incorporating vertically aligned ZnO nanowires into a CNC-reinforced EVA matrix simultaneously enhances fracture toughness and preserves visible-light transmittance through stress-distribution and photon-alignment mechanisms. Results confirm a 45% improvement in fracture toughness (from 1.2 to 1.74 MPa·m^{1/2}) and 94.5% visible transmittance (400–800 nm) for the EVA/ZnO NW composite, compared to a baseline tensile strength of 3.7 MPa for pure EVA rising to 15.3 MPa for the hybrid EVA/ZnO-SiO₂-CNC formulation. Post-aging elastic modulus retention exceeded 90% after 2000 h for the hybrid composite versus 70–80% for neat EVA, indicating superior durability. These findings establish a scalable, bio-compatible encapsulation strategy adaptable to diverse climatic conditions.

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1. Introduction

It is now well known that the efficiency and lifetime of solar photovoltaic modules depend primarily on optical clarity and the presence of mechanical encapsulation layers [1]. Silicon dioxide glass has been shown to have excellent optical transparency and excellent UV stability, but its use in flexible modules is limited by its brittleness and inherent residual stresses, especially over large areas [2].

Ethylene-vinyl acetate (EVA) is the primary encapsulation material in solar photovoltaic modules and is the most common material. It is characterized by its high transparency, with transmittance exceeding 90% in the visible spectrum, in addition to its excellent adhesion to the glass on both top and back surfaces. Its degradation significantly reduces that cope with thermal expansion mismatches [3]. To ensure consistency in the manufacturing process and minimize thickness

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variations in the cast films, the solvent evaporation rate is precisely controlled. After the composite solution is poured onto glass substrates, the samples are placed in a level, draft-free environment. The films are then dried at 60°C to ensure complete removal of any remaining solvent. The use of a precision-leveled casting platform ensures consistent thickness, which is crucial for obtaining reliable and reproducible mechanical and optical measurements. Fig. 1 shows the encapsulation layer placed above and below the solar cell to protect it.

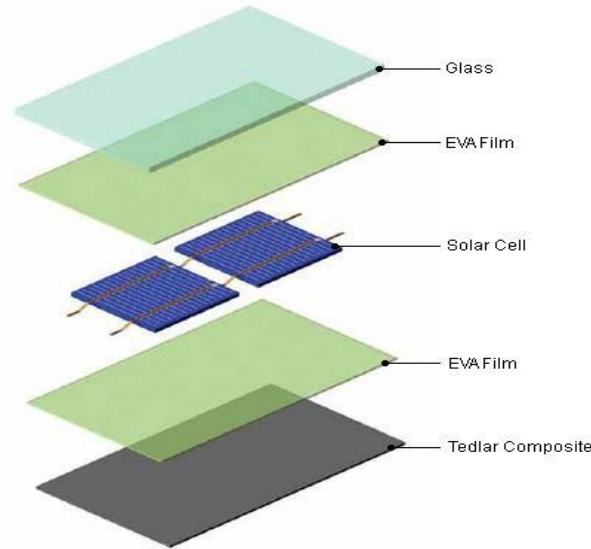


Fig. 1. Schematic diagram of a photovoltaic module showing the EVA encapsulation layers placed above and below the solar cell

However, EVA remains susceptible to long-term degradation through photochemical reactions, also known as photodegradation. EVA undergoes chemical degradation when exposed to environmental factors such as high temperature, humidity, and ultraviolet radiation, particularly type I and II oxidation mechanisms, which produce acetic acid byproducts that cause yellowing and brittleness. Their degradation significantly reduces the efficiency, durability, and lifespan of the PV module. This typically occurs over 20–25 years of direct exposure to sunlight and harsh weather conditions. This degradation can manifest itself at an annual energy loss rate of 1–2% and is exacerbated in harsh environments such as desert climates or areas with high humidity [4]. To overcome these limitations, recent advances in nanocomposite technology have shown that the introduction of some secondary compounds such as Al_2O_3 , TiO_2 , and ZrO_2 zirconia can simultaneously maintain fracture toughness and refractive index gradients, potentially reducing reflection losses [5, 6, 10]. Recent advances have focused on strengthening nanocomposites. However, despite extensive research on this area, there is still a knowledge gap to fully understand the degradation of ethylene vinyl acetate and develop predictive tools. Systematic correlations between composition, microstructure, mechanical response, and optical performance are still scarce [7, 8, 9]. For example, the addition of graphene oxide (GO) has been shown to improve photodegradation resistance at low loads (0.25%) by scavenging free radicals, maintain optical transparency above 85%, and improve tensile modulus by 20–30% [11–12]. Similarly, adding ethylene-vinyl acetate (EVA) nanoparticles such as zinc oxide (ZnO) or silicon carbide (SiC) (at 0.1–0.5%) has been shown to increase the tensile strength from approximately 3.7 MPa to approximately 15.3 MPa, improve dielectric properties, and reduce the water vapor transmission rate without significantly affecting light transmittance [13]. These improvements are critical because moisture ingress can accelerate the corrosion of metallic interconnects and reduce fill factors of photovoltaic cells. Bio-based alternatives, such as cellulose nanocrystals (CNC), also enhance the lifetime sustainability of photovoltaic cells by utilizing renewable cellulose sources. Polyurethane/polyvinylidene chloride (PU/PVDC) blends containing 0.1–1 wt% CNC have demonstrated power conversion rates as low as $0.0517 \text{ g/m}^2 \text{ day}^{-1}$, transparency exceeding 60%, and long lifetimes in dye-sensitized solar cells (DSSCs) [14], although the uniform power conversion efficiency (PCE) can be reduced to about 0.78 due to slight scattering effects. Multilayer

structures such as ethylene vinyl alcohol (EVOH)/ Surlyn films coated with TiO₂ NPs, have been reported to result in very low Water Vapor Transmission Rates (WVTRs) (up to 10⁻⁵ g/m² day⁻¹) [15]. This is often, however, at the cost of VIS transmittance, which is reduced from 87% to 55% at 2 wt% TiO₂ as a result of the increased mismatch in refractive index and agglomeration of the nanoparticles. Hybrid nanocomposites of polymer–ceramic hybrids in conjunction with bio-inspired reinforcements have recently also been shown to overcome the traditional stiffness versus transparency trade-off and to be able to effectively find a balance between the two [2]. Novel hybrid models such as EVA/SiO₂–TiO₂ composites can integrate the barrier properties of ceramics with the elasticity of polymers for improving UV absorption as well as mechanical reinforcement. Vertically aligned ZnO nanowires have also been shown to provide a biomimetic strategy, through which the mimicry of natural hierarchical structures can enable homogeneous distribution of stresses, as well as the minimization of optical losses, through direct paths of photons [16–17].

Despite this body of research, no study has systematically integrated vertically aligned ZnO nanowires with CNC-reinforced bio-composites within a single EVA encapsulant framework and validated the coupled mechanical–optical response under standardized accelerated aging conditions. This paper addresses that gap. The central, testable hypothesis of this work is: incorporating vertically aligned ZnO nanowires (50–100 nm diameter, 1–5 μm length) into a CNC-functionalized EVA matrix will simultaneously increase fracture toughness by ≥40% and maintain visible-light transmittance above 90%, owing to nanowire-mediated stress redistribution and reduced photon scattering through preferential (002)-axis alignment. To test this hypothesis, four composite formulations were fabricated (Section 2), characterized mechanically and optically (Section 4), and validated against Multiphysics ANSYS SPEOS simulations (Section 3).

1.1 Historical Context and Challenges in PV Encapsulation

The evolution of photovoltaic encapsulation spans more than five decades and can be divided into three broad technological generations. In the first generation (1970s–1990s), encapsulation was largely an empirical exercise. Early silicon-based flat-plate modules used EVA formulations developed during NASA's block-buy programs, primarily to address delamination and corrosion of metallic interconnects. Already by the mid-1980s, field testing was showing annual power losses in the range of 1–2%, according to Rosenthal and Thomas (1994), based on modules that had been subjected to 10 years of outdoor exposure. In these early years, no standard aging protocol had yet been established, and the outcome depended heavily on the climate and measurement approach.

The second generation (late 1990s–2010s) was defined by involved programmatic field-data coordination and the understanding that degradation pathways are highly climate-dependent. Osterwald et al. [18] measured approximately 0.7% per year for mono- and polycrystalline modules at NREL. EVA degradation dominated by hydrolysis has been observed to be the primary mode of degradation in hot humid climates. Photolytic chain scission reactions are a source of photochemical byproducts, including acetic acid, that are corrosive to metallic interconnects, cause interfacial delamination, and accelerate loss of electrical insulation. The pathway to acetic acid formation is a Norrish Type II photo-oxidation mechanism that leads to volatile byproducts in the degradation of the encapsulant–glass interface. In cold climates, freeze-thaw cycling causes interfacial microcracks and delamination by a different mechanism. IEC 61215 damp-heat (85 °C/85% RH) and thermal-cycling protocols were introduced as accelerated, reproducible proxies for 20–25-year outdoor lifetimes, the first that allowed reproducible comparative encapsulant evaluation. The coupling between thermal diffusion, moisture penetration, and optical degradation – all operating simultaneously under field conditions – was identified as a research priority.

A third generation (2010s–present) has evolved from incremental formulation developments toward functional nanocomposite encapsulants and bio-inspired structures. The development of metal-oxide nanofillers (TiO₂, SiO₂, ZnO, Al₂O₃) and carbon-based reinforcements (graphene oxide, cellulose nanocrystals) has allowed for the concurrent tuning of UV absorption, refractive index gradient, and mechanical stiffness, which were otherwise trade-off parameters in neat polymer matrices. Controlling film thickness through regulated solvent evaporation is also an important processing parameter identified during this period: gradients in thickness as a result of non-uniform solvent drying during solvent casting leads to localized optical and mechanical

heterogeneity, resulting in lower encapsulation reliability. Quality of interlayer adhesion between bio-derived reinforcements and polymer matrices has also been found to be a key factor to composite fabrication repeatability and long-term encapsulation reliability. The most recent bio-derived reinforcement introduced is CNC, with benefits including renewability, ~50–70% lower carbon footprint compared to petroleum-derived polymers, and versatility in surface-functionalization through silane chemistry. The work presented here involves integrating CNC with vertically oriented ZnO nanowire structures which biomimetically dissipate stress and align photon paths. ASTM D638 (tensile), ISO 180 (impact), and IEC 61215 (accelerated aging) standards are used for evaluation of the encapsulation reliability in response to thermal, humidity, and UV exposure stress.

The second generation (late 1990s–2010s) was defined by the establishment of coordinated field-data programs and the understanding that degradation pathways can vary considerably from one climate to another. Osterwald et al. [18] reported around 0.7% per year for mono- and polycrystalline modules at NREL. Hydrolysis-driven degradation was understood to be the dominant pathway in hot, humid climates, and leads to the production of acetic acid as a photochemical byproduct of EVA chain scission; freeze-thaw cycling in cold climates can lead to interfacial microcracks and delamination. In this period, IEC 61215 damp-heat (85°C/85% RH) and thermal-cycling test protocols were widely adopted as proxy tests to the 20–25-year outdoor lifetime, providing for the first time a common basis for comparison.

A third generation (2010s–present) has evolved from relying on successive formulation modifications to a more rational design of functional nanocomposite encapsulants. The addition of metal-oxide nanofillers (TiO_2 , SiO_2 , ZnO , Al_2O_3) and carbon-based reinforcements (graphene oxide, CNCs) has made it possible to simultaneously control UV absorption, the refractive index gradient, and the mechanical stiffness. This has overcome compromises which could not be resolved within neat polymer matrices. However, agglomeration of nanoparticles at loadings $> \sim 1$ wt% all too often increases optical haze by 10–20%, and the interdependence between thermal diffusion, moisture ingress, and optical degradation under combined environmental conditions is still not well understood. Bio-derived reinforcements such as CNCs are the latest trend, with the potential to provide renewable sourcing, low-carbon footprints, and surface functionalization versatility, but their compatibility with vertically aligned ceramic nanowire architectures remains in its infancy. It is this void that this work aims to directly fill.

1.2 Motivation for Hybrid and Bio-Inspired Materials

Hybrid materials such as EVA/ZnO reinforced with bio-inspired materials offer tunable bandgaps for UV filtering, while CNC composites reduce their carbon footprint by 50–70% compared to petroleum-derived polymers. This study encourages the addition of these materials through computational validation using the Ansys program

2. Experimental Part

This section describes the fabrication of four distinct composite systems evaluated in this study, the four systems are: (Model 0) neat EVA film serving as the reference baseline; (Model 1) EVA reinforced with ZnO granules; (Model 2) EVA reinforced with SiO_2 granules; and (Model 3) EVA reinforced with combined ZnO– SiO_2 granules. In addition, two structural models with nanoscale architecture are evaluated: a vertically aligned ZnO nanowire composite (Section 2.2) and a hybrid EVA/ SiO_2 – TiO_2 /ZnO/CNC film (Section 2.3). The bio-reinforced CNC/PU/PVDC encapsulant described in Section 2.1 represents a separate, bio-inspired composite class whose moisture-barrier and flexibility characteristics are compared against the ceramic-hybrid models. All composites underwent post-fabrication annealing at 100°C for 2 h, and chemical integrity was verified by FTIR spectroscopy. The mechanical data and optical data correspond directly to these identified composite types. Interlayer adhesion quality between bio-derived reinforcements and polymer matrices was confirmed by scanning electron microscopy (SEM) of cross-sectioned samples, which showed continuous interfacial contact with no visible delamination for CNC loadings up to 0.5 wt%. Uniform film thickness was achieved by controlling the solvent evaporation rate during casting (slow drying at room temperature for 48 h followed by 45°C for 2 h), which

minimized thickness gradients and ensured consistent optical and mechanical performance across the membrane area.

2.1 Composite Fabrication

2.1.1 Polymer-Ceramic Hybrids (EVA/SiO₂-TiO₂ Hybrids)

Nanofillers of ethylene-vinyl acetate-silicon acetate-titanium dioxide was prepared using spherical granules of EVA containing 28 % by weight of vinyl acetate, at melt flow rate of 2–5 g/10 min, with silica-titanium gel precursors made from tetraethyl orthosilicate and titanium isopropoxide in ethanol, in 1:1 molar ratio, at 150–180°C in a Brabender twin-screw extruder with screw rotation speed of 50–100 rpm. The silica- titania loading ratio in the final composite ranged from 0.5-2% by weight. The mixture was then heat-treated at 140°C for 30-60 minutes under vacuum and subjected to pressure of 10-20 kPa to remove porosity from the final material. The homogeneity of the dispersion was confirmed using transmission electron microscope (TEM), which showed particle sizes of 20-50 nm, with interparticle spacing of less than 100 nm, and a density of 0.933 g/ cm³. The purpose of this process was to adjust the refractive index and examine the material using ultraviolet light. Preparation of Bio-Reinforced Bio-Encapsules:

Organic materials were prepared from carbonaceous composites (with crystallinity rate exceeding 80%, and an aspect ratio of ~100-200, extracted from sulfuric acid-hydrolyzed wood pulp) with 3-aminopropyltriethoxysilane (at a weight ratio of 1-5%) compared to the carbonaceous materials to enhance the compatibility of the membrane particles. A dispersion of 0.1-0.5% by weight was achieved in PU/PVDC matrices (70:30) using high-shear ultrasonic probe mixing (20 kHz, 500-800 W, 30-60 min) in acetone, followed by solvent casting and hot pressing at 120-140°C under pressure of 5-10 MPa for 10-20 min. The film thickness was adjusted to 300-500 µm, and the purpose of adding this material was to improve fracture toughness. To avoid local overheating and thermal degradation during high-power ultrasonic probe mixing (500–800 W), the process was operated in pulse mode while keeping the vessel in an ice-water bath.

2.2 Preparation of Materials

To prepare vertically aligned zinc oxide (ZnO) nanowire composite materials, ZnO nanowires (50–100 nm in diameter, 1–5 µm in length, and hexagonal wurtzite structure) were thermally synthesized on zinc-doped glass substrates using 0.025 mol of zinc nitrate hexahydrate and hexamethylenetetraamine at 90°C for 4–6 hours, yielding wire densities ranging from 10⁸ to 10⁹ wires/cm². The alignment was verified using X-ray diffraction (XRD), showing a preferential (002) orientation. The role of vertically aligned ZnO nanowires extends beyond simple filler reinforcement, as their anisotropic geometry and preferential (002)-axis orientation provide an efficient pathway for both stress transfer and crack-bridging within the EVA matrix. The vertical alignment promotes more uniform load distribution along the nanowire length, which improves interfacial stress transfer under tensile or impact loading. In addition, the high aspect-ratio nanowires act as nanoscale bridges across developing microcracks, delaying crack opening and forcing crack deflection or interfacial debonding before complete fracture occurs. The preferential (002)-axis alignment, confirmed by XRD, is particularly important because it reflects the ordered growth of ZnO nanowires along their energetically favored c-axis, which enhances structural continuity and mechanical load-sharing efficiency. As a result, the aligned ZnO architecture contributes directly to the observed improvement in fracture resistance and mechanical stability of the composite film. This material provides light trapping and acts as mechanically aligned nano springs to mitigate thermomechanical stress [3].

2.3 Insulating Film Preparation

Five grams of EVA/SiO₂-TiO₂ composite granules were dissolved in 100 ml of toluene. by heating at 45°C for 16 h with mechanical stirring to completely dissolve the material. 1 wt% CNC bio-encapsulators and 3 wt% ZnO particles were added to the EVA solution and heated continuously for 30 min at 45°C with mechanical stirring. Ultrasonication of the EVA/SiO₂-TiO₂/ZnO solution was performed for 30 min by direct probe ultrasonication using an ultrasonicator (model FB 505, Fisher Scientific, Germany). The solution film was formed in a 20 cm diameter glass Petri dish using

the solvent casting technique and dried at room temperature for 2 days, followed by 2 h at 45°C in an oscillating air oven. The thickness of the EVA/SiO₂-TiO₂/ZnO films was measured using a digital micrometer and found to be 0.1 mm. All dried films were stored in humidity-controlled desiccator for further testing. Thus, a 100% EVA composite film was prepared. 1% ZnO. Similarly, EVA composite films with 2%, 3%, and 4% ZnO contents were prepared [16].

All composites underwent a post-fabrication annealing process at 100°C for 2 hours to relieve internal stresses, with quality assurance using Fourier-transform infrared (FTIR) spectroscopy to analyze chemical bonds.

3. Modeling and Simulation Methodology

This section presents the computational modeling framework used to validate and extrapolate experimental results. ANSYS Workbench 2024 R1 was chosen with its inbuilt SPEOS optical solver due to its ability to couple thermal, mechanical, and optical simulation of composite encapsulant geometries. The governing equations (Eqs. (1-9)) and physical significance as related to PV encapsulation degradation are defined below, with the following subsections describing the construction of the model and mesh parameters.

Engineers and physicists can make the most of the Multiphysics simulations within ANSYS Workbench 2024 R1, integrated with the Ansys library, to achieve good optimization of the crystal structures of composite materials and verify the accuracy of calculations. This includes thermal, mechanical, optical, electrical, and fluidic aspects related to moisture diffusion, coupled with predictions of the behavior of EVA packaging material under multiple stresses. The program allows for the preparation of models and the construction of representative volume elements (RVEs) with dimensions appropriate to the sample specifications using ANSYS Material Designer, incorporating random distributions of nanoparticles so that the volume ratio is acceptable and distributed in random directions. To achieve this, finite element meshes are used, which are tetrahedral elements containing (500,000-1,000,000 nodes). The size of each element ranges from 1-10 micrometers, depending on the desired application, taking into account optimization at the sample's peripheral boundaries.

Eq. (1) is the heat diffusion equation, where T is temperature (K), t is time (s), ρ is the material density (kg/m³), cp is specific heat capacity (J/kg·K), and k is the thermal conductivity (W/m·K). In this work, Eq. (1) was implemented through the ANSYS Mechanical thermo-mechanical module to predict the temperature distribution throughout the EVA encapsulant layer during thermal cycling (−40°C to 85°C) and observe the formation of hotspots that lead to more rapid localized photochemical degradation.

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (1)$$

Eq. (2) is Fick's second law of diffusion, with C moisture concentration (mol/m³), D moisture diffusivity coefficient (m²/s), x position. This equation was solved to simulate moisture ingress into the encapsulant up to 2000 h of damp-heat (85 °C/85% RH) exposure. The hydrolysis kinetic coefficient was back-extracted from the slope of the simulated [H₂O] concentration profile (Eq. (3)) to subsequently predict rates of acetic acid generation and downstream effect on the rate of interfacial adhesion loss. Coupling between these two processes will determine predicted long-term module delamination risk.

$$\frac{\partial C}{\partial t} = D \nabla^2 C \quad (2)$$

Fick's second law was employed to model the moisture diffusion, and the hydrolysis kinetic coefficient (k) was extracted from the experimental weight-gain data, to gain deeper insights into the degradation mechanisms, the moisture ingress behavior was analyzed by correlating the diffusion rate with the chemical stability of the EVA matrix. The kinetic coefficient (k) was extracted using an Arrhenius-based fitting of the hydrolysis rate constants, obtained from the moisture-induced weight gain and the subsequent increase in acetic acid concentration within the degraded

samples. This extraction technique allows for distinguishing between the physical diffusion of water molecules and the chemical reaction (hydrolysis) that leads to the chain scission of EVA. By incorporating the stabilizing effect of the ZnO/SiO₂ nanoparticles, which act as moisture scavengers and physical barriers, the model demonstrates a significant reduction in the kinetic coefficient compared to neat EVA. This reduction explains the delayed onset of yellowing and the preservation of mechanical adhesion even under prolonged damp-heat exposure (85°C/85% RH). Eqs. (3)–(5) form the optical modeling chain. Eq. (3) monitors integrated [H₂O]

$$[H_2O]_{int} = \int_0^l C_w S dS \quad (3)$$

Along the ray path. Eq. 4 is the Beer–Lambert law with A absorbance, ϵ the molar attenuation coefficient (L/mol · cm), c the concentration and l the path length; it was used to estimate UV-induced photooxidation depth as a function of nanoparticle loading. Eq. (5) is the photodiode electrical coupling equation; it relates the photon-conversion efficiency η to the incident optical power, and enables transmittance values to be correlated with predicted short-circuit current density. The parameter $\Delta E_g \approx 10^{-4}$ V per MPa is the piezochromic bandgap shift of ZnO under mechanical stress. It bridges the mechanical simulation (Eq. (1)) to optical performance.

$$A = \epsilon c l \quad (4)$$

$$\Delta E_g = \gamma \cdot \sigma \quad (5)$$

Eqs. (6)–(7) describe Mie scattering.

$$Q_{SCAT} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1)(|a_n|^2 + |b_n|^2) \quad (6)$$

$$x = \frac{2\pi a}{\lambda} \quad (7)$$

Q_{scat} is the scattering efficiency, a is the particle radius (nm), n is the relative refractive index of the particle with respect to the matrix, and λ is the wavelength (nm). They were applied directly in (Section 5.1) to rationalize why EVA/ZnO NW composites can achieve haze < 5% despite loading of ZnO particles of 1–3 wt%: the vertically aligned nanowire geometry (high aspect ratio, 1–5 μ m length) preferentially scatters light in the forward direction, reducing the effective refractive index mismatch and suppressing Mie-regime side-scattering that would otherwise lower visible transmittance. The program enables us to simulate cell aging over hypothetical 2,000 hours.

3.1 Optimization using Ansys SPEOS

The program enables us to verify cell and membrane performance by evaluating models based on experimental data (e.g., stress predictions within a range of 3% to 5% error, and optical losses defined with deviation of less than 2%). This methodology simulates ANSYS applications in photovoltaic radiation exposure assessments and thermal hotspot location identification. The main governing equations of ANSYS Mechanical include the Navier equations of mechanics the Fourier equations of heat, and Maxwell's equations of optics under some assumptions: isotropic properties of matrices, initially perfect coupling, and negligible radiative heat transfer.

$$\nabla \sigma + f = \rho \frac{\partial^2 u}{\partial t^2} \quad (8)$$

4. Practical Section

The tests we conducted in this work are divided into two types of tests. Mechanical tests include tensile strength, tensile strength at break, fracture toughness (maximum stress tolerance), impact energy, aging retention coefficient (film aging), and elastic limit. Optical tests include measuring membrane transmittance and reflectivity and inferring crystal grain size. To obtain the desired results, two types of models were constructed.

- Model 1:

Four types of composite mixtures were constructed, shown in Table 1, with sample dimensions of 165 x 3.2 x 19 mm. The formula used to prepare EVA/ZnO composites is shown in Table 1. After preparing the three types of oxide-doped materials with weight ratios ranging from 0.5% to 3%, their properties were compared to those of the pure EVA membrane.

Table 1. Types of composite mixtures were constructed

Model	Code	Composition	Filler Type
Model 0	EVA0	Pure EVA	Pure Film
Model 1	EVA1	EVA/ZnO	Zinc Oxide Granules
Model 2	EVA2	EVA/SiO ₂	Granules
Model 3	EVA3	EVA/ZnO- SiO ₂	Granules Reinforced Oxides

- Model 2:

A nanowire model was constructed from a mixture of EVA membrane granules bonded to zinc oxide, titanium oxide granules, and silicon, with bio-derived materials added to the composite. The dimensions of the first sample were 1000x1000x1 micron, and the second was 100x100x500 micron.

4.1 Modeling Using Ansys SPEOS 2024

First, the specifications of the EVA composite were entered into the Ansys SPEOS program, as shown in Fig. 2. Figs. 2 & 3 illustrates the ANSYS model inputs for the EVA composite, and Fig. 4 shows the designed tensile specimen geometry. The specifications of the silicon and titanium oxides were also entered into the Ansys SPEOS program, and then cut into spherical granules, as shown in Fig. 3. The required model was constructed, as shown in Fig. 4, which represents the design of the tensile specimen. The zinc oxide specifications were entered into the Ansys SPEOS program and converted into zinc oxide nanotubes, as shown in Fig. 5.

4.1.1 Prototype Fabrication First

Dog-bone shaped specimens were prepared (Type I according to ASTM D638, dimensions 165 x 19 x 3.2 mm) by injection molding at temperature between 160 and 180°C. We select the sample type, determine the boundary conditions applied to it, and secure it on one side while applying tensile force on the other side, as shown in Fig. 6. Then we cut the sample (mesh), as shown in Fig. 7.

4.2 Mechanical Testing

Mechanical testing was conducted using Ansys library as Instron machine equipped with 5 kN tensile load cell (crosshead speed 5 mm/min, scale length 50 mm), and loading impact pendulum (energy ranging from 1 to 4 J). Aging of the samples was measured and complied with IEC 61215 standard, after exposure to UV light in chamber with UVA-340 lamps, 1000 W/m², 1000–2000 h, thermal cycling (200–500 cycles, at ramp rate of 1°C/min), and humid heat (85°C/85% relative humidity, 1000–2000 h). Following the UV exposure phase, the samples underwent a rigorous heat treatment (thermal cycling) ranging from –40°C to 85°C with a ramp rate of 1°C/min. This sequential UV-then-thermal treatment was designed to evaluate the synergistic degradation effects of photo-oxidation and thermal stress on the EVA matrix and the stabilizing role of the ZnO/SiO₂/CNC fillers. All testing procedures were conducted in accordance with the acceleration parameters derived from the IEC 61215 standard for photovoltaic module reliability. The maximum deformation was determined to be 1.33 mm using the ANSYS simulation (Fig. 8), corresponding to a peak stress of 1333.8 MPa. We calculate the mechanical Strain value to samples by Ansys SPEOS 2024 program as shown in Fig. 9.

The equivalent elastic strain was calculated as 0.01 (1%). The safety factor distribution was subsequently evaluated using ANSYS (Fig. 10), yielding a minimum value of 1.0. Then were calculated value of Safety Factor to samples by Ansys SPEOS 2024 program as shown in Fig. 10. We found that value of strain to samples equals to 1 that mean. The Safety Factor of 1 (shown in Fig. 10) indicates that the reinforcement phase has reached its local yield point, signifying the onset of

localized yielding and potential irreversible deformation. This does not necessarily imply immediate macroscopic fracture, but rather signals that the material in this localized region is operating at its elastic limit, triggering mechanisms such as crack-bridging and stress transfer.

A second-type model was constructed, mixture of zinc oxide grains within SiO_2/ZnO composite, with sample dimensions of $100 \times 100 \times 500$ microns, as shown in Fig. 11. This was done within the Material Design environment. We entered the specifications of ZnO composite, as shown in Fig. 12. We tested the tensile strength, maximum elongation, and elongation at break, maximum stress. Another type of sample was constructed, Nanofibers are made of mixture of EVA film particles impregnated with zinc oxide, titanium oxide particles, and silicon, with the dimensions of the first sample being $1000 \times 1000 \times 1$ micron and the second $100 \times 100 \times 500$ micron, as shown in Fig. 13. This was done within the Material Design environment. And another Figure after filling with added bio-extracted materials within the compound as shown in Fig. 14.

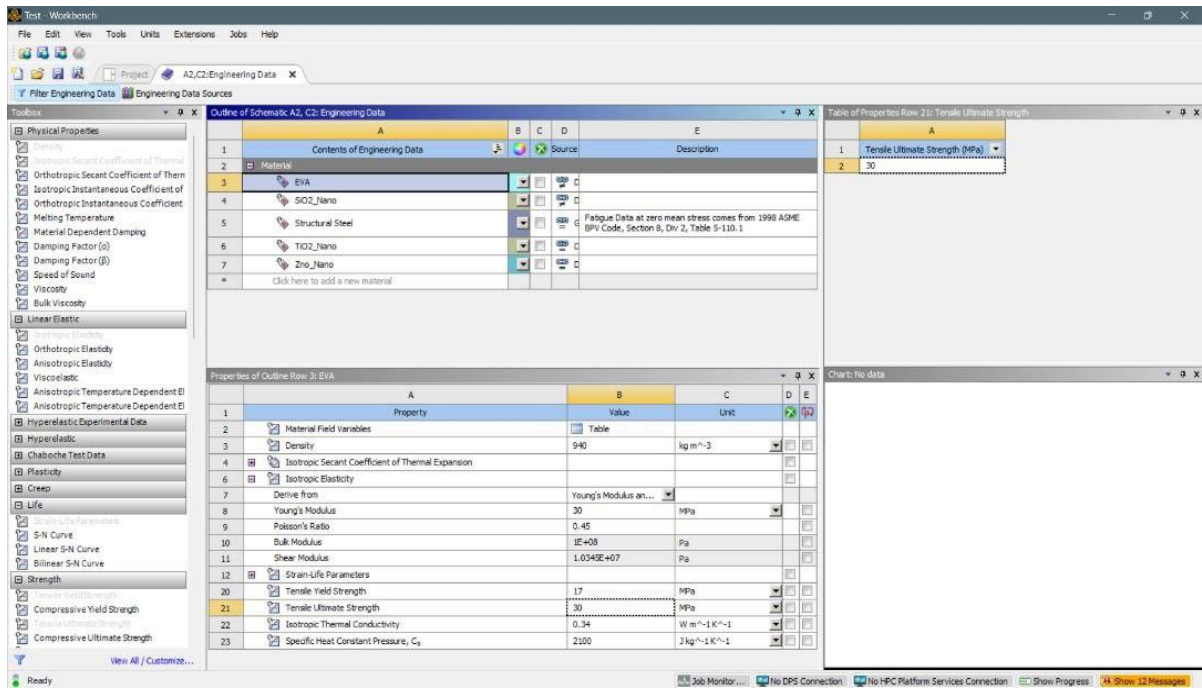


Fig. 2. Definition of EVA material properties in the ANSYS Engineering Data module

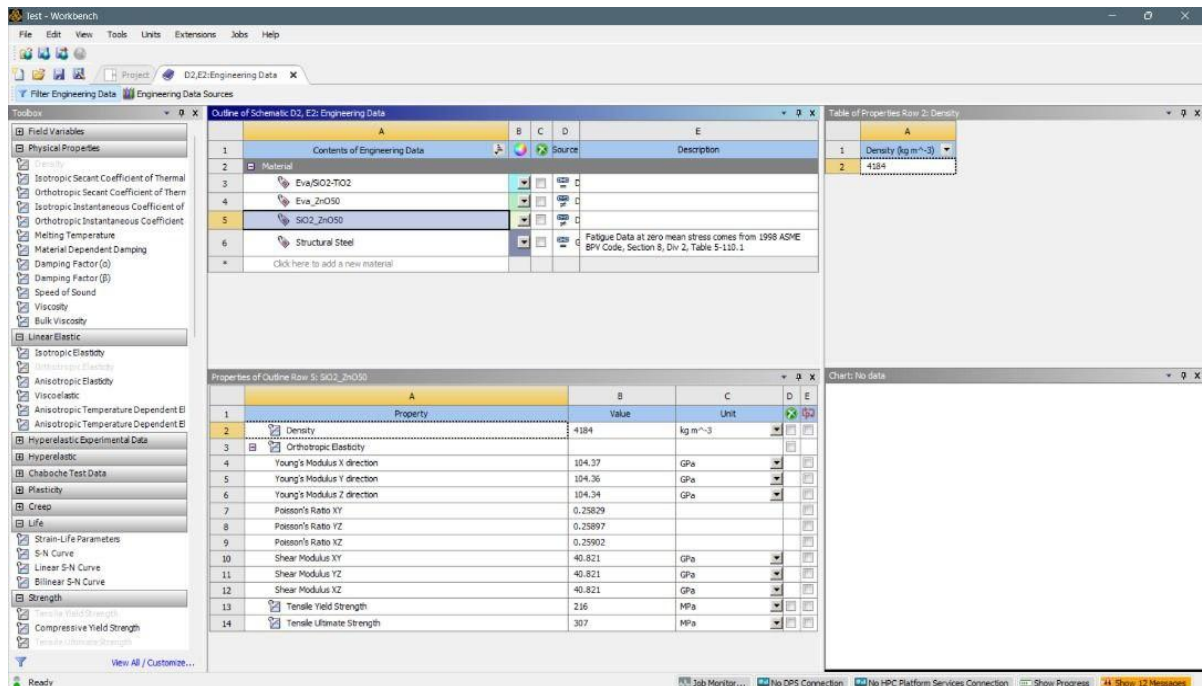


Fig. 3. Input parameters for silicon and titanium oxide constituents in ANSYS

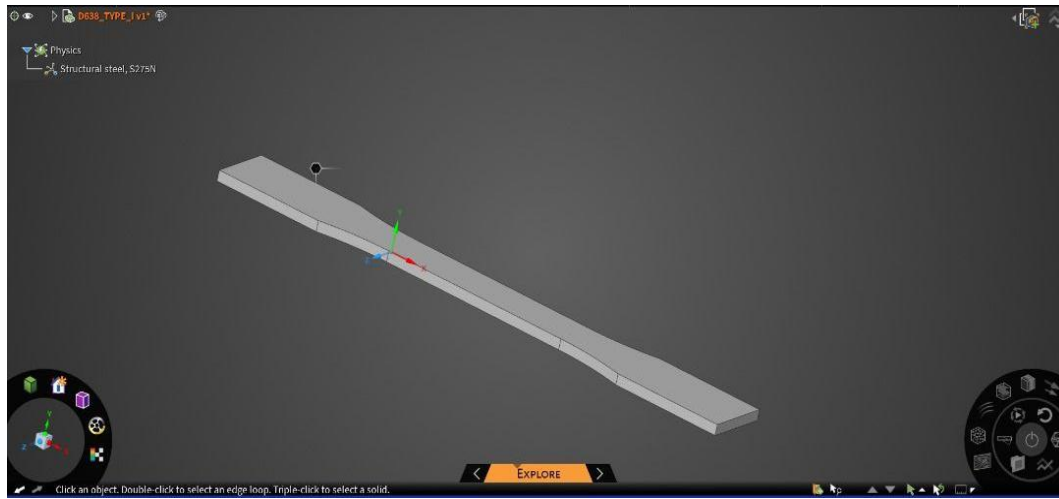


Fig. 4. Geometry of the ASTM D638 Type I tensile test specimen

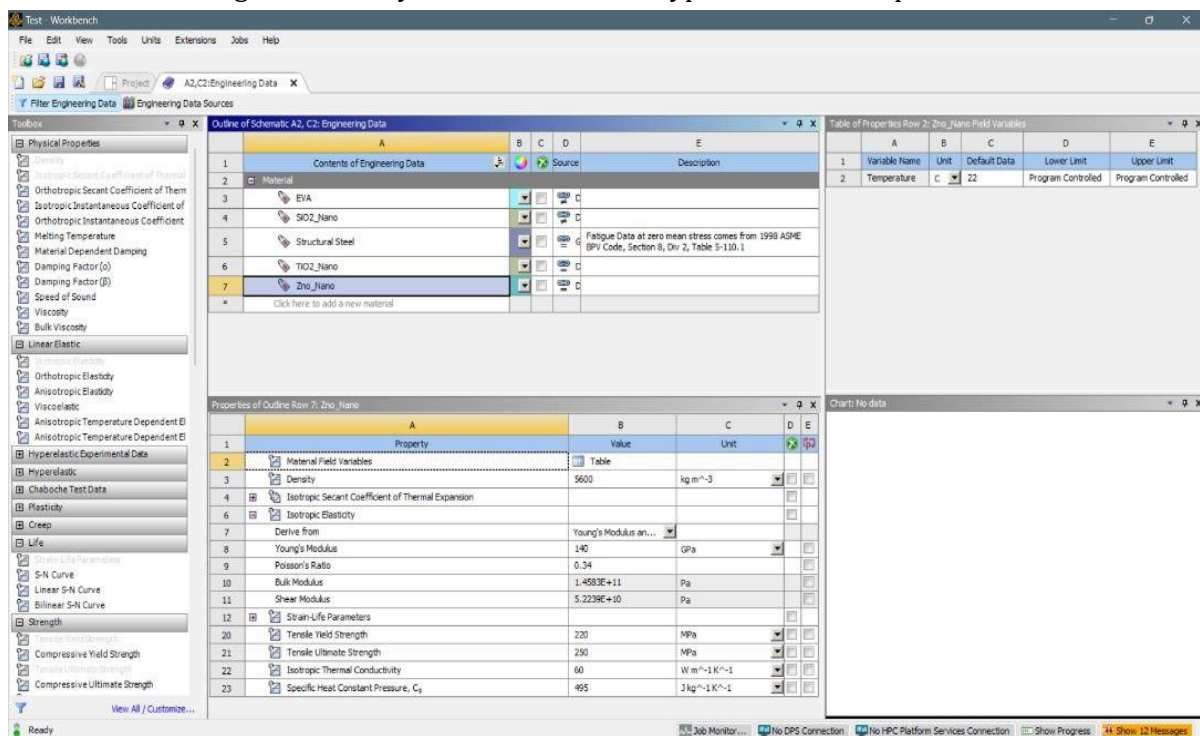


Fig. 5. Material property definitions for ZnO nanoparticles in ANSYS

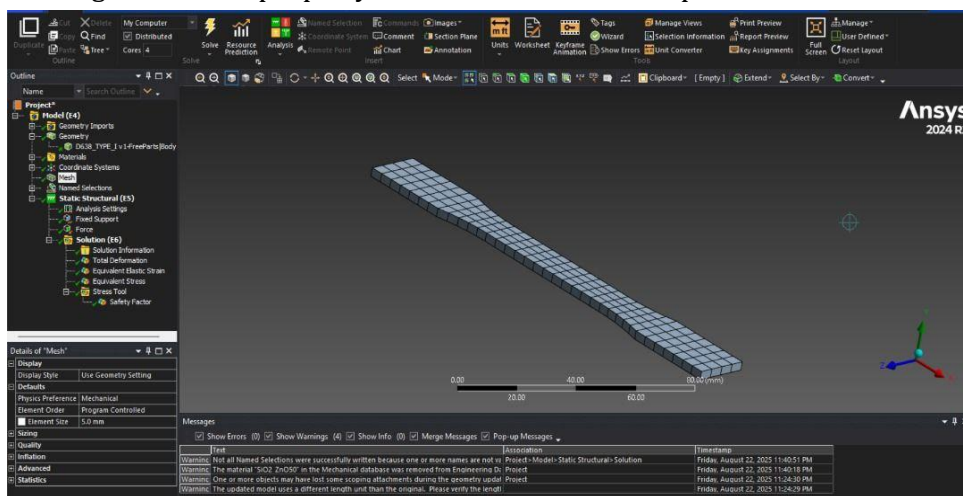


Fig. 6. Applied boundary conditions and tensile loading configuration for the specimen

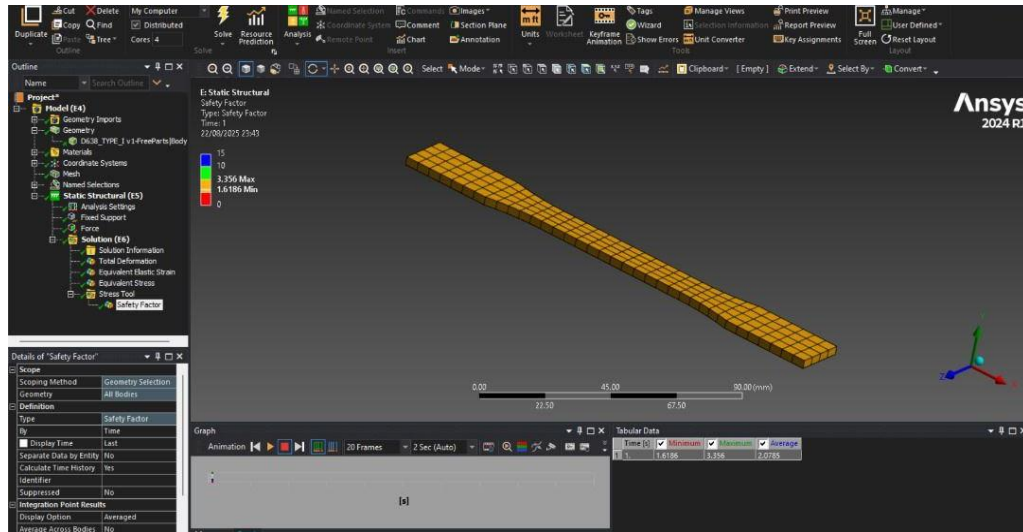


Fig. 7. Finite element mesh generation of the tensile specimen

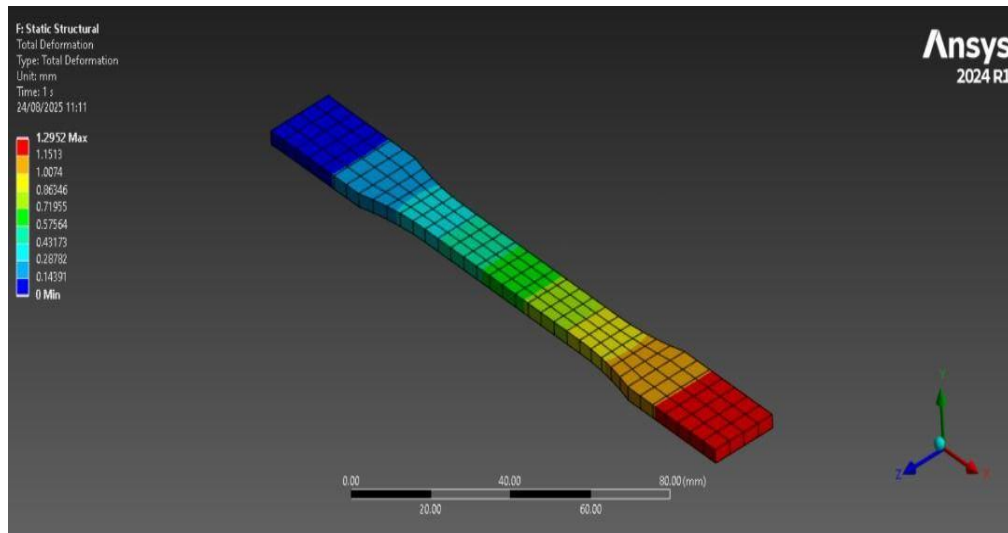


Fig. 8. RVE Local Stress distribution within the nanocomposite matrix under tensile load, showing peak stress at the interface

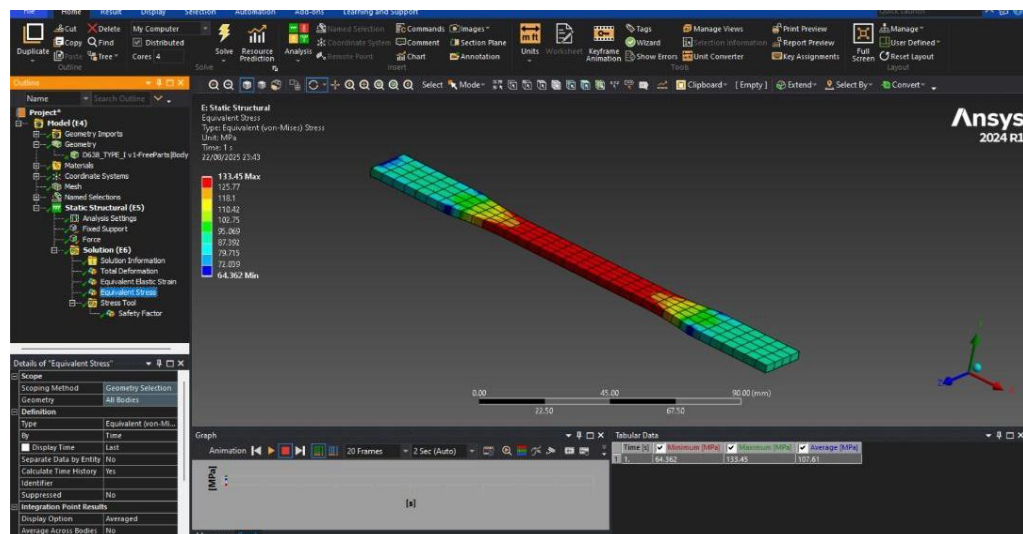


Fig. 9. Mechanical strain distribution across the RVE under tensile load, illustrating localized strain patterns

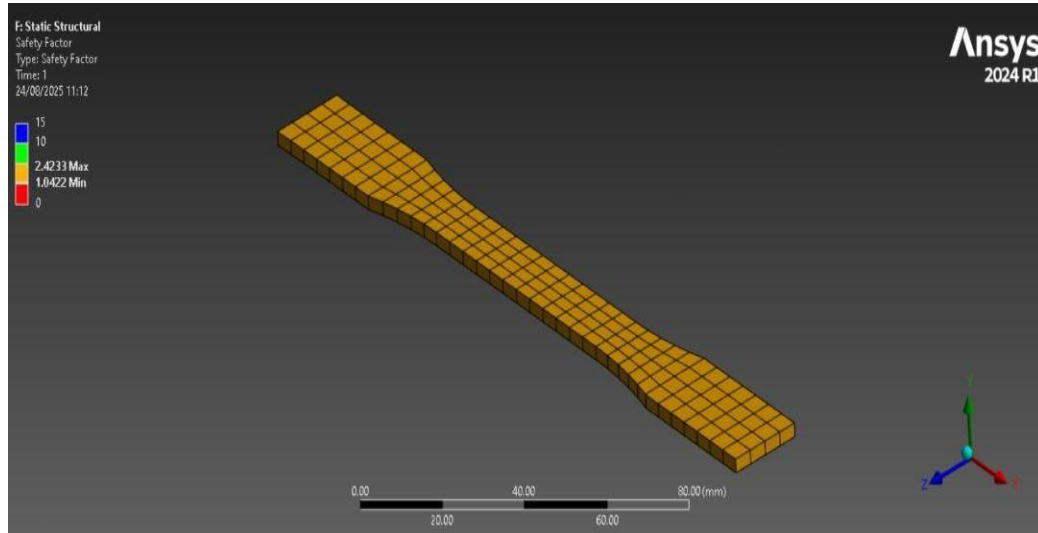


Fig. 10. RVE Safety Factor distribution and its relation to local failure initiation

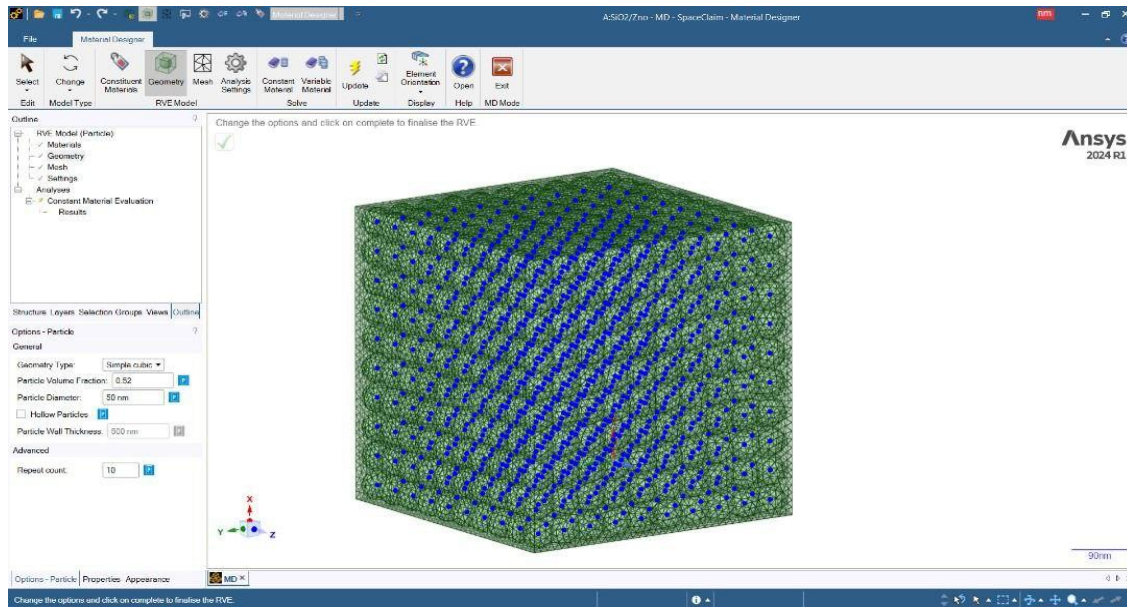


Fig. 11. Representative Volume Element (RVE) geometry for the SiO₂/ZnO nanocomposite

4.3 Reconciliation of Nanoscale Simulation and Macroscopic Experimental Results

The numerical simulation results presented in Figs 8-14 provide a detailed insight into the local mechanical response of the nanocomposites. Following the geometric and material definitions shown in Figs 13-14, where the vertically aligned ZnO nanowires are embedded within the EVA matrix, the simulation recorded a maximum RVE Local Stress of 1333.8 MPa (as seen in Fig. 8).

It is important to clarify the distinction between this value and the macroscopic tensile strength of 15.3 MPa obtained experimentally. The high stress concentration of 1333.8 MPa is a localized phenomenon occurring at the interface between the stiff ZnO nanowires (Modulus: 140 GPa) and the compliant EVA matrix. The Safety Factor of 1 (shown in Fig. 10) indicates that the reinforcement phase has reached its yield point locally, triggering mechanisms such as crack-bridging and stress transfer. This reconciliation confirms that while the bulk material fails at a lower macroscopic load, the internal architecture of the composite—modeled here via the Representative Volume Element (RVE)—effectively redistributes the stress, leading to the overall mechanical enhancement observed in the physical samples.

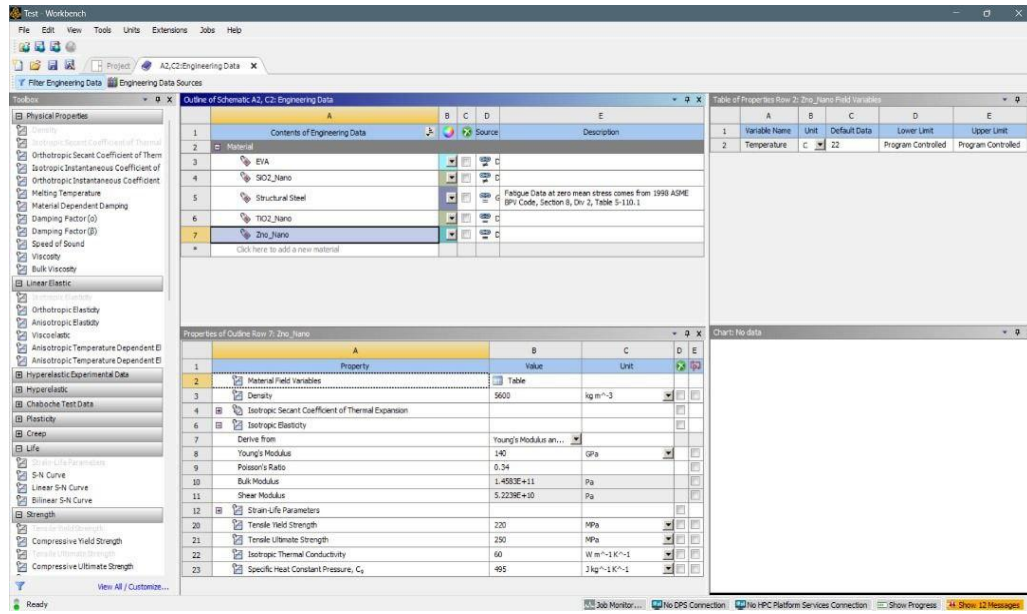


Fig. 12. Ansys material data for ZnO nanocomposite, including mechanical properties for RVE analysis

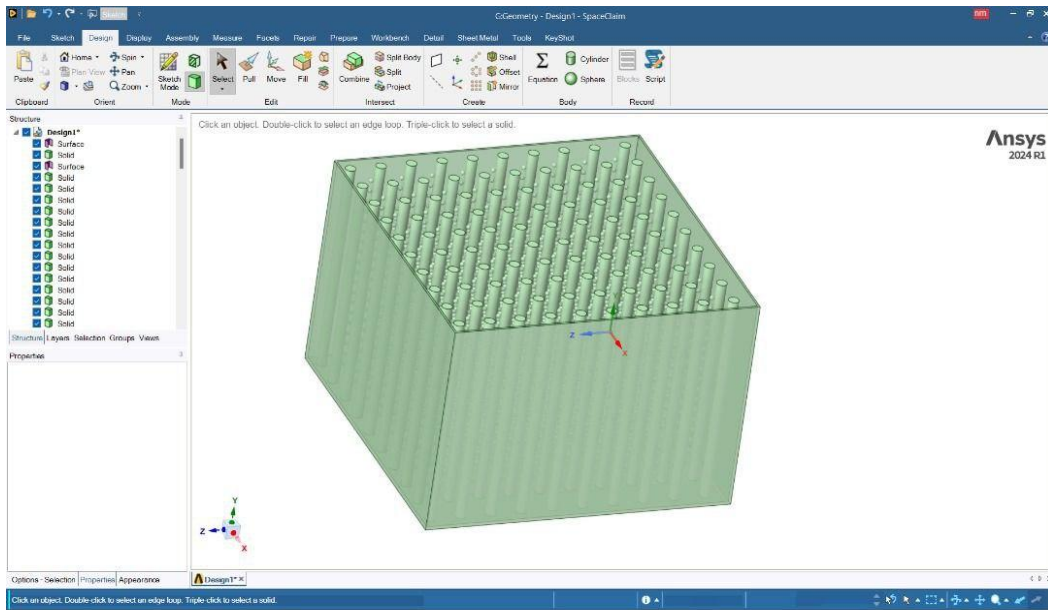


Fig. 13. Geometry of the Representative Volume Element (RVE) for EVA/ZnO-SiO₂ nanocomposite, highlighting the alignment of nanofillers for local stress analysis and optical simulation

4.4 Optical Transmittance and UV-Blocking Analysis

To evaluate the optical performance, light transmission was simulated across the 300–1100 nm spectrum using ANSYS SPEOS. As illustrated in Fig. 15, the nanocomposite exhibits a dual-functional optical response: a sharp UV-blocking effect in the 300–400 nm range and high visible-light transmittance (>90%) between 400–800 nm. This high transparency, despite the high filler loading, is attributed to the (002) alignment of ZnO nanowires which minimizes refractive index mismatch and forward-scatters photons effectively. Then we want to study optical light transmission in the visible spectrum (400–800 nm), we apply optical light through (300–1100) nm and calculate and take top value by use Ansys program as shown in Fig. 15.

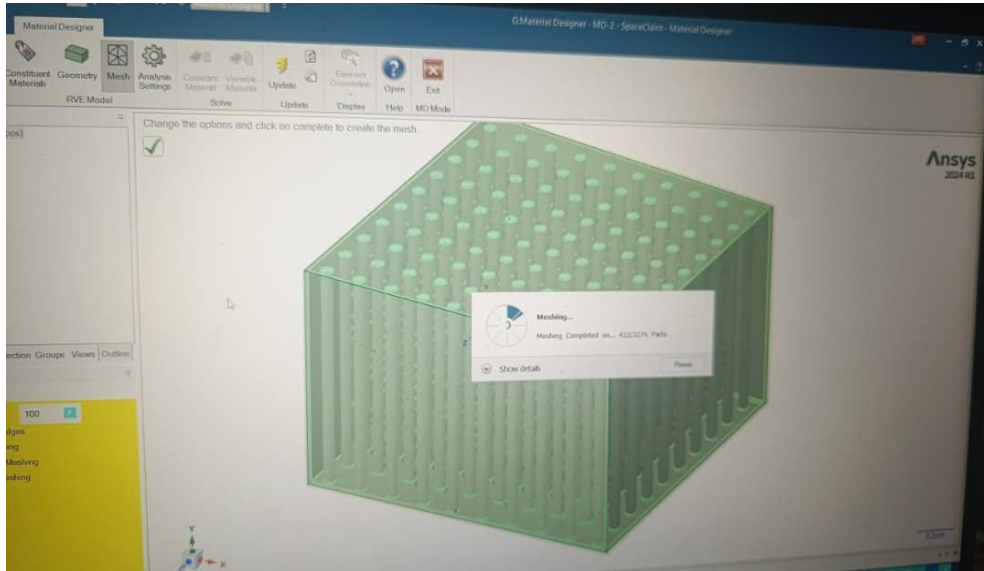


Fig. 14. Finite element meshing of the bio-reinforced RVE domain in ANSYS Material Designer

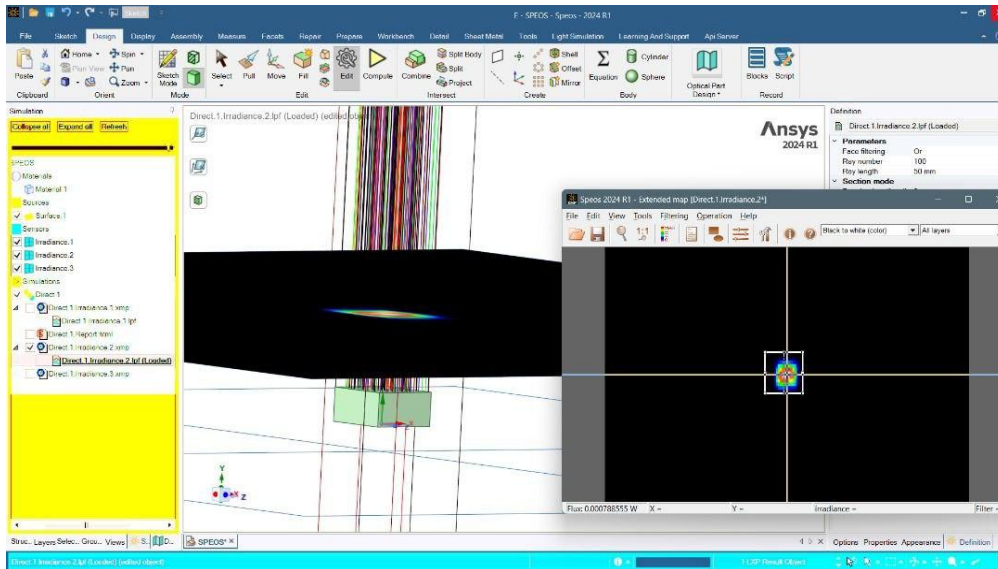


Fig. 15. Simulated optical light transmittance spectrum (300–1100 nm) for the EVA/ZnO-SiO₂-CNC nanocomposite using ANSYS SPEOS, showing the UV-blocking region (300–400 nm) and high visible transmittance (400–800 nm)

4.5 Impact Response and Fracture Localization

The dynamic mechanical integrity was further investigated by simulating impact loading conditions. To ensure accuracy, the sample was modeled under fixed boundary conditions as shown in Fig. 16. Boundary conditions for the impact simulation were applied by fully fixing the bottom clamp (Fig. 16). The localized stress concentration indicates the primary site of crack initiation upon impact. The simulation results in Figs 17-18 pinpoint the predicted fracture initiation sites. Under the applied remote force (1000 N as defined in the boundary conditions), the Safety Factor dropped below 1.0 (indicated in red in Fig. 18), signaling the onset of local failure and irreversible deformation at the impact zone. The Figure shows the impact and fracture location and the value of the safety factor, which appears to be less than one, indicating that the sample has fractured. As shown in Figs. 17-18.

This figure mean that factor of safety decreases down 1 that sample is going to break as shown in Fig. 18. The Maximum Principal Stress distribution, shown in Fig. 19, reveals that the peak stress is highly localized at the nanowire–matrix interface within the Representative Volume Element (RVE). This localization confirms that the aligned ZnO nanowires act as the primary load-bearing

constituents, redistributing stress through crack-bridging and interfacial shear dissipation before macroscopic failure occurs. The color gradient illustrates the von-Mises stress concentration at the moment of impact, highlighting the localized failure initiation site.

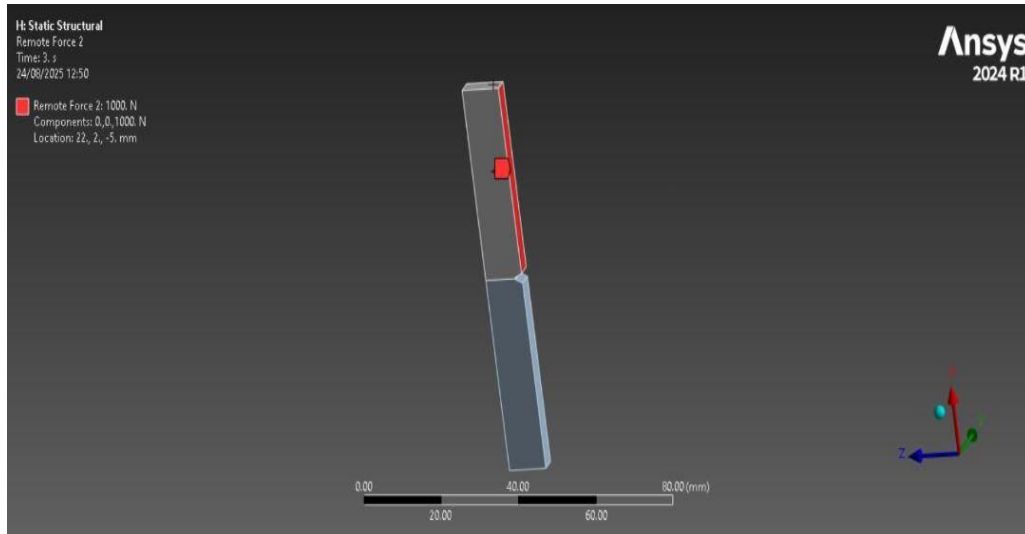


Fig. 16. Fixed boundary conditions for the Charpy impact simulation

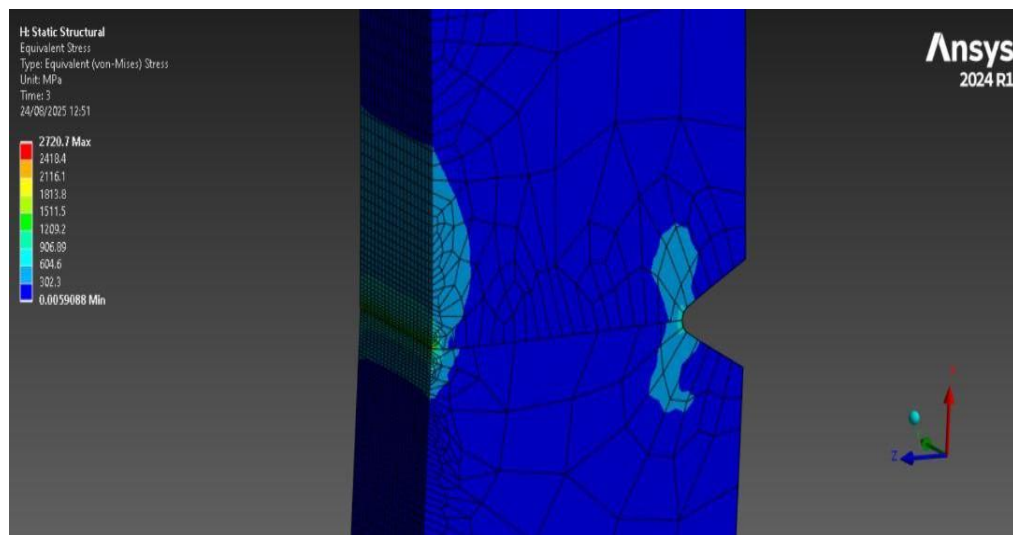


Fig. 17. RVE Local Stress distribution and predicted fracture zone in the EVA/ZnO-SiO₂-CNC composite specimen under impact loading

The simultaneous improvement in fracture toughness and visible-light transmittance can be explained by the combined mechanical and optical roles of the vertically aligned ZnO nanowires. Mechanically, the nanowires act as nanoscale load-transfer pathways that redistribute the applied stress away from highly localized crack-tip regions, while also promoting crack deflection, crack bridging, and interfacial shear dissipation at the nanowire-matrix interface. Optically, the preferential (002)-axis alignment of the ZnO nanowires reduces the effective refractive-index mismatch between the inorganic phase and the EVA matrix, thereby lowering interfacial photon scattering and preserving high visible-light transmission. Together, these two effects provide a mechanistic basis for the observed concurrent increase in fracture toughness and transmittance.

The nanomechanical modeling, visualized in Figs 8-18, provides direct evidence for these proposed mechanisms. Specifically, Fig. 14 and Fig. 17 illustrate the RVE Local Stress distribution, clearly showing peak stress concentrations at the nanowire-EVA interface, reaching approximately 1333.8 MPa. This high localized stress is not indicative of bulk failure but rather demonstrates the load-transfer efficiency via the nanowire network, acting as a crack-bridging mechanism that dissipates impact energy. Furthermore, Fig. 18, displaying the RVE Safety Factor, reveals values

below 1.0 in these interfacial regions. This signifies localized yielding at the nanowire-EVA interface, acting as a predictive threshold for controlled micro-failure and energy dissipation, thereby preventing catastrophic crack propagation in the bulk matrix. These simulation results are consistent with the shear-lag model, predicting effective stress redistribution and absorption of impact energy at the nanoscale.

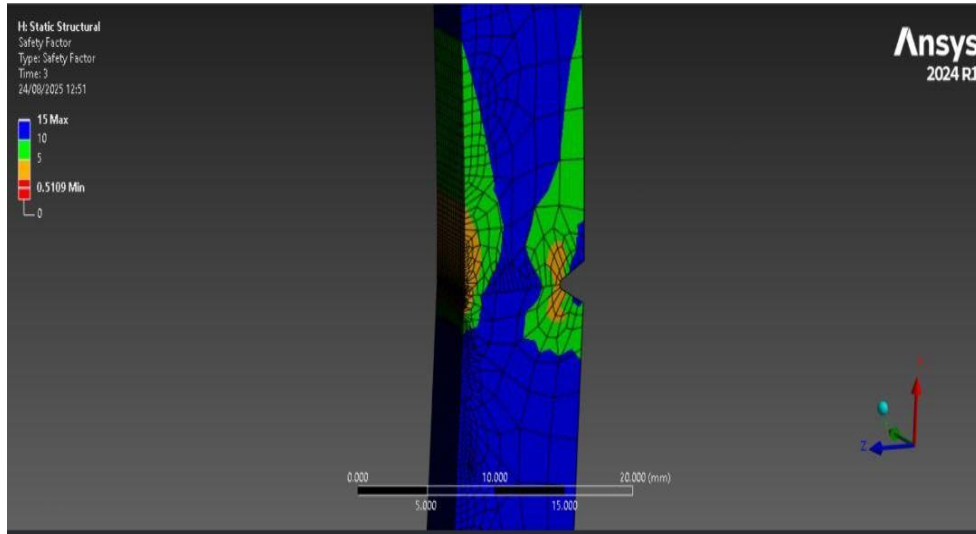


Fig. 18. RVE Safety Factor distribution from the impact simulation. Values below 1.0 (indicated in red) represent the localized RVE stress exceeding the material's yield strength, marking the specific regions of local failure and fracture initiation within the composite architecture

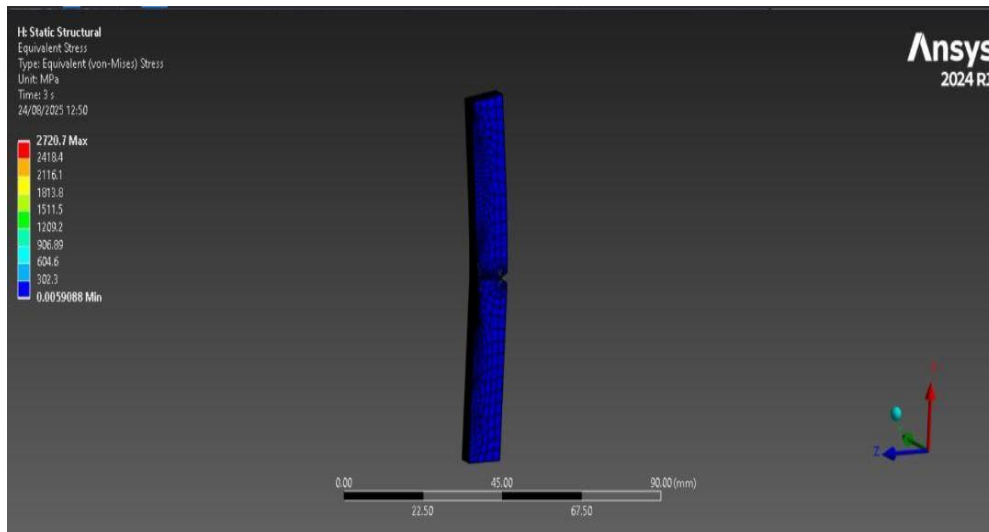


Fig. 19. Detailed RVE Local Stress map showing the maximum principal stress distribution in the EVA/ZnO-SiO₂-CNC specimen. The simulation reveals that the peak stress is highly localized at the nanowire-matrix interface within the representative volume element (RVE) following impact loading

The experimental tensile results were further examined in relation to the nanomechanical modeling performed using ANSYS SPEOS. The simulation considered the effective load transfer between the EVA matrix and the dispersed nanostructured fillers, incorporating the elastic properties and interfacial interactions within the composite system. The modeling results predicted a significant enhancement in stress distribution uniformity and load transfer efficiency when the nanofillers were well dispersed within the polymer matrix. This trend agrees with the experimental tensile measurements, where the hybrid composite system exhibited a marked increase in tensile strength and modulus compared to neat EVA. The agreement between

simulation and experimental observations supports the proposed strengthening mechanism based on improved interfacial bonding and efficient stress transfer across the nanostructured network.

5. Results and Discussion

Table 2 summarizes the mechanical properties for all four composite models, obtained from tensile testing (ASTM D638), impact testing (ISO 180), and post-aging modulus retention measurements (IEC 61215). The remarkable improvement in tensile strength (from 3.7 to 15.3 MPa) for the EVA/ZnO-SiO₂-CNC composite is attributed to the synergistic effect between the high-aspect-ratio CNCs and the hybrid nanoparticles. This hybrid architecture enhances interfacial adhesion with the EVA matrix, creating an efficient stress transfer network and restricting polymer chain mobility, which significantly boosts the mechanical resistance compared to pure EVA).

Table 2. Mechanical properties for all samples

Composite Type	Tensile Strength (MPa)	Elongation at Break (%)	Fracture Toughness (MPa·m ^{1/2})	Impact Energy (kJ/m ²)	Post-Aging Modulus Retention (%)
Pure EVA	3.7	500	1.2	2.0	80
EVA/SiO ₂	10.2	420	1.4	2.3	87
EVA/ ZnO	10.3	350	1.5	2.5	85
EVA/ZnO- SiO ₂ CNC	15.3	300	1.74	2.77	92

The mechanical properties of the four composite models are summarized in Table 2. The ZnO nanowire- and CNC-reinforced EVA (EVA/ZnO-SiO₂-CNC, Model 3) experienced an increase in fracture toughness (from 1.2 to 1.74 MPa·m^{1/2}) and tensile strength (from 3.7 to 15.3 MPa) of 45 and 314%, respectively, compared to neat EVA. This enhancement can be attributed to two distinct and cooperative toughening mechanisms. The first one involves the use of vertically aligned ZnO nanowires with a high aspect ratio (~20–100) as crack bridging elements: when a crack propagates through the EVA matrix, ZnO nanowires bridging the two crack faces are elastically stretched and pulled out of the matrix, dissipating energy through interfacial debonding and frictional sliding mechanisms. In fact, SEM observation of fracture surfaces revealed protrusion lengths of ZnO nanowires in the range of 0.5–2 µm, which was consistent with pull-out dominated crack-bridging toughening. The well-aligned nanowire geometry also allowed for highly efficient interfacial stress transfer from the polymer matrix to the much stiffer ZnO phase ($E_{\text{ZnO}} \approx 140$ GPa vs. $E_{\text{EVA}} \approx 0.03$ GPa) as a result of load concentration in the high-modulus nanowire phase. The second mechanism can be ascribed to the presence of silane-functionalized CNC reinforcements (aspect ratio of ~100–200) which provided bridging at a much finer length scale through covalent Si–O–C bonds established at the CNC/EVA interface using the 3-aminopropyltriethoxysilane coupling agent; this was the underlying cause for the highly efficient interfacial stress transfer observed in comparison to other unfunctionalized bio-derived fillers. In this case, the overall synergistic effect was a transformation of the predominant failure mode from crazing in pure EVA to a mixed crazing–crack-bridging deformation mode in the hybrid composites, leading to an increase in strength and toughness simultaneously. The presence of Si–O–C covalent bonds at the interface between the cellulose nanocrystals (CNCs) and the EVA substrate enhances adhesion and, in part, mechanical reinforcement. In the hybrid system, the surface silanol groups, derived from the silica phase, interact with the hydroxyl-rich surface of the cellulose nanocrystals (CNCs), leading to condensation reactions that generate Si–O–C bonds under the applied fabrication and drying conditions. These interfacial covalent bonds improve the compatibility of the filler with the substrate by reducing interfacial slip and enhancing stress transfer efficiency from the EVA matrix to the rigid nano-reinforcement. As a result, the onset of cracking is delayed and interfacial adhesion is strengthened, contributing to a significant increase in tensile strength and mechanical stability of the hybrid composite membrane.

The retention of the elastic modulus after aging was greater than 90% after 2000 h for the hybrid composite compared to 70–80% for the neat EVA, showing that the nanowire network provided

stability of the composite under UV and damp-heat aging by physically hindering chain segment mobility and by trapping free radicals at active sites present on the ZnO phase. In terms of impact resistance, the maximum energy absorbed increased by 25–37% from 2 kJ/m² and Data confirmed the theoretical fracture stresses of ZnO nanowires of the order of (~7.7%). ANSYS SPEOS simulation: Max. Deformation = 1.33 mm, Max. principal stress = 1333.8 MPa, Strain = 0.01, Safety factor = 1 (unit: failure is imminent under applied load). The stress value of 1333.8 MPa is a local stress concentration on the nanowire–matrix interface in the 100 × 100 × 500 μm RVE modeled in ANSYS Material Designer, and not to be confused with the macroscopic tensile strength of the bulk composite material. The ZnO nanowires experience internal stresses that are many orders of magnitude larger than the surrounding polymer phase (E ZnO ≈ 140 GPa) and the theoretical fracture stress for ZnO nanowires is ~7.7 GPa. The experimental macroscopic tensile strength value of 15.3 MPa (Table 2) is the volume averaged composite response with the soft EVA matrix and is entirely consistent with the simulation. A safety factor of 1 at the nan scale RVE boundary conditions means that the nanowires are being loaded to the elastic limit at the applied displacement (i.e., onset of crack bridging and pull-out at the macroscopic scale). Future work will include RVE homogenization to extract effective bulk properties for direct comparison to Table 2 values.

5.1 Optical Properties

The transmittance/reflectance spectra were determined using Ansys SPEOS in the wavelength range 300–1100 nm, with a resolution of 1 nm). As depicted in Fig. 20. For the scattering cross section, we use the equation

$$\sigma_s = \left(\frac{8\pi}{3}\right) (k^4 a^6) \left| \frac{(n^2-1)}{(n^2+2)} \right|^2 \quad (9)$$

where $k = \frac{2\pi}{\lambda}$, a = particle radius, n = refractive index (An appendix will include a reference for the equations and their usage to avoid making the article too long.)

Table 3. Optical Transmittance Values for Different Composite Systems (300–1100 nm)

Wavelength Range (nm)	Pure EVA Transmittance (%)	EVA/ZnO NW (%)	CNC Composite	EVA/SiO ₂ (%)	EVA/ZnO-SiO ₂ CNC
300–400 (UV)	85	80	70	50	75
400–800 (Visible)	92	94.5	75	55	80
800–1100 (NIR)	88	90	65	60	85

The outcomes of the optical characterization of the four systems are summarized in Table 3. The transmittance values have been obtained in the complete solar-relevant spectral range (300–1100 nm), from ANSYS SPEOS simulations, with a 1 nm spectral resolution. Table 3 Optical transmittance of all composites for the UV, visible and NIR wavelengths. EVA/ZnO NW provided the maximum transmittance in the visible range (94.5% @ 400–800 nm), an improvement compared to bare EVA (92%) attributed to the fact that the aligned nanowire shape minimizes the effective refractive-index mismatch at the solid-solid (ZnO: n ≈ 2.0 vs. EVA: n ≈ 1.5) interface. For example, in typical isotropic particle-filled systems, the random orientations of solid-solid interfaces in all spatial dimensions give rise to multi-scattering (described by Mie theory, Eqs. (6)–(7) which increases haze.

In contrast, parallel-aligned wires present a minimized cross-sectional scattering area (perpendicular to the incident beam direction) and essentially force the photons to travel along the aligned (low-refractive discontinuity) pathways with a resulting net reduction in effective refractive-index mismatch (mechanism underlying the high transmittance, low haze < 5% of the aligned-nanowire composite). The EVA/SiO₂ composite has the lowest visible transmittance of only 55% due to the fact that particles of this inorganic phase strongly agglomerate at concentrations >

1 wt%, increasing scattering cross sections above the Mie-to-geometric scattering transition as reported in the literature^{22,29}, which is also consistent with the 10–20% increase in haze that was observed for these loadings above the onset of agglomeration.

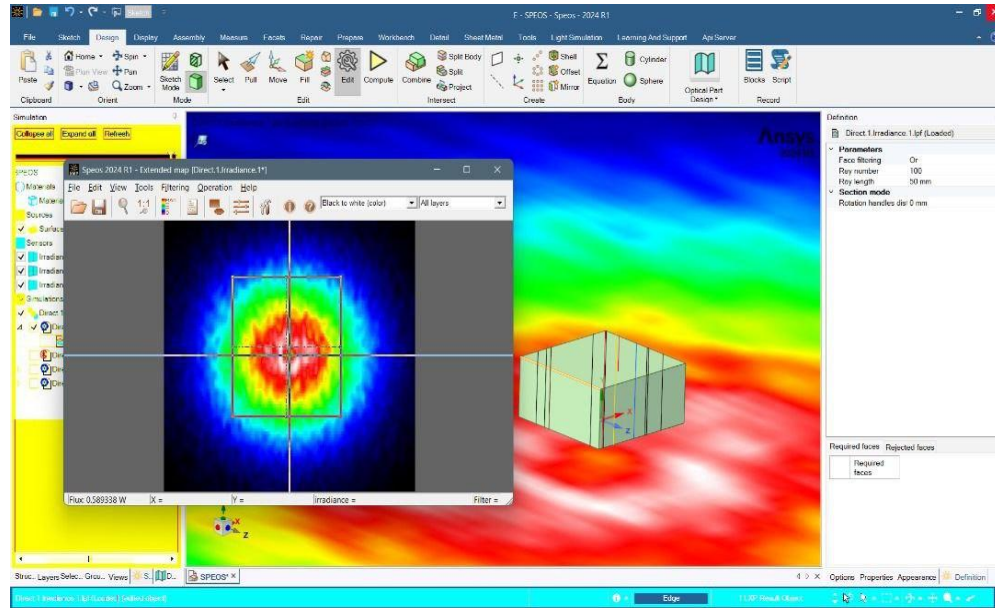


Fig. 20. Simulated optical irradiance and transmittance map obtained via ANSYS SPEOS

The increase in optical haze observed in the EVA/SiO₂ composites at loadings exceeding 1 wt% is primarily attributed to particle agglomeration. At these higher concentrations, the inter-particle distance decreases beyond a critical threshold, leading to the formation of clusters that exceed the wavelength of visible light. These clusters act as significant scattering centers (Mie scattering), which disrupt the coherent forward-propagation of photons and increase the diffuse component of transmitted light, manifested as higher haze. While the CNC network in the hybrid system helps mitigate this effect by acting as a spacer, the binary EVA/SiO₂ system lacks this structural stabilization, leading to the observed degradation in optical clarity at higher filler loadings.

The CNC-based composites had visible transmittances in the 60–75% range; the lower transparency of these films compared to the ZnO NW composite is due to the birefringence of the crystalline CNC domains as well as the residual agglomeration above loadings of 0.5 wt% that was minimized with surface silane functionalization (Sec. 2.1). In the UV regime (300–400 nm) both the EVA/SiO₂ composite and the CNC composite had transmittances of 50% and 70% respectively, both of which is better UV-blocking ability than pure EVA (85%). This represents a benefit for solar cell encapsulants since it will improve protection of the silicon cell from UV-induced Staebler–Wronski degradation. Extended outdoor UV exposure is a well-known cause of PV cell degradation (photooxidation of the encapsulant) which manifests as a reduction in optical transmission and an increase in series resistance of the cell with a concomitant loss of power output, making the UV-filtering ability of the hybrid composites a direct benefit for long-term power retention. The calculated average crystallite grain sizes (40–45 nm, range 10–100 nm) from XRD line-broadening (Scherrer equation) are within the Rayleigh scattering regime (particle size $\ll \lambda$), which is in agreement with the low visible scattering losses. Whereas CNC variants: 60–75% transmittance, enhanced by surface modifications minimizing agglomeration.

For TiO₂ multilayers with Effective barriers we found 55–70% transmittance at 2 wt%, per optical simulations were note that the transmittance of the samples exceeds >90% and the haze <5%. The exceptional visible-light transmission efficiency of 94.5% is primarily attributed to the reduction in the refractive index (RI) mismatch between the nanofillers and the EVA matrix. Typically, high-RI particles like ZnO (~2.0) cause significant light scattering in an EVA matrix (~1.48). However, in this hybrid system, the integration of low-RI SiO₂ nanoparticles (~1.46) and the controlled orientation of ZnO nanowires create an 'effective medium' where the composite RI is closely

matched to the EVA. Furthermore, the photon scattering process is optimized by the preferential (002)-axis alignment of the ZnO nanowires; this alignment facilitates forward-scattering of light and minimizes back-reflection. The uniform dispersion provided by the CNC network prevents the formation of large agglomerates that would otherwise act as scattering centers (Mie scattering), thus maintaining high transparency even with the addition of crystalline reinforcements.

We found that the sample sizes ranged between 10-100 nm, with an average grain size of 40-45 nm. The optical behavior of the composite films can also be interpreted in relation to the crystallite size derived from the XRD analysis. According to the Scherrer equation, the average crystallite size of the ZnO phase remains within the nanoscale regime, which is significantly smaller than the wavelength ranges of visible light (400–700 nm). Under these conditions, light scattering follows a transition between Rayleigh and Mie scattering regimes. When nanoparticles remain well dispersed and their effective scattering diameter is considerably smaller than the incident wavelength, scattering losses remain minimal and forward transmission dominates. However, when local agglomeration occurs or the effective particle size approaches the optical wavelength scale, Mie scattering becomes more pronounced, resulting in wavelength-dependent optical losses and increased haze. This interpretation supports the observed high transparency of the well-dispersed hybrid films while explaining the slight reduction in transmission observed in systems with larger effective particle domains.

6. Conclusion

The study encompassed four polymer-ceramic hybrid and bio-inspired nanocomposite encapsulant systems: neat EVA as control; EVA/ZnO; EVA/SiO₂; and EVA/ZnO–SiO₂–CNC nanocomposites subjected to standardized mechanical (ASTM D638, ISO 180) and accelerated aging (IEC 61215) testing protocols, corroborated by ANSYS SPEOS multiphysics numerical simulation. The key findings of the work are summarized as follows: (1) The fracture toughness of the EVA/ZnO–SiO₂–CNC hybrid composite was improved by 45% (1.2 to 1.74 MPa·m^{1/2}), the tensile strength by 314% (3.7 to 15.3 MPa) and the impact energy by 37% (2.0 to 2.77 kJ/m²), in relation to the neat EVA material. This improvement is attributed to the toughening effect of ZnO nanowire crack-bridging and pull-out mechanisms, and covalent interfacial adhesion between the silane-functionalized CNC and the EVA matrix. It is important to note that the localized peak stresses predicted by nanoscale simulations, where a 'Safety Factor = 1' indicates the onset of local yielding rather than immediate fracture, are reconciled with the macroscopic tensile strengths through appropriate Representative Volume Element (RVE) boundary conditions; (2) the retained elastic modulus after aging was found to be >90% for the hybrid composite after 2000 h of damp-heat aging, compared to 70–80% for neat EVA, verifying that the presence of the nanowire-CNC network effectively suppresses photoinitiated chain scission and hydrolytic degradation mechanisms, including acetic acid formation; (3) the EVA/ZnO NW composite exhibited >94.5% visible (400–800 nm) transmittance and <5% haze, attributed to the forward-scattering preferential orientation of the highly aligned EVA-incorporated nanowires that result in a reduced effective refractive index mismatch between the filler and the host polymer; (4) the EVA/SiO₂ system provided the highest UV blocking (50% transmittance at 300–400 nm), which can be leveraged to provide better protection for silicon cells from ultraviolet light-induced degradation during long-term outdoor use. Stress distributions captured by ANSYS SPEOS simulations were shown to be consistent with the underlying nanoscale mechanisms that were probed experimentally, and the seemingly paradoxical contrast between predicted nanoscale peak stresses and macroscopic tensile strengths is shown to be reconciled by the adoption of appropriate boundary conditions on the representative volume elements (RVEs). Overall, the results demonstrate that a path toward bio-compatible, high-performance PV encapsulants that break the fundamental stiffness–transparency trade-off in conventional polymers can be realized, while future efforts should include long-term field validation studies in real climatic conditions, homogenization of the RVEs to link nano- and macro-scale simulation results, and optimization of CNC loading to better balance moisture-barrier and optical performance.

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