

Mechanical Response and Fracture Morphology of Abaca Fiber-Reinforced Unsaturated Polyester Composites: The Role of Fiber Mass Fraction and Alkali Treatment

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Abstract

This study investigates the effect of alkali-treated abaca fiber mass fraction (10 wt.%, 15 wt.%, and 20 wt.%) on the mechanical response and fracture morphology of unsaturated polyester composites fabricated via compression molding, compared with an untreated 20 wt.% control. Composite specimens were characterized according to ASTM D638 and ASTM D6110, complemented by Scanning Electron Microscopy (SEM) analysis. Results demonstrated a progressive enhancement in tensile strength with increasing treated fiber fraction, rising from 10.90 ± 1.17 MPa for the control to 23.90 ± 2.90 MPa for the 20 wt.% alkali-treated composite, representing a 119.3% improvement attributable to surface modification. Young's modulus similarly increased from 188.98 ± 25.64 MPa (control) to 286.85 ± 13.36 MPa (20 wt.% treated). Impact energy absorption and toughness reached maximum values of 15.48 ± 2.72 J and 0.1190 ± 0.0200 J/mm² at 20 wt.% treated fiber loading, corresponding to improvements of 96.9% and 92.0% over the untreated control, respectively. SEM analysis confirmed that the 20 wt.% treated composite exhibited optimized interfacial bonding, characterized by minimal void content and a predominance of fiber fracture over pull-out, whereas the untreated control displayed dominant fiber pull-out due to weak interfacial adhesion caused by natural impurities. Alkali treatment combined

with 20 wt.% fiber loading is identified as the configuration for lightweight structural applications.

Keywords: Abaca fiber, alkali treatment, unsaturated polyester composite, tensile strength, impact toughness

1- Introduction

The increasing global demand for high-performance structural materials has led to the widespread use of synthetic fiber-reinforced composites, particularly glass fiber and carbon fiber-reinforced polymers, across transport, aerospace, marine, construction, and energy sectors [1]. Production of synthetic fiber composites in Europe is estimated at 2.39 million metric tons in 2011, rising to approximately 2.56 million metric tons by 2023 [2]. The extensive utilization of synthetic fibers raises significant environmental concerns due to their contribution to industrial solid waste accumulation [3]. In response to environmental sustainability targets, the global composites industry has increasingly shifted its focus toward natural fiber-reinforced polymer composites (NFRCs). NFRCs offer a compelling combination of advantages over their synthetic counterparts, including lower density, renewability, biodegradability, reduced processing energy consumption, and competitive mechanical properties at significantly lower material cost [4,5].

Among the broad spectrum of natural fibers investigated for composite reinforcement, abaca fiber has emerged as one of the most technically promising candidates. Abaca is a leaf fiber extracted from the pseudostem of the abaca plant, a species of the banana family native to the Philippines and widely cultivated across tropical regions including Indonesia, Ecuador, and Costa Rica [6]. Abaca fiber is distinguished by its exceptionally high cellulose content (60–70%), low microfibrillar angle (approximately 3°), high aspect ratio, and superior tensile strength (400–980 MPa), which collectively contribute to its outstanding mechanical reinforcement capability in polymer matrices [7]. In addition to its mechanical

merits, abaca fiber demonstrates remarkable natural resistance to saltwater degradation, making it particularly attractive for marine and outdoor structural applications. The fiber is fully biodegradable and can be cultivated with minimal agrochemical inputs, rendering it a genuinely sustainable raw material. The global market demand for abaca fiber is estimated at approximately 600,000 tons per year, with the Philippines currently supplying around 80,000 tons and Ecuador contributing approximately 10,000 tons annually [8,9]. As a tropical country with highly favorable agroclimatic conditions for abaca cultivation, Indonesia possesses significant untapped potential to expand abaca production and develop value-added abaca fiber composite products for both domestic and export markets.

The incorporation of abaca fiber as reinforcement in polymer composites has been the subject of growing research interest over the past decade. Abaca fiber-reinforced composites have demonstrated promising mechanical performance across various matrix systems, including epoxy, polypropylene, and polyester resins, with reported tensile strength values ranging from 20 to 120 MPa depending on fiber treatment, volume fraction, and fabrication method [10]. Several fabrication techniques have been employed for abaca fiber composites, including hand lay-up, resin transfer molding, and compression molding, with the latter offering superior fiber-matrix compaction, more uniform thickness, and reduced void content compared to open-mold processes [11,12]. Despite these advantages, the direct utilization of raw abaca fiber as composite reinforcement presents significant challenges. The fiber surface is naturally coated with lignin (5–10%), hemicellulose (20–25%), pectin, and waxy substances, which impart hydrophilicity to the fiber surface and create physicochemical incompatibility with hydrophobic polymer matrices [13]. This incompatibility results in poor interfacial adhesion, manifested as fiber pull-out, debonding, and void formation during loading, which collectively limit the load transfer efficiency and mechanical performance of the resulting composite. Alkali treatment (mercerization) using

sodium hydroxide (NaOH) solution has been established as the most widely adopted and cost-effective surface modification technique for natural fibers [14], effectively removing surface impurities, lignin, and hemicellulose, thereby increasing fiber surface roughness, exposing reactive cellulose hydroxyl groups, and significantly enhancing fiber-matrix interfacial bonding [15,16].

Existing studies on abaca fiber-reinforced composites have predominantly focused on epoxy or thermoplastic matrix systems, wherein alkali pre-treatments have been shown to consistently enhance mechanical properties [11,17,18]. However, the distinct curing kinetics, high volumetric shrinkage rate, and specific viscosity of unsaturated polyester (UP) resins present unique interfacial challenges that cannot be directly extrapolated from epoxy-based studies. Furthermore, the complex interplay between alkali-induced fiber surface roughness, resin wettability, and fiber compaction mechanisms under compression molding remains insufficiently characterized. In this study advances current knowledge by elucidating the specific synergistic effects of NaOH mercerization and controlled fiber mass fractions (10–20 wt.%) on the stress-transfer mechanisms and fracture evolution in compression-molded abaca/unsaturated polyester composites. This study strictly isolates the aforementioned variables to establish a clear structure-property relationship for UP-based systems. To benchmark the scientific contribution and mechanical improvements achieved in this study, the results are critically compared against recent state-of-the-art natural fiber composite literature.

The mechanical response and fracture morphology of abaca fiber-reinforced unsaturated polyester composites remain insufficiently characterized, particularly regarding fiber mass fraction variations (10–20 wt.%) under compression molding. To address the aforementioned knowledge gaps, this study systematically examines the influence of varying abaca fiber mass fractions (0 wt.%, 10 wt.%, 15 wt.%, and 20 wt.%) on the

mechanical responses and fracture surface morphology of alkali-pretreated abaca fiber/unsaturated polyester composites. Mechanical characterization encompasses Young's modulus, tensile strength, strain at break, impact energy absorption, and impact toughness. Scanning Electron Microscopy (SEM) analysis is employed to elucidate the structure-property relationships governing the observed mechanical behavior, with particular emphasis on fiber-matrix interfacial quality, defect distribution, and dominant failure mechanisms across the investigated mass fraction range. The findings of this study are expected to provide quantitative, evidence-based guidance for the optimized design of sustainable abaca fiber composite materials, contributing to the broader development of lightweight and environmentally responsible materials for industrial structural applications.

2- Methodology

2-1- Material

The abaca fiber was sourced from Sleman, Central Java (Indonesia). NaOH was sourced from Loba Chemie, India, polyester resin from PT. Justus Kimiaraya (Surabaya, Indonesia), methyl ethyl ketone peroxide (MEKP) catalyst, and resin diluent (styrene monomer) from CV. Tri Tunggal, Malang (Indonesia).

2-2- Experimental Design

Experimental research was conducted with two independent variables: the fiber surface treatment (control vs. 20% NaOH-treated) and the fiber mass fraction (10 wt.%, 15 wt.%, and 20 wt.%). The control was an unsaturated polyester resin-based composite with reinforcement of untreated 20 wt.% abaca fiber. The untreated 20 wt.% composite was selected as the control to enable direct quantification of the contribution of alkali surface modification at equivalent fiber loading. All composites were manufactured by compression molding. The dependent variables evaluated were the mechanical properties, including tensile strength and Young's modulus (ASTM D638), impact energy absorption and impact

toughness (ASTM D6110), and fracture morphology via SEM analysis. One-Way ANOVA was applied for statistical analysis, with Tukey's post-hoc test ($\alpha = 0.05$).

2-3- Procedure

2-3-1- Abaca Fiber Preparation

Abaca fibers were separated from their pseudostems and cleaned to remove surface dirt by soaking in distilled water for 30 minutes to remove dirt and residual content, followed by draining. The cleaned fibers were subsequently dried in a dehydrator oven at 60°C for 9 hours to achieve a consistent moisture and weight content prior to further processing. Fiber length was maintained in the range of 15 mm by manual cutting prior to composite fabrication.

2-3-2- Alkali Treatment of Abaca Fiber

Alkali treatment was conducted by immersing dried abaca fibers in 20 wt.% NaOH aqueous solution for 1 hour at $25 \pm 2^\circ\text{C}$. After immersion, the fibers were thoroughly rinsed with distilled water to remove residual NaOH until the rinsed water achieved a pH of 7.0. Abaca fibers were dried in a dehydrator at 60°C for 10 hours. The NaOH concentration of 20 wt.% and soaking duration of 1 hour were selected based on established protocols for natural fiber mercerization reported in the literature [14].

2-3-3- Process of Making Abaca Fiber Composite Boards

After alkali treatment and drying, the abaca fibers were weighed to achieve the target mass fractions (10, 15, and 20 wt.% relative to total composite mass). The unsaturated polyester resin was prepared by adding 1 wt.% MEKP catalyst and 5 wt.% styrene monomer diluent, and mixed thoroughly for 3 minutes to ensure homogeneity. The weighed fibers were then manually mixed with the prepared resin system in the corresponding mass ratios (fiber:resin = 10:90, 15:85, and 20:80 by mass, respectively) until uniform fiber distribution was achieved. The fiber-resin mixture was placed into a cleaned acrylic mold with internal

dimensions of 150 mm × 150 mm × 10 mm. The mold surfaces were coated with wax prior to filling to facilitate easier release of composite [19].

2-3-4- Tensile Test

Tensile testing was conducted using a Universal Testing Machine (UTM) at the Malang State Polytechnic Workshop (Malang, Indonesia), following ASTM D638 [20]. Composite panels were machined into Type I dog-bone specimens. Specimen was pulled at a crosshead speed of 1 mm/min with three replicates per formulation (n = 3). Tensile force was applied gradually until specimen fracture. Tensile strength (MPa) and Young's modulus (MPa) were determined using Eq. (1) and Eq. (2), respectively.

$$\sigma = \frac{F}{A} \quad (1)$$

$$E = \frac{\sigma}{\varepsilon} \quad (2)$$

2-3-5- Impact Testing

Impact testing was performed using a Charpy Impact Tester (Gotech Testing, China). Specimens were prepared following ASTM D6110 with dimensions of 127 mm × 12.7 mm × 10 mm. A single-edge V-notch with a depth of 2.54 mm and an included angle of 45° was machined at the specimen midpoint using a notching tool, as required by ASTM D6110. Three replicates per formulation (n = 3) were tested. Impact testing was conducted by releasing a pendulum hammer to strike the notched face of specimen at its midpoint. The energy absorbed by the specimen during fracture was recorded from the tester scale.

2-3-6- Surface Morphology Analysis

Fracture surface morphology was observed under a Hitachi TM4000Plus SEM (Japan). Specimens for SEM analysis were taken from fracture surfaces of tensile and impact test samples. Specimen samples were prepared with dimensions 10 mm x 10 mm x 10 mm. SEM images were acquired at a magnification of 40× to observe the fracture surface

characteristics, including fiber pull-out, debonding, void distribution, and matrix cracking patterns.

3- Results and Discussions

3-1- Tensile Properties

Tensile test of the abaca fiber/unsaturated polyester composites resulted in three primary mechanical parameters: tensile strength, Young's modulus, and strain at break, with results shown in Fig. 1 and summarized in Table 1. The tensile strength value is used to determine the strength of the composite to withstand tensile loads [21]. Abaca fiber composite has a minimum value of 10.902 MPa. The stress value increases with the addition of 5 wt.% fiber mass fraction, with the highest stress value obtained at a fiber variation of 20 wt.% with a value of 23.900 MPa (Fig. 1A). The strain value is obtained from the change in length of the tensile test material compared to its initial length, which occurs as a result of the application of tensile force [22]. The abaca fiber composite value in the control sample was 5.84%, then decreased to 5.375% at a mass fraction of 10 wt.%, then the strain value gradually increased to a mass fraction variation of 20 wt.%, which had a value of 8.3125%. The Young's modulus value determines the extent to which a material can stretch elastically when subjected to tensile force [23,24]. The lowest value obtained was 188.975 MPa with control variation (Fig. 1B). The Young's modulus value increases as the mass fraction increases. The highest value obtained was 286.849 MPa with a mass fraction variation of 20 wt.%. This phenomenon is also in line with results by Ravindran et al. [24].

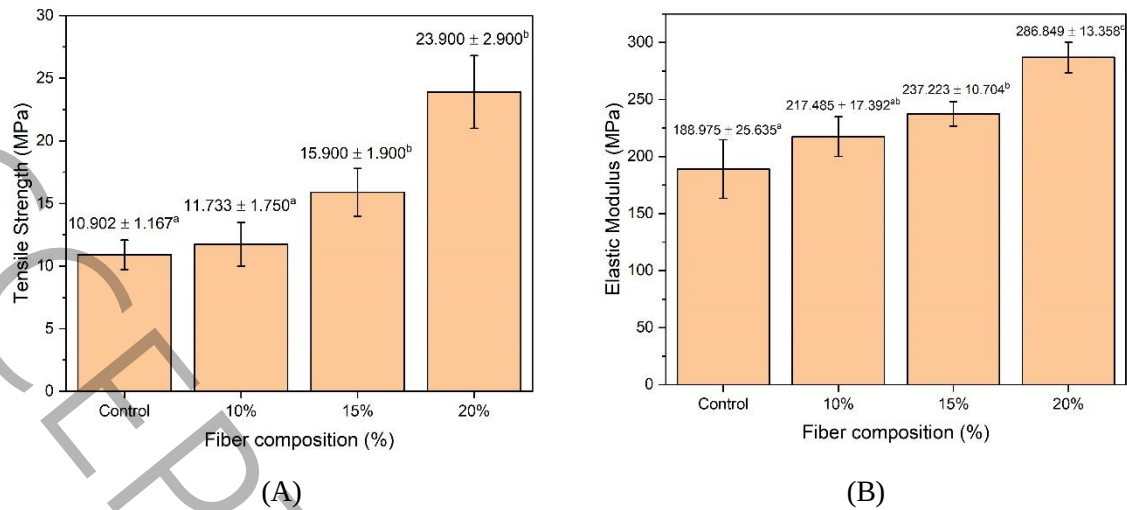


Fig. 1. Results of mechanical test of (A) Tensile test and (B) Elastic modulus of abaca fiber composite boards

Table 1. Tensile properties of abaca fiber/unsaturated polyester composites as a function of fiber mass fraction

Fiber Mass Fraction	Tensile Strength (MPa)	Young's Modulus (MPa)
Control (untreated 20wt.% abaca fiber)	10.90 ± 1.17 ^a	188.97 ± 25.64 ^a
10 wt.%	11.73 ± 1.75 ^a	217.49 ± 17.39 ^a
15 wt.%	15.90 ± 1.90 ^b	237.22 ± 10.70 ^{ab}
20 wt.%	23.90 ± 2.90 ^c	286.849 ± 13.36 ^b

Table 2 summarizes the One-way ANOVA analysis for the tensile strength data. The analysis indicates a significant difference in tensile strength among treatments due to variations in mass fraction ($p < 0.001$). The highest Young's modulus value obtained was 286.849 MPa with a mass fraction variation of 20 wt.%. This increase in stiffness with higher fiber content aligns with the expectations of the rule-of-mixtures model, which posits that the modulus increases proportionally with the volume fraction of the stiffer reinforcing fiber.

This phenomenon is also in line with results by Ravindran et al. [23]. However, it is anticipated that an optimum content exists near this 20 wt.% threshold, beyond which further fiber addition would likely cause agglomeration and inadequate resin wetting, deteriorating mechanical properties.

Table 2. One-way ANOVA of tensile strength data

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	317.99008	105.99669	25.78163	1.8273E-4
Error	8	32.89061	4.11133		
Total	11	350.88069			

The optimized tensile strength of 23.90 MPa and Young's modulus of 286.85 MPa were achieved at the 20 wt.% treated formulation demonstrates a competitive mechanical profile when compared to studies of natural fiber composites. While epoxy-based abaca composites reported in earlier studies Punyamurthy et al. [17] often achieve higher absolute tensile strengths due to the inherently superior load-bearing capacity of the epoxy matrix, the 119.3% relative improvement obtained in our unsaturated polyester system highlights the exceptional efficacy of the chosen surface modification. Furthermore, the tensile performance of these 20 wt.% treated abaca/polyester composites is highly competitive with, and in some cases surpasses, recently reported values for comparable alkali-treated kenaf or bamboo reinforced polyester systems [25,26]. This critical comparison confirms that the optimized combination of 20 wt.% abaca fiber and mercerization successfully bridges the mechanical performance gap typically associated with lower-cost unsaturated polyester matrices, providing a viable alternative to more expensive epoxy systems for specific applications.

3-2- Impact Properties

Impact testing aims to determine how a material responds to sudden loads to ascertain its ability to absorb energy [27]. Impact testing on abaca fiber composites was conducted on four composite groups with varying fiber masses. ASTM D6110 was used as a reference. The samples tested were abaca fiber composites with varying control mass fractions of 10 wt.%, 15 wt.%, and 20 wt.%. The impact test results are shown in Fig. 2 and Table 3.

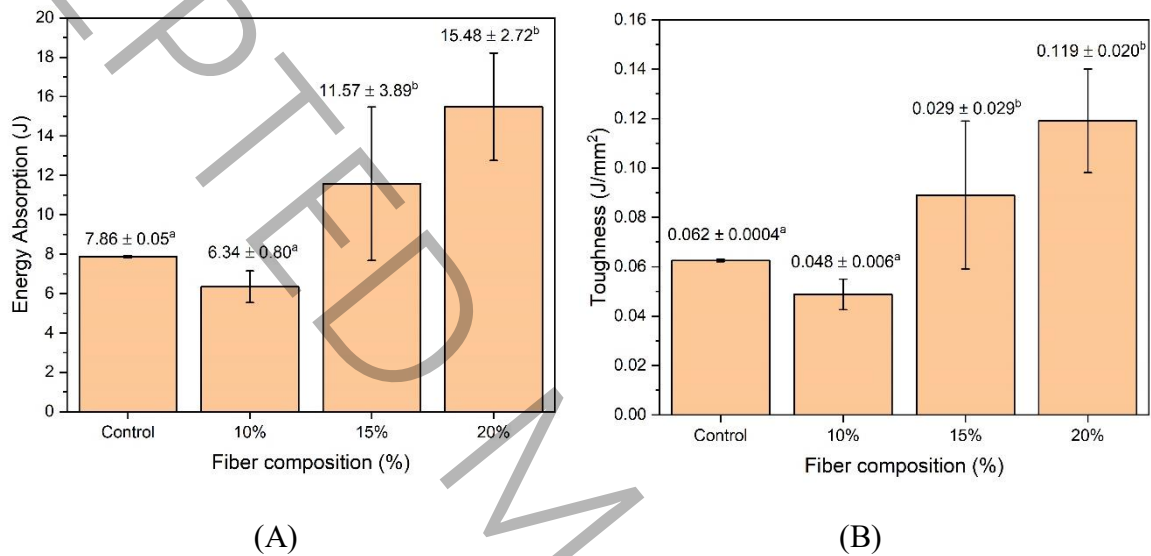


Fig. 2. Impact test results: (A) Energy absorption and (B) Toughness on abaca fiber composite boards

Table 3. Toughness of abaca fiber/unsaturated polyester composites

Fiber Mass Fraction	Absorption Energy (J)	Impact Toughness (J/mm ²)
Control (untreated 20 wt.% abaca fiber)	7.86 ± 0.05 ^a	0.0620 ± 0.0004 ^a
10 wt.%	6.34 ± 0.80 ^a	0.0488 ± 0.0060 ^a
15 wt.%	11.57 ± 3.89 ^{ab}	0.0890 ± 0.0290 ^{ab}
20 wt.%	15.48 ± 2.72 ^b	0.1190 ± 0.0200 ^b

Energy absorption is used to determine a material's ability to absorb energy during impact. The abaca fiber composite in the control sample had an energy absorption value of 7.86 J, which then decreased to 6.34 J at a mass fraction of 10 wt.%, which was also the lowest value; then the energy absorption value increased to 15.48 J at a mass fraction variation of 20 wt.%. The One-way ANOVA analysis for the energy absorption (Table 4) data indicates a significant difference in energy absorption among treatments due to variations in mass fraction ($p < 0.001$). Toughness is used to determine a material's ability to resist fracture and its ability to undergo plastic deformation before breaking. The abaca fiber composite in the control sample had a value of 0.062 J/mm², which then decreased to 0.048 J/mm² at a mass fraction variation of 10 wt.%. The toughness value then gradually increased to 0.119 J/mm² at a mass fraction of 20 wt.%.

Table 4. One-way ANOVA of energy absorption data

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	150.00787	50.00262	8.59961	0.00695
Error	8	46.5162	5.81452		
Total	11	196.52407			

An initial reduction in impact energy absorption and toughness was observed when comparing the untreated control (7.86 J; 0.062 J/mm²) to the 10 wt.% treated composite (6.34 J; 0.0488 J/mm²). The control contains 20 wt.% abaca fiber compared to 10 wt.% treated abaca fiber. So, the insufficient fiber mass fraction in the 10 wt.% formulation, which falls below the critical threshold required for effective reinforcement. This result proves that fiber loading has influence on the toughness of composite [28]. However, as the fiber fraction increased beyond this critical threshold to 15 wt.%, energy absorption increased to 15.48 J and toughness reached 0.1190 J/mm². This proves that alkali treatment is effective in improving the interfacial strength of composite, so that although composite has lower

fraction of abaca fiber, the impact toughness is higher. These results are in line with increasing composite structure reinforced with bamboo fiber composite [25], kenaf [26], flax and jute [18]. This marked improvement signifies that higher fiber densities successfully activate synergistic toughening mechanisms, including extensive crack deflection [29], fiber bridging [30], and energy-dissipating fiber fracture [31].

Compared to recent impact studies on natural fiber composites [18,27], the maximum impact energy absorption of 15.48 J obtained in this study indicates a highly efficient energy dissipation capability. This value represents a significant structural enhancement over untreated synthetic and natural fiber blends in similar polyester matrices, confirming that the optimized 20 wt.% treated abaca network effectively alters the crack propagation path and absorbs substantial impact energy prior to ultimate catastrophic failure.

3-3- Composite Fracture Morphology

Fracture morphology after tensile test is depicted in Fig. 3. The results of the tensile test morphology of abaca fiber composites show that mechanical properties increase with increasing fiber mass fraction. Tensile stress values increased from 10.90 MPa (control without alkalization) to 11.73 MPa (10 wt.% mass fraction), 15.90 MPa (15 wt.%), and reached the highest value of 23.90 MPa at a mass fraction of 20 wt.%, indicating that the fiber acts as the primary reinforcement in resisting tensile loads [32]. The low control sample value (10.90 MPa) may be caused by the bond between fibers and matrix due to absence of alkali treatment, which can leave behind a layer of lignin and impurities that act as inhibitors [33]. The strain also increased gradually from 5.37% (control) to 8.31% (20 wt.% fraction), because fibers that undergo the alkali treatment process can form stronger mechanical bonds with the matrix, enabling them to withstand greater deformation before breaking [23]. Young's modulus increased from 188.975 MPa (control) to 286.849 MPa (20 wt.% fraction), reflecting an increase in composite stiffness due to more uniform fiber distribution and

efficient load transfer. This suggests that increasing fiber mass fraction to 20 wt.% not only improves tensile strength and strain, but also optimizes elasticity of material through a better surface reinforcement mechanism.

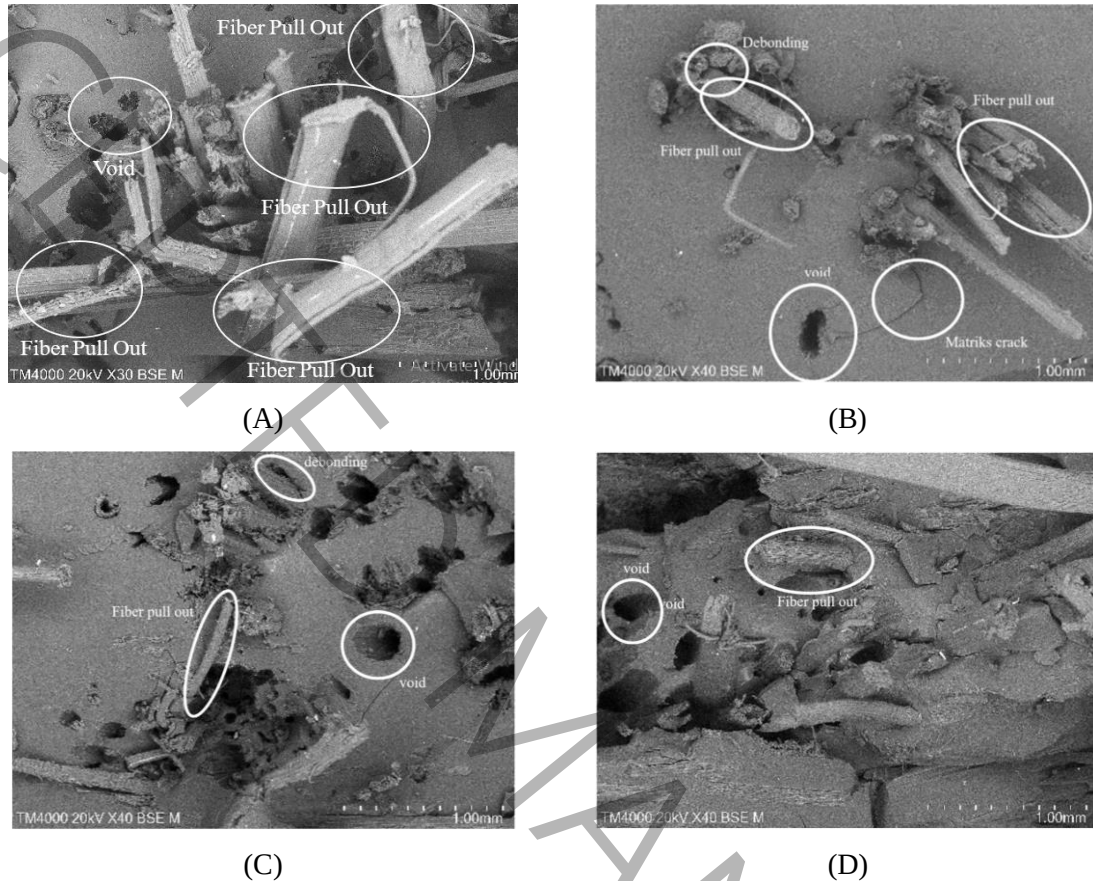


Fig. 3. Morphology of fracture surface of tensile specimen of abaca fiber composites with mass fraction of (a) 20 wt.% untreated control, (b) 10 wt.%, (c) 15 wt.%, (d) 20 wt.% with 40x magnification

The morphological results of abaca fiber composites analyzed using SEM show that variations in fiber mass fraction (10 wt.%, 15 wt.%, and 20 wt.%) can affect surface characteristics between fibers and matrix (Fig. 4). In control composite sample without alkalization, the phenomenon of fiber pull-out can be said to be dominant, caused by the weak bond between fibers and matrix due to lignin and hemicellulose layers [34], which have hydrophobic properties that can inhibit the fibers from bonding with the matrix, so that the fiber surface appears cleaner without any resin adhering to the matrix [35]. A 15 wt.%

increase in fiber mass fraction improves fiber homogeneity and distribution, which can improve fiber-matrix bonding to reduce debonding, although matrix crack failure is still evident [36]. A mass fraction of 20 wt.% indicates a more even fiber distribution, which effectively reduces voids and fiber pull-out, and can reduce matrix cracking with better stress transfer, resulting in improved composite strength. These results indicate that adding up to 20 wt.% fiber mass fractions can improve the surface morphology and mechanical properties of the composite. A macroscopic overview of the fracture surface characteristics indicates that while higher magnification would offer deeper insights into nanoscale fiber-matrix interactions, this magnification sufficiently illustrates large-scale phenomena such as debonding, fiber pull-out, void distribution, and matrix cracking patterns.

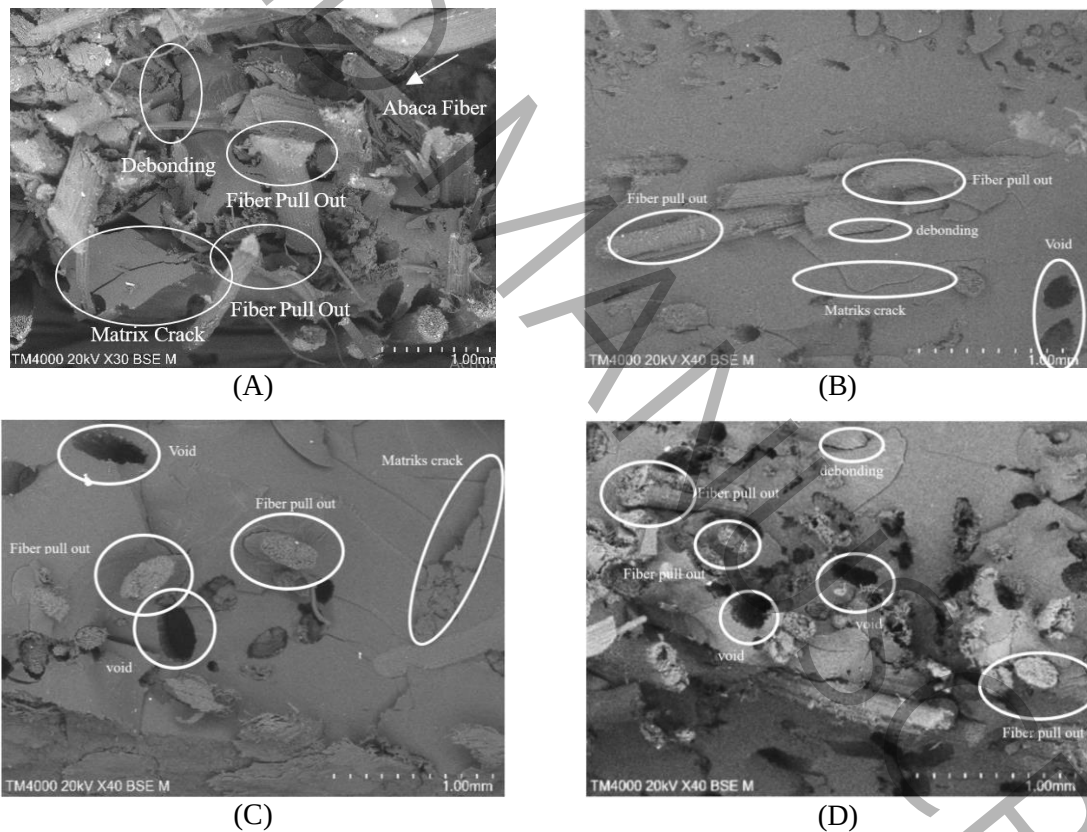


Fig. 4. Impact fracture morphology of abaca fiber/unsaturated polyester composites at 40 $\times$ magnification: (a) 20 wt.% untreated control, and alkali-treated composites with fiber mass fractions of (b) 10 wt.%, (c) 15 wt.%, and (d) 20 wt.%.

4- Conclusions

This study successfully evaluated the combined effects of alkali treatment and fiber mass fraction (10–20 wt.%) on the mechanical performance and fracture morphology of abaca fiber/unsaturated polyester composites. Compared to the untreated 20 wt.% abaca composite control, the 20 wt.% alkali-treated composite demonstrated superior mechanical integrity, achieving a 119.3% increase in tensile strength (23.90 MPa) and a 51.8% increase in Young's modulus (286.85 MPa). This significant enhancement proves that the removal of surface impurities (lignin and hemicellulose) by NaOH mercerization effectively exposes active cellulose sites and improves fiber-matrix mechanical interlocking. Impact energy absorption and toughness also peaked at the 20 wt.% treated fiber loading, exhibiting improvements of 96.9% and 92.0%, respectively, over the untreated control by activating effective toughening mechanisms such as controlled crack deflection and fiber fracture. Microstructural analysis via SEM corroborated these macro-mechanical findings; while the untreated control suffered from extensive fiber pull-out and debonding due to poor interfacial adhesion, the 20 wt.% treated formulation displayed robust interfacial bonding with reduced void density and a more homogeneous fiber distribution. Consequently, within the range investigated (10–20 wt.%), the 20 wt.% alkali-treated formulation demonstrated the best overall performance. This configuration is recommended as a promising route for producing lightweight bio-composites suitable for general, non-load-bearing applications.

Acknowledgement

We extend our gratitude to LPPM UM for the undergraduate thesis publication grant program under contract no. 14.04.1486/UN32.14.1/LT/2026.

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