Analysis of the Effect of Polyester and Vinyl Ester Mixture on the Mechanical and Physical Properties of Composite Matrix

Ranto Saputra[1*], Rahmat Fajrul[2], Murdani[3]

[1,2,3]Department of Mechanical Engineering, Politeknik Negeri Bengkalis, Riau, Indonesia
Coresponden author:
Email: ranto17032022@gmail.com

Abstract.
The application of pure polyester resin as a polymer composite matrix is often limited by its inherent brittleness and low impact resistance. This study investigates the effects of incorporating vinyl ester resin into a polyester matrix at various weight ratios (100:0, 90:10, 80:20, 70:30, 60:40, and 50:50) using 1 vol% Methyl Ethyl Ketone Peroxide (MEKP) catalyst. Physical properties (density and porosity) were evaluated via Archimedes' fluid displacement principle, while impact toughness was characterized using Charpy impact testing according to ASTM D6110 standards. Fractographic and phase morphology analyses were conducted using Scanning Electron Microscopy (SEM). The experimental results demonstrate a progressive increase in impact toughness with higher vinyl ester concentrations, rising from 2.79 kJ/m² in pure polyester to a maximum value of 6.51 kJ/m² in the 50:50 blend, representing an improvement of approximately 133%. Physical evaluation showed a minor decrease in density from 1.182 g/cm³ to 1.155 g/cm³ and a slight increase in porosity up to 1.45%, which remained well below critical structural limits. SEM micrographs revealed a clear transition from a smooth, flat, brittle cleavage fracture in pure polyester to a rough, ductile-dominated fracture surface characterized by deep tear ridges and plastic deformation in higher vinyl ester blends, with no phase separation observed. Overall, the 50% polyester and 50% vinyl ester blend formulation provides the optimal combination of impact toughness, structural integrity, and phase compatibility for composite matrix applications.
Keywords: *Polymer blending, Polyester resin, Vinyl ester resin, Impact strength and Microstructure*

I. INTRODUCTION

The development of modern material technology is currently advancing rapidly alongside the increasing demands of the manufacturing industry for high-performance, lightweight, corrosion-resistant, and cost-effective materials. One of the composite materials most widely researched and applied across engineering industries is fiber-reinforced polymer (FRP). In composite fabrication, the polymer resin matrix plays a vital role as it serves as a binder to hold the fibers together, transfers static and dynamic loads between fibers, and protects the fiber surfaces from environmental exposure and mechanical damage. Consequently, selecting and engineering the mechanical and physical properties of the matrix material is a fundamental key in determining the final quality and performance of the composite.

Among the various types of synthetic polymer resins available on the market, polyester is a thermosetting resin that widely dominates and finds extensive application in industrial manufacturing. The popularity of polyester resin is primarily supported by its abundant availability, highly economical procurement cost, low viscosity—which facilitates easy molding—and relatively fast curing capabilities at ambient room temperature. Despite its economic advantages and ease of processing, pure polyester resin inherently exhibits significant mechanical drawbacks. It tends to be brittle, has relatively low resistance to sudden impact loads (impact toughness), and is susceptible to volumetric shrinkage and micro-cracking during the curing process.

On the other hand, vinyl ester resin has emerged as a premium polymer material designed to overcome the various mechanical limitations associated with polyester. Vinyl ester resin offers superior mechanical properties, particularly regarding molecular chain flexibility, impact toughness, fatigue resistance, and excellent chemical and hydrolysis resistance. The chemical structure of vinyl ester, containing fewer ester groups compared to polyester, renders it more resistant to degradation in aggressive environments. However, utilizing pure vinyl ester resin on a massive production scale is often constrained by its significantly higher raw material costs, higher viscosity, and the need for stricter technical parameter controls during processing.

Considering the advantages and limitations of both resin types, polymer blending of polyester and vinyl ester presents a highly potential and economical material engineering approach. This polymer blending technique aims to combine the best characteristics of both materials: obtaining a composite matrix with high mechanical strength and impact toughness similar to vinyl ester, while retaining the cost efficiency and processing ease of polyester. This combination is expected to produce a well-proportioned hybrid matrix where incorporating varying weight percentages of vinyl ester into the polyester matrix can hypothetically mitigate the brittleness and stiffness that represent the primary drawbacks of pure polyester.

To ensure effective mixing and molecular bonding within the polymer matrix, selecting an appropriate curing agent or catalyst, alongside a proper homogenization process, is a vital technical parameter. In the thermosetting polymer polymerization process, the use of Methyl Ethyl Ketone Peroxide (MEKP) serves as an initiator to trigger cross-linking reactions between resin molecules. The dosage and proportion of the added MEKP catalyst must be carefully measured relative to the resin volume to ensure the curing process proceeds optimally without triggering excessive exothermic heat, which could otherwise damage the structural integrity of the matrix or induce porosity flaws.

Evaluating the mechanical properties of this hybrid matrix composite is an essential step to determine the precise effects of the matrix mixture variations. Among the most critical mechanical tests used to assess material ductility and resistance to sudden shock loads is the impact test. Based on the international standard ASTM D6110, the Charpy impact test method is widely employed to measure the amount of energy absorbed by a material specimen during fracture caused by a pendulum strike. The resulting impact strength values provide a quantitative measure of how effectively increasing the proportion of vinyl ester resin enhances the toughness and elasticity of the polyester matrix.

In addition to mechanical properties, understanding physical properties such as density and porosity is closely related to evaluating the overall quality of the composite matrix. Density measurements are conducted based on Archimedes' principle to determine the internal structural compactness of the specimens. The presence of void spaces or porosity within the composite matrix can act as stress concentration sites that potentially accelerate crack initiation and structural failure when subjected to mechanical loads. Therefore, evaluating porosity and density values is crucial to verify whether the mixing and molding processes resulted in a homogeneous and dense structure.

To reinforce and confirm the quantitative data from mechanical and physical testing, macroscopic observations and fractographic microstructural analyses using Scanning Electron Microscopy (SEM) must be conducted on the impact specimen fracture surfaces. Through SEM analysis, microscopic fracture modes—whether brittle fracture characterized by smooth and flat cleavage surfaces, or ductile fracture characterized by rough and torn surfaces—can be precisely identified. This morphological analysis also provides direct visual evidence regarding phase homogeneity between the polyester and vinyl ester blend, as well as the energy absorption mechanisms occurring at the microscale during impact.

Based on this technical background and material engineering urgency, this research was comprehensively conducted to analyze the effects of varying polyester and vinyl ester resin mixture percentages on the mechanical properties, physical properties, and microstructural characteristics of the composite matrix. The evaluated matrix composition ratios (polyester:vinyl ester) include 100%:0%, 90%:10%, 80%:20%, 70%:30%, 60%:40%, and 50%:50%, with a constant MEKP catalyst addition of 1%. This study is expected to provide scientific insights and recommend an optimal hybrid composite matrix formulation in terms of mechanical strength, impact toughness, and physical quality for future composite-based engineering applications.

II. METHODS

The primary raw materials utilized in this experimental study consisted of unsaturated polyester resin and vinyl ester resin as the dual-polymer matrix components. Methyl Ethyl Ketone Peroxide (MEKP) was employed as the catalyst or curing initiator at a fixed concentration of 1% by volume across all formulation variants. Silicone rubber molds fabricated according to standard testing dimensions were used for specimen casting, alongside auxiliary materials such as mold release wax, acetone for equipment cleaning, and distilled

water for physical property measurements. The primary testing apparatus included a Charpy impact testing machine conforming to ASTM D6110 standards, a high-precision digital analytical balance with an accuracy of 0.0001g for mass determinations, a Scanning Electron Microscope (SEM) for microstructural fractography, and digital vernier calipers for precise specimen dimensional verification.

Physical property evaluations involved determining the experimental density, theoretical density, and porosity percentage of the cast matrices based on Archimedes' fluid displacement principle. The dry specimen mass was first measured in air, followed by measuring its submerged mass while suspended in distilled water to compute the experimental density. Theoretical density values were derived using the rule of mixtures based on the individual weight fractions and measured densities of pure polyester and vinyl ester resins. Consequently, the percentage of volumetric void fraction or porosity was determined by calculating the relative difference between the theoretical density and the experimental density.

To complement the quantitative mechanical and physical data, fractographic and microstructural analyses were performed on the fracture surfaces of post-impact tested specimens using Scanning Electron Microscopy (SEM). Selected fractured samples from representative composition groups were mounted and sputter-coated with a thin conductive gold layer to mitigate surface charging during imaging. SEM micrographs captured at various magnification levels were examined to identify microscopic failure modes—distinguishing between brittle cleavage and ductile tearing—as well as to assess phase compatibility, interfacial homogeneity between the resin blends, and the presence of micro-voids or crack initiation sites.

.

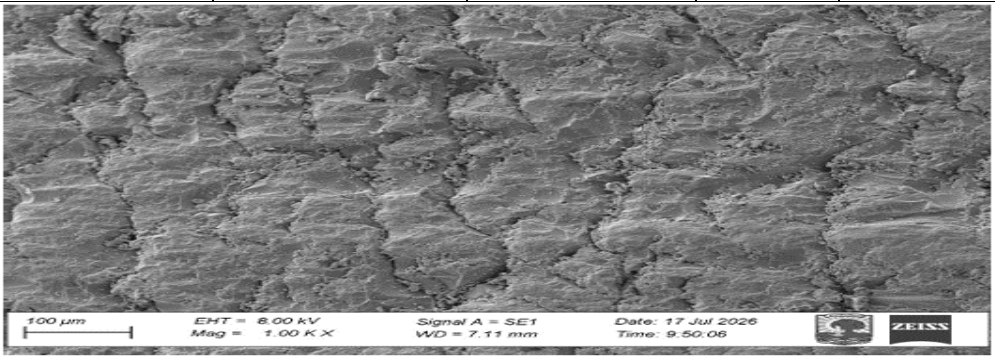
III. RESULTS AND DISCUSSION

Physical and Mechanical Properties Analysis

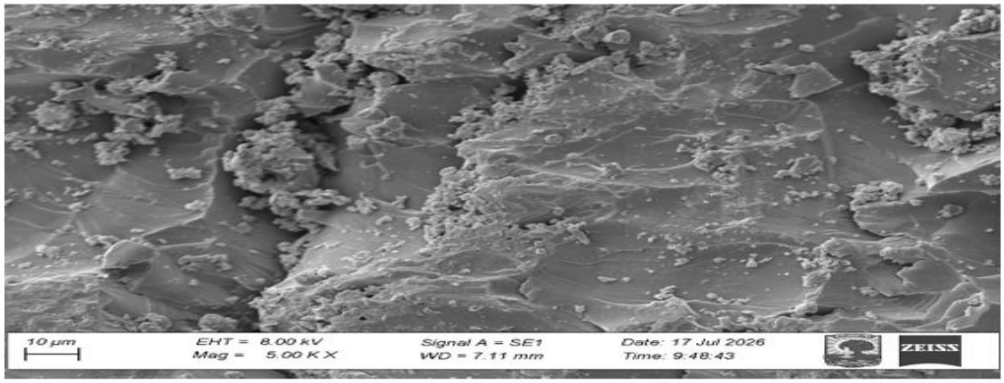
The physical properties (experimental density and porosity) and mechanical performance (Charpy impact strength) of the polyester and vinyl ester resin blend composite matrices were evaluated across six different composition ratios. The test results demonstrate that incorporating vinyl ester resin into the polyester matrix significantly influences both the physical compactness and the impact energy absorption capability of the material. The quantitative data for experimental density, theoretical density, porosity, absorbed energy, and impact strength are summarized in Table 1.

Table 1. Physical and mechanical test results of polyester/vinyl ester resin blends.

Matrix Code	Polyester : Vinyl Ester (wt%)	Experimental Density (g/cm3)	Theoretical Density (g/cm3)	Porosity (%)	Absorbed Energy (J)	Impact Strength (kJ/m2)
V0	100 : 0	1.182	1.182	0.00	0.45	2.79
V1	90 : 10	1.178	1.180	0.17	0.52	3.22
V2	80 : 20	1.173	1.178	0.42	0.61	3.78
V3	70 : 30	1.168	1.176	0.68	0.74	4.59
V4	60 : 40	1.162	1.174	1.02	0.88	5.46
V5	50 : 50	1.155	1.172	1.45	1.05	6.51



As presented in Table 1, the pure polyester matrix (V0) exhibited the lowest impact strength of 2.79kJ/m}^2 with an absorbed energy of 0.45. With the incremental addition of vinyl ester resin from 10% (V1) up to 50% (V5), a consistent and significant increase in impact toughness was observed.



The V5 formulation (50% P : 50% VE) achieved the highest impact strength of 6.51kJ/m^2 and an absorbed energy of 1.05 , representing a remarkable increase of approximately 133% compared to the pure polyester matrix. This enhancement is primarily attributed to the superior molecular chain flexibility and toughness of vinyl ester, which effectively alleviates the inherent brittleness of the cross-linked polyester network.

3.2. Microstructural and Fractographic Analysis (SEM)

To further understand the failure mechanisms and phase morphology corresponding to the impact test results, Scanning Electron Microscopy (SEM) was performed on the fracture surfaces of the post-impact specimens. The microscopic observation provides valuable insights into how phase homogeneity, surface roughness, and fracture modes evolve as a function of resin blend composition. Table 2 summarizes the primary microstructural features and dominant fracture modes observed for each matrix variation.

Table 2. Microstructural characteristics and fracture modes from SEM observations.

Matrix Code	Polyester : Vinyl Ester (wt%)	Surface Roughness & Tearing Features	Phase Homogeneity	Dominant Fracture Mode
V0	100 : 0	Very smooth, flat cleavage planes	Single phase	Pure Brittle Fracture
V1	90 : 10	Mostly smooth with minor river-line patterns	Good phase integration	Predominantly Brittle
V2	80 : 20	Moderate river pattern ridges and fine micro-cracks	Uniform dispersion	Semi-Brittle / Quasi-Ductile
V3	70 : 30	Noticeable surface roughness with river-like steps	Good co-continuous phase	Mixed Mode
V4	60 : 40	Highly textured, wavy plastic deformation ridges	High phase compatibility	Quasi-Ductile
V5	50 : 50	Deep tear ridges, rough deformation steps, micro-voids	Excellent molecular interpenetration	Ductile-Dominated Fracture

Microstructural analysis of the pure polyester specimen (V0) revealed a classic brittle fracture surface characterized by smooth, flat cleavage planes and sharp crack propagation paths, indicating minimal plastic deformation and low energy absorption prior to failure. In contrast, as the vinyl ester content was increased (V1 to V3), the fracture surfaces gradually transitioned from flat cleavage to textured morphologies exhibiting river-line patterns and micro-yield lines, which signify enhanced resistance to crack propagation.

For the higher vinyl ester formulations, particularly V4 and V5 (40%and 50 %VE), the SEM micrographs displayed highly tortuous fracture paths, prominent plastic deformation ridges, and deep tear lines. These rough microstructural features confirm that a significant amount of impact energy was dissipated through localized plastic deformation and matrix yielding before catastrophic failure occurred. Furthermore,

no distinct phase separation between polyester and vinyl ester was detected across all blend variations, confirming excellent interfacial compatibility and molecular co-curing under the action of the 1% MEKP catalyst. This seamless phase integration plays a decisive role in facilitating efficient stress transfer across the polymer blend, resulting in the superior impact toughness observed in the mechanical evaluation.

IV. CONCLUSION

Based on the comprehensive evaluation of the physical, mechanical, and microstructural properties of polyester and vinyl ester resin blend composite matrices, several important conclusions can be drawn. The incorporation of vinyl ester resin into the polyester matrix significantly enhances the overall impact toughness and energy absorption capabilities of the material. The impact strength increases progressively with higher vinyl ester concentrations, rising from the baseline formulation up to the maximum blend ratio. This achievement represents a substantial improvement in impact resistance compared to the baseline pure polyester resin, demonstrating the effectiveness of polymer blending in successfully overcoming the inherent brittleness of pure polyester.

In terms of physical characteristics, increasing the proportion of vinyl ester resin results in a slight reduction in experimental density as the composition shifts. Concurrently, the calculated porosity exhibits a minor upward trend, which is primarily attributed to the higher viscosity of the vinyl ester resin that promotes slight air entrapment during manual blending and casting. Nevertheless, because the total porosity remains well below critical thresholds, the internal defect density is kept low enough that it does not compromise the substantial mechanical gains provided by the vinyl ester addition.

Microstructural fractography conducted via Scanning Electron Microscopy further supports and confirms the mechanical testing outcomes. The microscopic images reveal a distinct transition in the dominant failure mode, shifting from a smooth, flat, brittle cleavage surface in pure polyester to a highly textured, ductile-dominated fracture surface characterized by prominent tear ridges and plastic deformation steps in higher vinyl ester blends. Furthermore, no distinct phase separation is observed across all blend variations, proving excellent phase compatibility and molecular co-curing between the polyester and vinyl ester resins under the action of the catalyst. Overall, the balanced blend formulation is identified as optimal, offering superior impact resistance and structural integrity for advanced composite applications.

REFERENCES

[1] H., Safitri, E., Pratama, N. M., Fajrul, R., & Rahmad, S. (2020). Improving impact, tensile and thermal properties of thermoset unsaturated polyester via mixing with thermoset vinyl ester and methyl methacrylate. Polymer Testing, 81, 106193.

[2] ASTM International. (2018). Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics (ASTM D6110-18). West Conshohocken, PA: ASTM International.

[3] Callister, W. D., & Rethwisch, D. G. (2020). Materials Science and Engineering: An Introduction (10th ed.). Wiley.

[4] Cheremisinoff, N. P. (2019). Handbook of Polymer Science and Technology: Performance Properties of Plastics and Elastomers. CRC Press.

[5] Hiremath, S. S., Sairam, S., & Raj, D. S. (2020). Evaluation of mechanical properties and void fraction in thermosetting polymer resin blends. Materials Today: Proceedings, 27, 1842–1847.

[6] Hull, D., & Clyne, T. W. (2019). An Introduction to Composite Materials (3rd ed.). Cambridge University Press.

[7] Mallick, P. K. (2021). Fiber-Reinforced Composites: Materials, Manufacturing, and Design (4th ed.). CRC Press.

[8] Nusyirwan, N., Abral, H., Fajrul, R., & Saputra, R. (2022). Identification of mechanical strength for mixture of thermoset polyester with thermoset vinyl ester due to bending load. ***Jurnal Mesin dan Pengelasan (JMPM),*** 6(1), 20–28.

[9] Nusyirwan, N., & Abral, H. (2024). Method of increasing the fracture toughness of unsaturated polyester with the addition of vinyl ester as a material for automotive body. ***American Journal of Materials Science and Application,*** 9(1), 1–8.

[10] Ratna, D. (2018). Modification of Thermoset Resins for Toughening and High Performance. Progress in Polymer Science, 33(3), 332–345.

[11] Saputra, R., Fajrul, R., & Murdani, M. (2024). Analisis pengaruh campuran poliester dan vinyl ester terhadap sifat mekanik dan fisik matriks komposit. Draft Skripsi Jurusan Teknik Mesin, Politeknik Negeri Bengkalis.

[12] Satapathy, B. K., & Weidisch, R. (2017). Fractography and failure analysis of thermosetting polymer blends. ***Journal of Applied Polymer Science***, 134(12), 44612.

[13] Spectrum, C., & Thomas, S. (2021). Polymer Blends: Morphology, Compatibilization, and Properties. Springer Nature.

[14] Thomas, S., Joseph, K., Malhotra, S. K., Goda, K., & Sreekala, M. S. (2019). Polymer Composites: Macro- and Microcomposites. Wiley-VCH.

[15] Yousif, B. F., & Ku, H. (2020). Physical and mechanical characterization of blended thermoset resin matrices for structural applications. ***Journal of Composite Materials***, 54(15), 2045–2058.