Jurnal Rekayasa Mesin
p-ISSN: 1411-6863, e-ISSN: 2540-7678
Vol.21, No.2, August **2026**, hal. 169-176

Engineering the Impact Toughness and Morphological Integrity of Ramie Fiber Reinforced Rosin Composites via Plasticizer Optimization

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Submitted: 03-06-2026; Accepted: 20-07-2026; Published: 31-08-2026

Abstract

Driven by rapid technological advancements, material trends have increasingly shifted toward Natural Composites (NACO), primarily owing to their renewability and recyclability. Nevertheless, the utilization of natural resins such as rosin (gondorukem) as a matrix frequently yields brittle characteristics, necessitating the incorporation of plasticizers to enhance their mechanical properties. Despite this, the specific influence of varying plasticizer concentrations on the physical stability, underlying fracture mechanisms, and macro and microstructural properties of rosin ramie composites remains largely unexplored. This study aims to engineer and evaluate the effect of plasticizer concentration (15% and 30%) on the impact toughness, absorbed energy, and structural characteristics of rosin matrix ramie fiber composites. An experimental approach was employed using ASTM D256 standard for impact testing, coupled with macro and microstructural morphological analyses. The findings indicate that the maximum average impact toughness reached 0.0735 J/mm² at a 30% plasticizer concentration. Interestingly, the maximum single absorbed energy of 9.880 J was observed at 15% concentration, yielding a specific impact value of 0.0689 J/mm². This discrepancy occurs because the 30% plasticizer provides a more uniform plastic deformation capability across samples, whereas the 15% concentration exhibits localized rigid resistance before catastrophic failure. Morphological analyses revealed fracture mechanisms including fiber pull out, matrix cracking, and oxidation, which correlate directly with the mechanical performance. Altering the plasticizer concentration significantly influences the polymer chain mobility and interfacial bonding of the composites. The 30% concentration optimally prevents micro crack propagation, offering significant practical value for developing sustainable, impact resistant green engineering materials.

Keywords: *absorbed energy; green engineering materials; impact toughness; morphological analysis; rosin ramie composites.*

Abstrak

Didorong oleh kemajuan teknologi yang pesat, tren material semakin bergeser ke arah Komposit Alami (NACO), terutama karena sifatnya yang dapat diperbarui dan didaur ulang. Namun demikian, penggunaan resin alami seperti rosin (gondorukem) sebagai matriks seringkali menghasilkan karakteristik rapuh, sehingga diperlukan penambahan plasticizer untuk meningkatkan sifat mekaniknya. Meskipun demikian, pengaruh variasi dari konsentrasi plasticizer berpengaruh terhadap stabilitas fisik, mekanisme fraktur yang mendasarinya, dan sifat makro dan mikrostruktural komposit rosin rami masih belum banyak dieksplorasi. Studi ini bertujuan untuk merekayasa dan mengevaluasi pengaruh konsentrasi plasticizer (15% dan 30%) terhadap ketangguhan impak, energi yang diserap, dan karakteristik struktural komposit serat rami matriks rosin. Pendekatan eksperimental digunakan dengan menggunakan standar ASTM D256 untuk pengujian impak, yang dipadukan dengan analisis morfologi makro dan mikrostruktural. Hasil penelitian menunjukkan bahwa ketangguhan impak rata-rata maksimum mencapai 0,0735 J/mm² pada konsentrasi plasticizer 30%. Menariknya, energi serapan tunggal maksimum sebesar 9,880 J diamati pada konsentrasi 15%, menghasilkan nilai dampak spesifik sebesar 0,0689 J/mm². Perbedaan ini terjadi karena plasticizer 30% memberikan kemampuan deformasi plastis yang lebih seragam di seluruh sampel, sedangkan konsentrasi 15% menunjukkan resistensi kaku yang terlokalisasi sebelum kegagalan katastropik. Analisis morfologi mengungkapkan mekanisme fraktur termasuk penarikan serat, retak matriks, dan oksidasi, yang berkorelasi langsung dengan kinerja mekanik. Mengubah konsentrasi plasticizer secara signifikan memengaruhi mobilitas rantai polimer dan ikatan antarmuka komposit. Konsentrasi 30% secara optimal mencegah penyebaran retakan mikro, menawarkan nilai praktis yang signifikan untuk pengembangan material rekayasa hijau yang berkelanjutan dan tahan benturan.

Kata kunci: absorbed energy; green engineering materials; impact toughness; morphological analysis; rosin ramie composites.

1. Introduction

A contemporary paradigm shift in materials technology is catalyzing a transition away from conventional synthetic composites in favor of Natural Composites (NACO) [1]. This developmental imperative is underpinned by the favorable ecological profile of NACO, characterized by their environmental compatibility, high recyclability, and renewable nature [2]. Consequently, the acceleration of innovation is now increasingly directed toward harnessing biodegradable composite biomaterials, capitalizing on the vast potential of natural fibers and resins that are abundantly available in the natural environment [3].

Within the realm of natural reinforcements, ramie fiber (*Boehmeria nivea*) has emerged as a premier candidate, distinguished by its low density, superior moisture resistance, and mechanical performance that rivals that of synthetic fibers [4]. This structural superiority is deeply rooted in its intrinsic chemical composition; specifically, the cellulose fraction dominates, comprising 69% to 91% of the material, which is substantially higher than its hemicellulose content of merely 5% to 15%. Such a high cellulose ratio directly correlates with exceptional tensile strength, yielding values that typically range from 400 to 938 MPa. Consequently, ramie fiber is widely recognized as one of the most rigid and robust natural fibers available, rendering it a highly promising reinforcing agent for enhancing the overall mechanical integrity of composite materials [5].

As the binding phase (matrix), *Resina Colophonium* (rosin) presents substantial potential due to its thermoplastic nature, enabling it to liquefy upon heating and resolidify upon cooling [6]. The application of this pine derived resin as an organic matrix is further validated by its sufficient adhesive capability and inherent hydrophobicity, which are highly desirable for engineered composite structures [7]. Previous studies have demonstrated that integrating this matrix can significantly enhance the material's tensile strength, elevating it from 162.27 MPa at a 15% mass fraction to a peak of 244.35 MPa at 30%, before subsequently declining. Nevertheless, the primary limitation of rosin lies in its inherent brittleness and high susceptibility to fracture in its solid state. To mitigate this constraint, matrix modification is undertaken by incorporating plasticizing agents namely, glycerol and corn starch to induce plasticity and concurrently enhance the material's ductility [8].

Prior investigations into the effects of incorporating glycerol and corn starch plasticizers into a rosin matrix reinforced with ramie fibers were pioneered by Zein et al. [9]. Utilizing hand lay up and compression molding techniques in strict accordance with the ASTM D5942-96 standard, their research evaluated various combinations of plasticizer concentrations (15 wt% and 20 wt%) alongside differing fiber mass fractions (20 wt%, 25 wt%, and 30 wt%). The resulting data revealed a fluctuating trend in the composite's impact toughness; notably, the peak impact toughness was recorded at 0.588 J/mm² for the configuration comprising a 20 wt% fiber mass fraction and a 20 wt% plasticizer concentration [10].

Although the mechanical properties (such as impact and tensile behaviors) of rosin matrix ramie composites have been extensively documented, a comprehensive investigation into the implications of varying plasticizer concentrations on their physical stability and macro and microstructural characteristics remains largely unexplored. To address this specific research gap, the present study employs an experimental approach to thoroughly investigate the influence of varying plasticizer concentrations specifically at 15% and 30% on the impact toughness and the macro and microstructural morphology of rosin matrix ramie fiber composites.

2. Material and Method

This study employs a laboratory based experimental approach to evaluate the influence of plasticizer concentration on the physical and mechanical properties of the composite. Guided by the experimental design, the fabrication process was structured into two primary variants, both characterized by a unidirectional fiber alignment at a 0° angle. The first variant incorporates a 15% plasticizer addition, whereas the second introduces a 30% plasticizer content relative to the total rosin matrix [11].

The preliminary phase of this research commenced with a comprehensive literature review, followed by the meticulous preparation of all requisite equipment and materials. The primary constituents utilized in this study were natural ramie fibers and rosin resin. Prior to composite fabrication, the ramie fibers were subjected to an alkali treatment, which involved submerging them in a sodium hydroxide (NaOH) solution for a duration of 2 hours [12]. This pretreatment is strategically designed to degrade and eliminate lignin, hemicellulose, and surface impurities, thereby significantly enhancing the interfacial bonding strength between the ramie fibers and the rosin matrix.

2.1. Sample Preparation

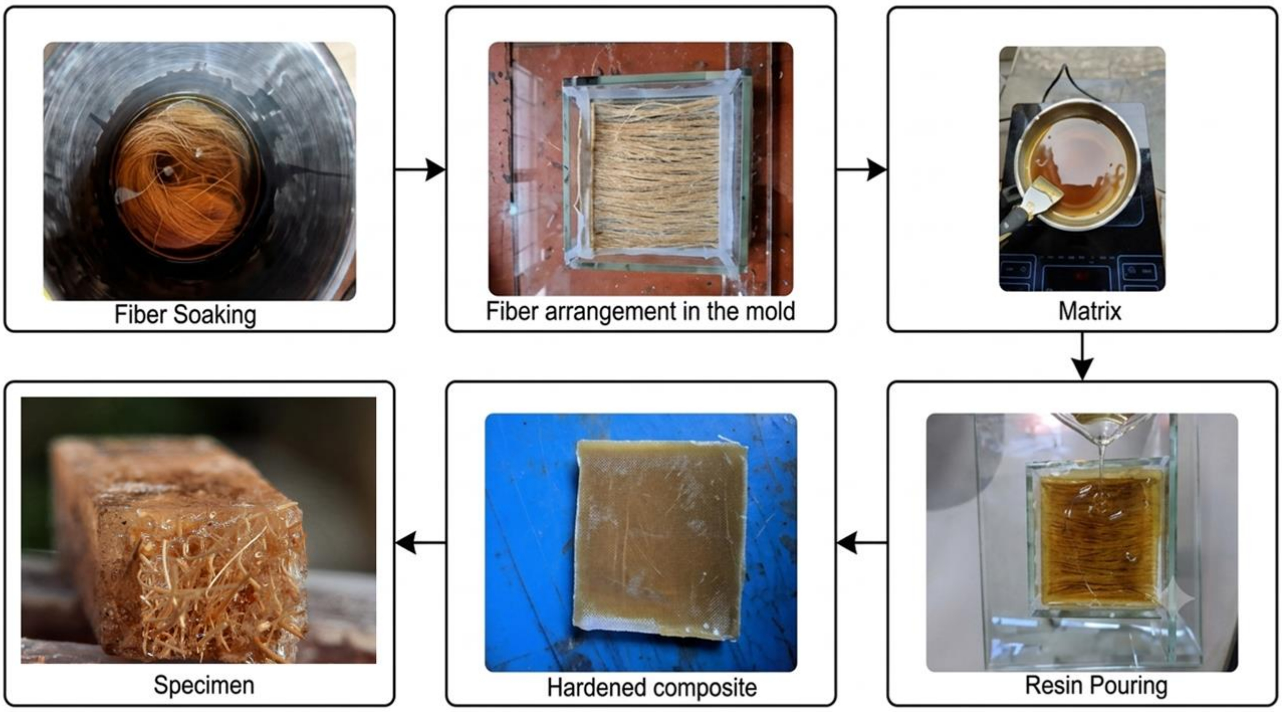

Figure 1. Composite Fabrication Process with Gondorukem Reinforcement

The composite fabrication was executed utilizing the hand lay up technique within a glass mold. Following the drying process, the ramie fibers were meticulously aligned in a unidirectional configuration at a 0° angle inside the mold. Concurrently, the rosin matrix was blended with the plasticizer at the predetermined concentrations of 15% and 30% [13]. This homogenous matrix mixture was subsequently poured uniformly over the arranged ramie fibers. The assembly was then allowed to cure at ambient temperature until the matrix fully solidified. Upon complete curing, the fabricated composite was carefully demolded with the assistance of a scraper [14].

Following fabrication, the composite panels underwent a meticulous specimen preparation process. The cutting procedure was executed with strict adherence to the standard dimensional requirements for impact testing, yielding specimens measuring 55 mm in length, 10 mm in width, and 10 mm in thickness. Once the specimens were properly dimensioned, the study proceeded to the material characterization phase. This evaluation encompassed both impact testing and comprehensive macro and microstructural analyses [15].

3. Results and Discussion

Evaluating the impact toughness of rosin matrix ramie fiber compositesmodified with glycerol and corn starch plasticizersis primarily aimed at identifying significant correlations between varying concentrations and the resulting physical characteristics of the material. Experimental data acquired via standardized thermal blending corroborates distinct alterations in mechanical properties when comparing the 15 wt% and 30 wt% plasticizer formulations [16]. Consequently, an in depth comparison of these two formulations serves as the focal point of the discussion. Within this context, the matrix plasticization phenomenon is comprehensively examined to pinpoint the optimal ratio that maximizes the composite's capacity for impact energy absorption.

Table 1. Impact Test Results

Variation	E (J)	HI (J/mm^2)	E Average (J)	HI Average (J/mm^2)
15%	7.428	0.0493	8.075	0.0588
	9.880	0.0689		
	6.917	0.0492		
30%	7.09	0.073	8.158	0.0735
	9.408	0.0799		
	7.976	0.0675		

The data presented in Table 1 indicate a progressive enhancement in the mechanical properties of the composites corresponding to increased plasticizer concentrations. The composite formulation incorporating 30% plasticizer exhibited the highest average impact toughness of 0.0735 J/mm² and an average absorbed energy of 8.158 J. By contrast, specimens formulated with a 15% plasticizer fraction demonstrated comparatively lower average performance (0.0588 J/mm² and 8.075 J) [15-16]. From a polymer engineering perspective, the underlying mechanism for this enhancement is attributed to the role of the plasticizer in increasing the free volume between the rosin polymer chains. A 30% plasticizer concentration effectively enhances the segmental mobility of the macromolecular chains, which reduces the inherent brittleness of the pure rosin matrix. This increased ductility allows the matrix to deform plastically and absorb more kinetic energy during a sudden impact before transferring the stress to the ramie fibers. These findings are consistent with previous studies by Zein et al, who noted that optimizing plasticizer ratios is critical for maximizing impact toughness in natural fiber reinforced resins.

To validate the observed mechanical phenomena and correlate the underlying molecular theory with the physical failure modes, macro and micrographic examinations were conducted on the rosin matrix ramie fiber composite specimens formulated with 15 wt% and 30 wt% plasticizer concentrations following impact testing [19-20]. This comprehensive visual analysis was critically directed toward elucidating the specific failure modes, the homogeneity of fiber dispersion, and the resulting surface topographical alterations. Ultimately, these morphological evaluations provide direct physical evidence of how varying plasticizer loadings within the polymer matrix dictate the structural integrity and damage mechanisms of the composite.

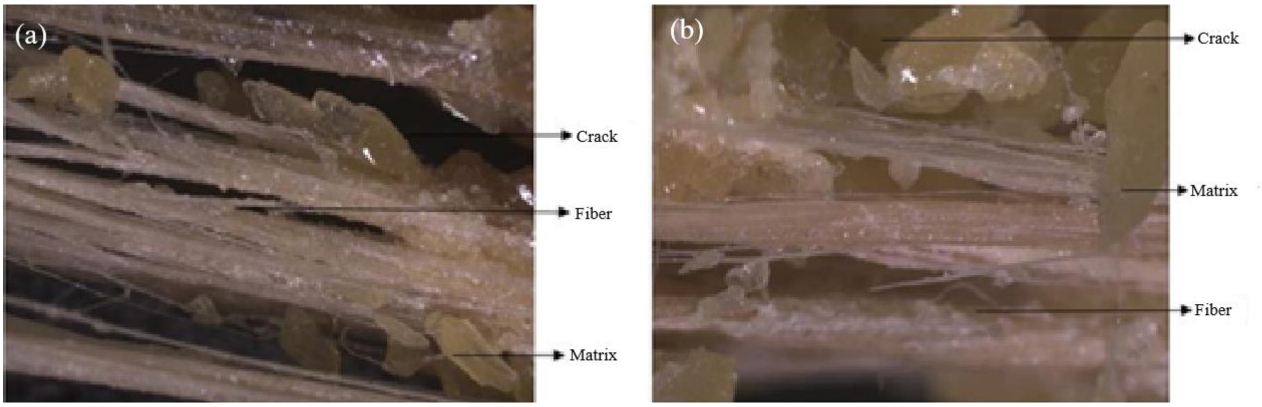

Figure 2. Results of Plasticizer Macrography Test after Impact Test (a) 15% and (b) 30%

Macrographic observations (Figure 2) explicitly corroborate the energy absorption mechanisms discussed previously. Specimens with 15% plasticizer experienced severe structural discontinuities, including localized micro cracks and void inclusions (Figure 2a). Because of the lower polymer chain mobility at 15%, the matrix was too rigid to dissipate the impact energy efficiently [21]. Conversely, elevating the plasticizer concentration to 30% induced substantial morphological refinement (Figure 2b). The enhanced fluidity of the matrix during fabrication optimized resin penetration into the intercellular spaces of the ramie fibers, creating a more compact architecture with minimized porosity.

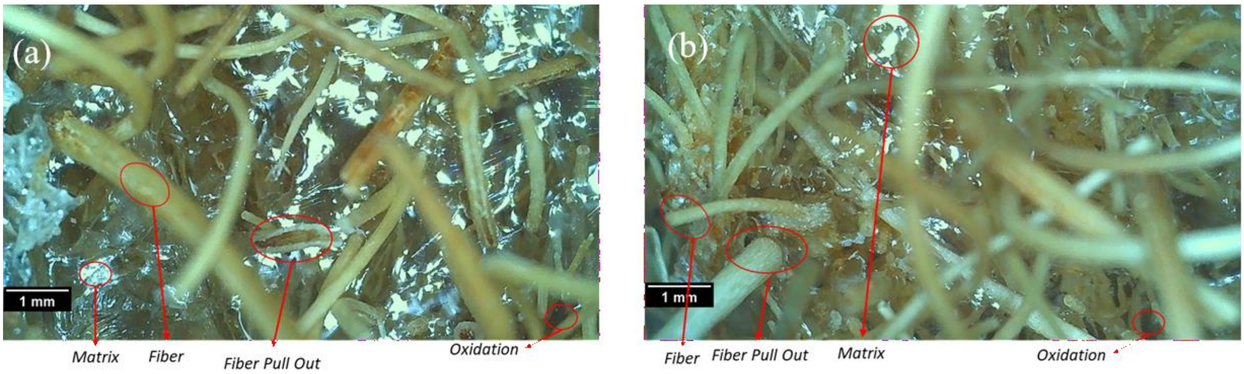

Figure 3. Micrographic Test of Plasticizer Composites (a) 15% and (b) 30% after Impact

Further micrographic analysis (Figure 3) provides deeper insight into the interfacial failure modes. The rigid matrix at 15% concentration led to rapid crack propagation and significant fiber pull out (Figure 3a). This fiber pull out indicates poor interfacial bonding, where the dynamic impact energy exceeded the adhesive strength between the ramie fibers and the rosin matrix [23]. At a 30% concentration, although oxidative degradation (dark morphological patterns) was still observed (Figure 3b), the strengthened interfacial mechanical interlocking significantly suppressed crack propagation. Ultimately, the strong internal cohesion provided by the 30% plasticizer effectively delayed catastrophic failure, thereby confirming its superior structural integrity and higher impact toughness.

4. Conclusion

This study successfully engineered and characterized ramie fiber reinforced natural composites using a rosin matrix modified with 15% and 30% plasticizer concentrations. The experimental results demonstrated that the impact toughness and energy absorption capacities are fundamentally governed by the plasticizer's ability to enhance polymer chain mobility and interfacial bonding. Mechanical optimization was achieved at a 30% plasticizer concentration, yielding a peak average impact toughness of 0.0735 J/mm². Macro and microstructural analyses validated these mechanical findings, revealing that composites with lower plasticizer content (15%) suffered from rigid matrix failure, evidenced by extensive micro cracking, void formation, and fiber pull out. In contrast, the 30% modification significantly suppressed crack propagation and improved fiber matrix adhesion. Ultimately, strategically modifying the plasticizer concentration is a critical engineering step to mitigate the inherent brittleness of natural resins. The 30% rosin ramie composite configuration demonstrates highly promising structural integrity, offering significant practical significance for the development of sustainable, impact resistant green materials in engineering applications.

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