Mechanical Strength Optimization of HDPE Biocomposite with Water Hyacinth Fiber Reinforcement using a Dispersing Agent

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ABSTRACT

This study investigates the impact of a polyamine amides dispersing agent (BYK W-980) on the mechanical performance of the High-Density Polyethylene/Water Hyacinth Fiber (HDPE)/(WHF) composites. The dispersing agent was employed to improve the fiber distribution, enhance the fiber-matrix interaction, and reduce the fiber agglomeration, which negatively affects the mechanical properties of the composite. The Scanning Electron Microscopy (SEM) analysis revealed that the dispersing agent, particularly DA2, effectively minimized fiber agglomeration and promoted a more uniform fiber distribution within the HDPE matrix. The density testing indicated a reduction in porosity and an increase in composite density following the dispersing agent treatment. The mechanical testing demonstrated significant improvements with DA2 yielding the optimal results: a 19.54% increase in tensile strength, a 24.33% increase in flexural modulus, and an 18.53% increase in impact strength. The X-ray Diffraction (XRD) analysis showed an increase in the crystallinity index of the WHF, suggesting enhanced structural regularity, which supported the observed improvements in mechanical performance. Overall, the utilization of the polyamine amides dispersing agent, particularly DA2, significantly enhanced the mechanical properties and fiber-matrix interaction of the HDPE/WHF composites.

Keywords-composite; dispersing agent; water hyacinth; HDPE; crystallinity; mechanical performance

I. INTRODUCTION

Synthetic fibers have been widely utilized as composite reinforcements due to their excellent mechanical properties and stability [1]. However, their non-biodegradable nature poses significant environmental threats [2]. To address these concerns, natural fibers have gained attention as sustainable alternatives, offering renewable and environmentally friendly benefits [3]. Among natural fibers, plant-based fibers have emerged as a preferred choice for composite development in industries, such as automotive, construction, and protective materials, where lightweight and high-strength materials are essential [4]. WHFs are particularly noteworthy due to their high cellulose content of 50.38%, and small cell diameter attributes that contribute to superior mechanical properties [5]. These fibers have shown potential as reinforcements in polymer composites [6]. The combination of WHF with HDPE, which has a relatively low melting temperature (T_m) of 131 °C, offers the potential to produce high-performance composite materials [7, 8]. The mechanical performance of composite materials is influenced by several factors, including fiber-matrix adhesion and fiber distribution [9]. Natural fibers are inherently hydrophilic, while HDPE and similar polymers are hydrophobic [10]. This disparity in polarity often results in weak bonding between the fibers and the matrix, leading to suboptimal mechanical properties in the composite [11]. To address this issue, several strategies have been explored, such as chemically modifying the polymer matrix, applying surface treatments to the fibers, and incorporating dispersing agents to improve fiber distribution [12-17]. Uneven fiber distribution can create weak zones within the composite, reducing its mechanical strength [18]. Ensuring proper fiber distribution is critical to achieving uniform load distribution within the

material, which enhances mechanical performance and reduces the likelihood of premature cracking or failure [12]. Dispersing agents play a key role in mitigating fiber agglomeration by generating repulsive forces that prevent the formation of fiber clusters, thereby ensuring a uniform dispersion of fibers throughout the matrix [19, 20].

In this study, BYK-W 980 was employed as a dispersing agent to improve the dispersion of WHF in the HDPE matrix. BYK-W 980 increases the surface energy of the fibers, promoting a stronger bonding between WHF and HDPE. The research focuses on optimizing the fiber distribution by varying the soaking time of WHF in the dispersing agent and evaluating its impact on composite quality.

II. EXPERIMENTAL SETUP

A systematic selection of materials was undertaken to fabricate the biocomposites, focusing on availability, mechanical properties, and compatibility. HDPE was selected as the matrix material due to its superior mechanical strength and thermal stability. WHF were chosen as the reinforcement phase for their environmental sustainability and favorable reinforcing properties.

A. Materials

The materials used to fabricate the biocomposites included:

- HDPE: sourced from PT. Lotte Chemical Titan Nusantara, with a melting point ranging from 126 ℃ to 134 ℃ and a density of 930 to 960 kg/m³.
- Water Hyacinth: harvested from Rawa Pening in Salatiga, Indonesia, depicted in Figure 1(a).
- Dispersing agent: BYK W-980, procured from The Altana Group.
- Distilled water: obtained from Justus Kimia Raya, using the Waterone brand from Semarang, Central Java, Indonesia.

Fig. 1. a) Water hyacinth plant, b) dried water hyacinth stems, c) WHF.

B. Fiber Surface Treatment

The water hyacinth stems, displayed in Figure 1(b), were initially sun-dried for five days before oven-drying at 60°C for 60 minutes. The mechanical extraction of fibers followed, and the extracted fibers, as can be seen in Figure 1(c), were oven-dried again at 110°C for 45 minutes to remove residual stresses. The dried fibers were ground using a crusher machine and sieved through a 40-mesh sieve. The resulting fiber powder was fully immersed in a dispersing agent solution, prepared by mixing 0.5 ml of BYK-W 980 dispersing agent with 100 mL of ethanol [20]. Twenty grams of WHF were soaked in this solution for varied times, namely 1, 2, and 3 hours. The treated fibers were rinsed three times with 96% ethanol and oven-dried at 110°C for 70 minutes.

C. Composite Preparation

HDPE pellets were crushed into powder using a crusher machine. The powder was sieved through a 40-mesh sieve, excluding particles finer than 60-mesh. The composite was prepared with a fiber volume fraction of 30%. HDPE powder and WHF were mixed in a ball mill at 20 rpm for 60 minutes to ensure a uniform material distribution. Thermal mixing followed utilizing a twin-screw extruder with parameters of 160 °C 15 rpm. The extruded material was pelletized at 15 rpm. Treatment variations of the HDPE/WHF composites were assigned specific codes for analytical purposes, as portrayed in Table I.

TABLE I. THE NOMENCLATURE OF FIBER TREATMENT USED AS REINFORCEMENT IN HDPE/WHF COMPOSITES

Treatment Variation	Code	Description
Untreated fiber	UF	Fibers without treatment
Dispersing agent	DA1	The fibers were soaked in the dispersing agent for 1 hr
	DA2	The fibers were soaked in the dispersing agent for 2 hr
	DA3	The fibers were soaked in the dispersing agent for 3 hr

The final fabrication of the biocomposites involved mold preparation with astralon plastic and mirror glaze coatings. The pellets were poured into the molds and processed using a hot press machine set to 180 °C, with a holding time of 25 minutes and a pressing pressure of 0.34 MPa.

D. Testing Procedures

1) Tensile Testing

Morphological changes on the fracture cross-section of both treated and untreated HDPE composites were observed using a JEOL Benchtop Scanning Electron Microscope (JCM 7000)

2) Density Measurement

The density was measured according to ASTM D792-08 [21] using distilled water (997.54 kg/m³ density). The results were averaged from five specimens per variation.

3) Wettability Testing

Wettability testing was conducted following the ASTM D7334-08 standard [22], using contact angle measurements with an Olympus ZX7 microscope Distilled water and ethylene glycol, which served as the test liquids, with droplet volumes having been controlled at 1.5 µL. The surface energy was estimated deploying the Owens-Wendt method [23]:

$$\gamma_{L(1+cos\theta)} = 2\sqrt{\gamma_S^d}\sqrt{\gamma_L^d} + 2\sqrt{\gamma_S^p}\sqrt{\gamma_L^p} \quad (1)$$

where γ^d and γ^p represent dispersive and polar surface energies, and S and L correspond to the solid and liquid phases, respectively.

4) X-ray Diffarction

The crystallinity index was determined using a Shimadzu XRD-7000 with operating parameters of 40 kV and 30 mA, scanning from 10° to 50° at a 2°/min rate.

5) Flecural Strength

The flexural strength was tested employing the three-point bending method based on ASTM D790 [24] on a JTM-UTS 510 universal testing machine, with a crosshead rate of 2 mm/min and a 100 kg load cell.

6) Tensile Strength

The tensile strength was determined using a Universal Testing Machine (JTM-UTS 510) following ASTM D638 [25] guidelines. Five specimens per variation were analyzed for consistency.

7) Impact Strength

The unnotched impact strength was evaluated implementing the Izod impact test by ASTM D5941 [26]. Five specimens per variation were subjected to testing.

III. RESULTS AND DISCUSSION

Analytical tests, including SEM, wettability, density, tensile strength, bending, impact resistance, and XRD, were performed to evaluate the mechanical and morphological properties of the HDPE/WHF composite.

A. Surface Morphology

The SEM analysis provided detailed insights into the impact of the dispersing agent treatment on fiber surface morphology and fiber-matrix interaction. The SEM images, presented in Figure 2, revealed significant differences in fiber surface quality and distribution, which directly influenced the composite's mechanical performance. In the UF, illustrated in Figure 2(a), the SEM images displayed uneven fiber distribution and rough fiber surfaces. These features resulted in weak fiber-matrix interactions, leading to suboptimal mechanical properties, including reduced tensile and impact strengths. The presence of voids and agglomerations further weakened the composite's structural integrity.

Conversely, the composite treated with the dispersing agent DA2, observed in Figure 2(b), exhibited a significantly improved fiber distribution, with smoother fiber surfaces and minimal voids. These enhancements fostered better fiber-matrix interaction, leading to notable improvements in mechanical performance. The uniform fiber dispersion contributed to increased impact energy absorption and improved overall composite strength. However, the composite treated with DA3, displayed in Figure 2(c), showed signs of surface damage attributed to prolonged soaking time (3 hours). While the DA3-treated composites exhibited better fiber distribution than the UF, the excessive soaking duration led to fiber degradation, compromising mechanical performance. Despite some improvement over the untreated composite, the DA3 treatment was less effective than DA2, underscoring the importance of optimizing the chemical treatment parameters, such as soaking time, to balance the fiber dispersion and preservation of fiber integrity. These findings emphasize the critical role of the dispersing agents in improving fiber distribution and fiber-matrix bonding while highlighting the need for a careful optimization of the treatment conditions to maximize composite performance [27].

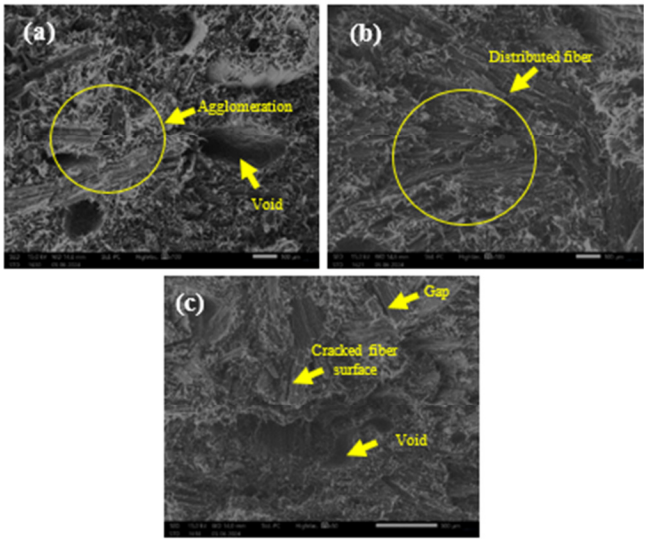

Fig. 2. HDPE/WHF composite tensile fracture surface morphology: (a) UF, (b) DA2, and (c) DA3.

B. Density and Porocity of Composite

The density and porosity testing of the HDPE/WHF composites provided further insight into the impact of the chemical treatments on the physical properties, corroborating the SEM analysis, as outlined in Table II.

TABLE II. DENSITY AND POROCITY OF HDPE/WHF COMPOSITES

Variations	Density (g/cm^3)	Porosity (%)
UF	0.970	4.01
DA1	1.011	3.97
DA2	1.019	3.32
DA3	1.014	3.91

The UF exhibited the lowest density at 0.97 g/cm³ and the highest porosity at 4.01%. In contrast, treatment with the dispersing agent DA2 significantly improved the material's properties, increasing the density to 1.019 g/cm³ and reducing porosity to 3.32%. These improvements suggest an enhanced fiber distribution and a reduction in voids within the composite structure. Additionally, the lower porosity and increased crystallinity observed in DA2 reflected an improved fiber-matrix adhesion, in line with the reduced contact angle and higher surface energy observed in the wettability tests, as displayed in Table III.

C. Contact Angle and Surface Energy

Wettability, the ability of a liquid to spread on a solid surface, plays a pivotal role in enhancing the adhesion between fibers and the polymer matrix, thus influencing the fiber dispersion and mechanical properties [28, 29]. This study examined the wettability by analyzing the contact angle, dispersion, polarity, and surface energy, as can be seen in Table III.

TABLE III. WETTABILITY PROPERTIES OF WHF

Material	Contact angle in distilled water (deg)	Contact angle in ethylene glycol (deg)	Dispersion (mN/m)	Polarity (mN/m)	Surface Energy (mN/m)
UF	67.82	69.21	1.17	45.18	46.35
DA1	65.22	68.21	0.76	50.64	51.40
DA2	63.31	65.02	1.22	50.34	51.56
DA3	64.83	67.01	1.02	49.60	50.62

The treatment with polyamine amides significantly improved the fiber-matrix interaction, evidenced by the reduced contact angles (e.g., 67.82° to 63.31° for DA2) and increased surface energy (51.56 mN/m for DA2). The improved wettability facilitated a stronger adhesion between the polar fibers and the non-polar HDPE matrix, enhancing fiber dispersion. These results aligned with previous findings, which observed that a decrease in the contact angle enhanced the adhesion on modified natural fiber surfaces [30-32]. Additionally, the dispersion and polarity values for DA2 (1.22 mN/m and 50.34 mN/m, respectively) exhibiting a balanced interaction between the polar and non-polar components, which promoted a better adhesion in the HDPE-based composites, which were inherently hydrophobic, as noted in previous studies [33]. The higher surface energy after treatment further supported the improved fiber-matrix interaction, as observed in the SEM images portrayed in Figure 2(b), where fiber distribution was more uniform. The fiber agglomeration, a critical issue in WHF composites, was also reduced by polyamine amides, preventing the uneven distribution and weak spots in the matrix, which ultimately enhanced the mechanical performance [34-35].

D. Crystallinity Index

The XRD analysis of the HDPE-WHF composites revealed shifts in the peak positions and notable changes in the crystallinity indices following the treatment with a dispersing agent, highlighting its influence on the crystallization behavior of the HDPE matrix, as illustrated in Figure 3.

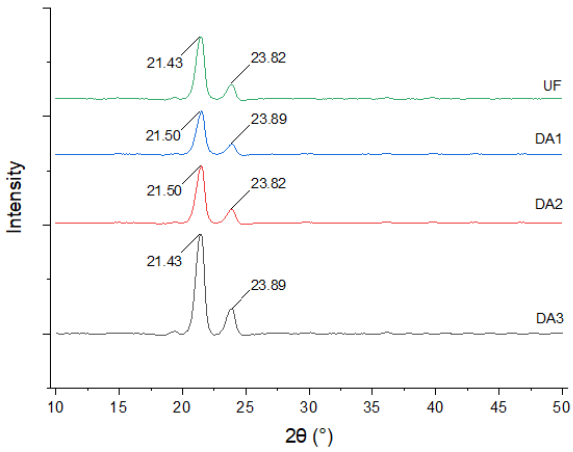

Fig. 3. Crystallinity index of HDPE/WHF composites.

The UF exhibited a crystallinity index of 53.74. Treatments with the dispersing agents DA1, DA2, and DA3 resulted in increased crystallinity indices of 54.35%, 57.96%, and 56.56%, respectively. These improvements indicate that the dispersing agent enhanced the fibers' polarity and surface energy, facilitating a more ordered crystalline structure by reducing the fiber agglomeration and improving the fiber distribution within the HDPE matrix [8]. The increase in crystallinity was directly linked to an improved fiber-matrix adhesion, which contributed to enhanced mechanical properties, including flexural, tensile, and impact strengths. The findings suggest that the more ordered crystalline arrangement strengthens the composite's structural integrity, reducing the weak zones and improving the load distribution. These observations align with previous studies emphasizing the beneficial effects of the increased crystallinity on composite performance, including higher mechanical strength and durability [36].

E. Bending Properties of Composite

The bending test results for the HDPE/WHF composites demonstrated significant improvements in flexural strength and modulus following the incorporation of a dispersing agent. These enhancements were attributed to the better fiber distribution within the matrix, as corroborated by the SEM imaging, wettability data, and XRD analysis. The dispersing agent facilitated a more uniform fiber alignment, reduced agglomeration, and an increased crystallinity, contributing to enhanced mechanical performance.

For the UF, the flexural strength was recorded at 16.96 MPa. In contrast, composites treated with DA1, DA2, and DA3 exhibited flexural strengths of 18.00 MPa (6.11%), 19.06 MPa (12.33%), and 18.62 MPa (9.75%), respectively, as depicted in Figure 4. Among these, the DA2-treated composite achieved the most significant improvement, aligning with prior studies that linked the enhanced fiber distribution to superior bending performance [37]. Similarly, the flexural modulus also showed substantial increases with the dispersing agent treatment. DA1 resulted in a modulus of 1217.54 MPa (10.25%), DA2 reached 1372.91 MPa (24.33%), and DA3 achieved 1275.92 MPa (15.57%), as portrayed in Figure 5. These findings are consistent with earlier research, which indicated that more uniform fiber distribution enhances the deformation resistance and delays the mechanical failure [38]. However, the DA3 treatment highlighted an optimal threshold for the dispersing agent usage. Beyond this point, excessive treatment may adversely affect the composite's mechanical properties, likely due to over-saturation or damage to the fibers during prolonged exposure [27].

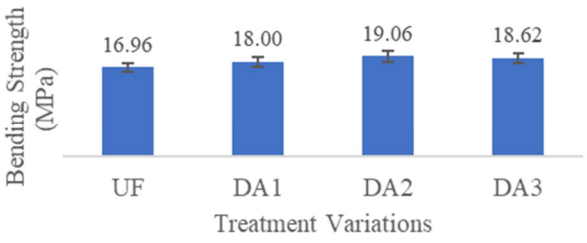

Fig. 4. HDPE/WHF composite bending strength.

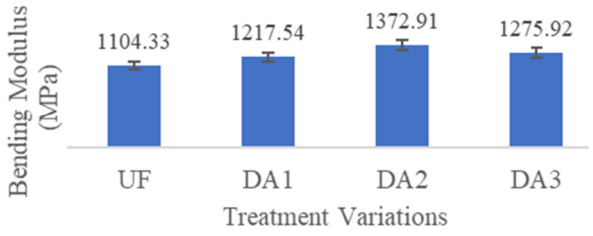

Fig. 5. HDPE/WHF composite bending modulus.

F. Tensile Properties of Composite

The tensile test results for the HDPE-WHF composites confirmed the trends observed in the bending tests, showcasing notable enhancements in both tensile strength and modulus of elasticity with the use of a dispersing agent. As shown in Figure 6, the UF had a tensile strength of 11.96 MPa. The treatment with DA1 increased this value to 12.79 MPa, reflecting a 6.94% improvement. This enhancement aligns with prior research attributing the improved fiber-matrix adhesion to the more uniform fiber distribution [12].

The DA2 treated composite exhibited a substantial improvement, reaching a tensile strength of 14.3 MPa (a 19.54% increase), reinforcing the observation that better fiber dispersion enhances the fiber-matrix interaction [39]. However, the DA3 treatment resulted in a slight reduction to 13.7 MPa, though it still represented a 14.56% improvement over the untreated composite. This finding corresponds with previous studies indicating that excessive chemical treatment could compromise the composite quality by damaging fibers or disrupting optimal dispersion [27]. The modulus of elasticity, illustrated in Figure 7, displayed similar trends. The untreated composite exhibited a modulus of 426.68 MPa, which increased to 559.75 MPa (31.16%) with DA1 treatment, which is consistent with earlier studies linking the modulus enhancement to the uniform fiber distribution within the matrix [30].

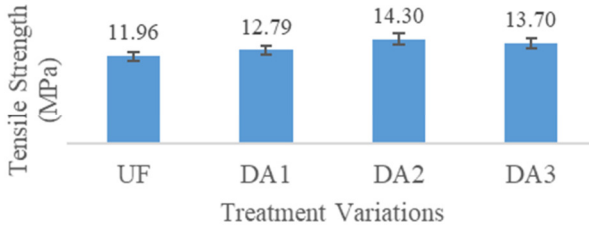

Fig. 6. HDPE/WHF composite tenile strength.

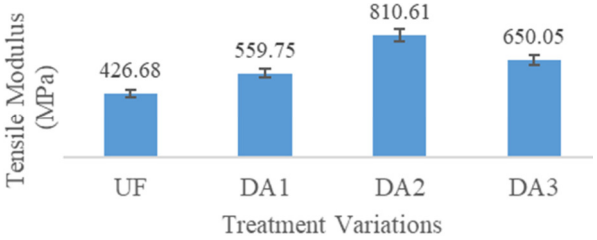

Fig. 7. HDPE/WHF composite tensile modulus.

The DA2 treatment further elevated the modulus to 810.61 MPa, an 89.95% improvement. The DA3 treatment resulted in a modulus of 650.05 MPa, a 52.38% increase compared to the untreated composite. These results illustrate that while the dispersing agent significantly improved the tensile properties, its effectiveness varied depending on the treatment formulation and soaking time, as highlighted in previous research [40].

G. Impact Strength

The impact test results further substantiated the mechanical property enhancements observed in the bending and tensile tests following the dispersing agent treatment. The impact testing, which evaluates a material's ability to absorb energy under dynamic loading conditions [33], revealed that the untreated HDPE/WHF composites (UF) exhibited an impact energy of 29.53 J/m², as can be seen in Figure 8. The treatment with DA1 improved this to 30.98 J/m², reflecting a 4.91% increase, aligning with the corresponding improvements in tensile and bending strengths (6.94% and 6.11%, respectively).

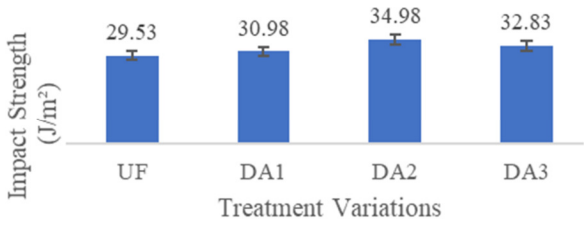

Fig. 8. Impact strength of HDPE/WHF composite.

This indicated that DA1 enhanced fiber distribution and improved the composite's resistance to dynamic loads. The DA2 treatment yielded the highest impact energy at 34.98 J/m², an 18.53% increase compared to the UF. This result aligned with the superior performance in tensile and bending tests and reflected the significant improvement in fiber-matrix adhesion and uniform fiber distribution facilitated by DA2 [19]. In contrast, the DA3-treated composite exhibited a slightly reduced impact energy of 32.83 J/m², an 11.19% improvement over UF but still lower than DA2. This reduction was attributed to potential fiber surface degradation caused by the prolonged soaking time, as evidenced by the SEM analysis presented in Figure 2(c). Despite this drawback, the DA3 composite maintained a higher impact energy compared to the untreated sample, corroborating the overall positive influence of the dispersing agent.

IV. CONCLUSION

This study underscores the potential of using the BYK W-980 dispersing agent, specifically the DA2 formulation, to enhance the mechanical and structural performance of the High-Density Polyethylene/Water Hyacinth Fiber (HDPE)/(WHF) composites. The DA2 treatment led to significant improvements in the mechanical properties of the latter, with increases in tensile strength (19.54%), flexural modulus (24.33%), and impact strength (18.53%). The Scanning Electron Microscopy (SEM), density, and X-ray Diffraction (XRD) analyses confirmed that the DA2 effectively reduced fiber agglomeration, decreased porosity, and enhanced

fiber crystallinity, all of which contributed to stronger fiber-matrix interactions. These results align with existing literature that highlights the importance of uniform fiber distribution for optimal composite performance. The study concludes that DA2 is the most effective dispersing agent for improving the mechanical properties of the HDPE composites, offering valuable insights for the development of polymer-based composites reinforced with natural fibers.

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