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Effect of Water Hyacinth Fiber Length and Content on the Torsional Strength of Epoxy Resin Composites

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Abstract

This study investigates the influence of water hyacinth fiber length and content on the torsional strength of epoxy resin composites. Utilizing an experimental design, specimens were prepared with varying fiber lengths (10 mm, 20 mm, 25 mm, and 135 mm) and content percentages (4%, 7%, and 10%) and subjected to torsional testing according to ASTM E-143 standards. The primary objective was to determine the optimal fiber configurations that enhance the composite's mechanical properties, particularly its resistance to torsional stress. Results indicated that shorter fiber lengths consistently yielded higher torsional strength, with the 20 mm fibers at a 7% content displaying the highest torque resistance, achieving a maximum of 1.418 Nm and a shear stress of 29.348 MPa. In contrast, longer fibers generally showed diminished performance, likely due to poorer resin penetration and fiber-matrix bonding. Regression analysis was employed to develop predictive models for the torsional behavior based on fiber dimensions and compositions, achieving high accuracy with coefficients of determination (R^2) ranging from 0.95 to 1.00, suggesting excellent model fits. These findings underscore the potential of using water hyacinth fibers as effective reinforcement in epoxy composites, particularly at optimal lengths and concentrations. The study contributes to the broader utilization of natural fibers in composites, offering a sustainable alternative to synthetic fibers with beneficial mechanical properties and environmental impacts.

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1. Introduction

The use of natural materials in composite manufacturing has seen a significant resurgence, driven by the need for sustainable development and environmental conservation. Among these materials, water hyacinth fiber has emerged as a promising candidate due to its rapid growth rate, low cost, and biodegradable properties. Composites made from natural fibers like water hyacinth are not only environmentally friendly but also offer the advantage of being lightweight while still providing appreciable mechanical strength and thermal resistance [1]. Despite these advantages, the application of water hyacinth fibers in epoxy resin composites poses specific challenges. The primary issues stem from the inherent properties of the fibers, including their high-water absorption capacity, which can compromise the fiber-matrix adhesion and thus the mechanical integrity of the composite. Moreover, the mechanical performance of these composites, particularly under torsional loads, is not well-understood, limiting their potential applications in industries where torsional strength is crucial [2].

The mechanical properties of water hyacinth fiber-reinforced composites have been shown to outperform those of other natural fibers, such as coir and banana fibers. For instance, demonstrated that composites reinforced with water hyacinth fibers exhibited superior tensile, flexural, and impact strengths compared to coir and Palmyra composites [3]. Furthermore, the extraction method of the fibers significantly affects their mechanical properties. Mechanically extracted fibers have been reported to yield higher tensile strength than those extracted through other methods [4]. This suggests that both the length and the extraction method of the fibers are critical factors in optimizing the performance of the composites.

Previous research has predominantly focused on tensile and compressive strengths of natural fiber composites, with limited insights into how these fibers perform under torsional stress. Studies such as those by Hanifi et al. (2020) have explored the effects of fiber arrangement and content in synthetic composites but have not addressed these aspects in water hyacinth-reinforced epoxy composites. Furthermore, while regression analysis has been widely used to predict tensile strength in fiber-reinforced composites, its application in modeling torsional strength in natural fiber composites remains scant [5]. The effect of fiber length on the mechanical properties of composites has been documented in various studies. For example, it has been observed that shorter fibers tend to lead to lower tensile strength due to inadequate stress transfer between the fibers and the matrix [6]. Conversely, longer fibers can enhance the load-bearing capacity of the composite, thereby improving its torsional strength. The optimal fiber length for achieving maximum mechanical performance is still a subject of ongoing research, but it is clear that there is a direct correlation between fiber length, content, and the overall mechanical properties of the composite [7].

Research by Bagir and Pradana (2008) on water hyacinth fiber composites showed a variation in tensile strength depending on fiber weight: a maximum of 19 N/mm2 at 20% fiber weight and a minimum of 11.5 N/mm2 at 15% fiber weight. The reduced strength at lower fiber weight was attributed to insufficient resin penetration due to excessive latex filler, which hindered effective bonding [8]. Similarly, studies on the impact resistance of composites reinforced with coconut and banana fibers found that increased fiber content improved the structural integrity of the matrix, preventing easy breakage. The strongest composite in the studied range consisted of 70% resin, 15% banana stem fiber, and 15% coconut coir powder, with a tensile strength of 0.172 N/mm2, surpassing the standard SNI 03-2105-2006 threshold of 0.147 N/mm2 [9]. Additionally, torsion testing on composites made with Waru fiber and a polyester matrix revealed that the optimal fiber orientation for torsional strength was at 70°, achieving a shear stress of 8.270 kg/mm2, compared to 7.207 kg/mm2 at 30° and 6.262 kg/mm2 at 50° [10]. Another study focusing on water hyacinth fibers evaluated their potential as natural fiber reinforcements in composite materials. Utilizing the ASTM D638 standard, the research explored different fiber volume fractions, notably 90% and 80%. Significant variations in mechanical properties were observed across different mixtures, highlighting the impact of fiber-resin ratios. The most notable results were achieved with a 5% fiber and 95% resin composition, where the highest average tensile strength was 9.10514 MPa and the peak load reached 1632.1 N/mm. Additionally, the greatest strain, at 6.6%, was also recorded in this composition, underscoring the critical role of fiber content in determining the mechanical performance of the composite [11]. In terms of fiber content, increasing the percentage of water hyacinth fibers in the composite matrix generally leads to improved mechanical properties, up to a certain threshold. Beyond this optimal point, however, the benefits may plateau or even decline due to issues such as fiber agglomeration and poor dispersion within the matrix [12]. This highlights the importance of carefully balancing fiber length and content to achieve the desired mechanical performance in epoxy resin composites.

Despite the growing use of natural fibers in composite materials, the effects of fiber length and content on the torsional strength of epoxy resin composites reinforced with water hyacinth remain largely unexplored. Previous studies have largely focused on tensile and compressive strengths, neglecting torsional strength, which is crucial for many engineering applications. This study addresses this gap using regression analysis to quantitatively determine how variations in water hyacinth fiber length and content influence torsional strength. This method allows for the development of predictive models that aid in optimizing composite design to achieve the best mechanical properties. Offering a detailed exploration of torsional behavior, this research enhances understanding of natural fiber composites, underscoring the potential of water hyacinth fibers to improve the durability and efficiency of environmentally sustainable materials. This study aims to bridge these gaps by systematically investigating the effect of water hyacinth fiber length and content on the torsional strength of epoxy resin composites. Through the use of a rigorous experimental design and regression analysis, this research seeks to develop predictive models that can accurately forecast how changes in fiber characteristics impact the torsional strength. The ultimate goal is to optimize composite design for enhanced performance, providing a robust foundation for the broader application of water hyacinth fibers in engineering materials.

2. Methods

2.1. Materials preparation

In this phase, all necessary equipment and materials are assembled for specimen fabrication. The tools include ASTM E143 compliant specimen printing equipment, digital scales, calipers, torsion testing equipment, and software. Materials used comprise epoxy resin, hardener, and non-stick paste to facilitate the molding process.

2.2. Water hyacinth fibre preparation

The water hyacinth plant undergoes a cleaning process where leaves and roots are removed to isolate the stem. The stem is then washed to remove dirt and mud and left to dry in sunlight for ten days. Once dried, fibers are extracted using a wire brush to separate the pure fiber from the stem. These fibers are then cut to predetermined lengths of 10, 20, 25, and 135 mm. The resin to epoxy ratio is maintained at 1:1, with fiber contents of 4%, 7%, and 10%, and corresponding epoxy resin contents of 90%, 93%, and 96%.

2.3. Specimen preparation

Specimens are prepared following ASTM E143 standards, which outline the method for measuring shear modulus at room temperatures [13]. Using the hand lay-up technique, fibers are aligned uniformly within a mold as shown in Figure 2. The epoxy resin mixture is carefully poured over the fibers, ensuring thorough saturation without disrupting the fiber alignment. The mold is left undisturbed for approximately 30 minutes to allow initial setting. It is then sealed, ensuring no gaps or potential leak points remain. Additional resin mixture is added to completely fill the mold. The setup is then allowed to cure at room temperature for about 9 hours. The composition of the composite materials is strictly controlled according to specified weight fractions.

2.4. Torsion test preparation and equipment setup

The preparation for torsion testing involves a series of steps to ensure the equipment's accuracy and functionality. Initially, all components of the torsion test equipment are checked to confirm they are functioning correctly. Sensors are calibrated to guarantee accurate data recording. Each shaft on the torsion testing tool is lubricated to reduce friction and ensure smooth operations. Additionally, torsion testing software is installed and set up on a computer or laptop, with a preliminary check performed by rotating the chuck to verify that the sensor accurately registers movement.

Following equipment setup, the specimens themselves are prepared. Their dimensions are precisely measured using calipers. These measurements are then meticulously entered into the testing software, aligning all test parameters with the specific requirements of the experiment.

The torsion test is designed to measure shear stress, shear strain, and shear modulus of the material under test. The specific formulas used are critical for analyzing the material's response to torsional forces. Shear stress τ_g is calculated using the following formula [14].

$$\tau_g = \frac{16.T_{max}}{\pi.d^3} \tag{1}$$

where T_{max} represents the maximum torsion moment in newton-meters, π approximates to 3.14, and d is the radius in millimeters.

Afterwards, the shear strain γ is determined by

$$\gamma = \frac{\theta.r_m}{L_u} \tag{2}$$

with θ as the angle of twist in degrees, r_m as the average radius, and L_u as the length of the specimen, both in millimeters.

Finally, shear modulus (G) is calculated by

$$G = \tau / \gamma \tag{3}$$

Where Equation (3) links shear stress and strain to reveal the material's stiffness under torsional loading.

3. Results and Discussion

3.1. Torsion test results

The torsion test was conducted by applying a bending force to the specimens until failure occurred. This test method effectively assesses the torsional strength and durability of the materials under study. The results, which represent the average values derived from the specimens tested, are detailed in Table 3 below. This table provides a quantitative overview of the mechanical behavior of the specimens when subjected to torsional stress, highlighting critical metrics such as maximum torque, shear stress, shear strain, and shear modulus.

Table 1. Fiber test results

Specimen	Torque (N.m)	Shear Stress (MPa)	Shear Strain	Shear Modulus
10mm/4%	0.247	5.817	0.401	13.561
10mm/7%	0.755	17.784	0.231	95.403
10mm/10%	0.586	13.867	0.492	29.169
20mm/4%	0.316	7.465	0.589	13.112
20mm/7%	1.418	29.348	0.114	258.555
20mm/10%	1.011	23.841	0.103	192.403
25mm/4%	0.945	22.286	0.064	369.408
25mm/7%	1.134	26.716	0.126	266.562
25mm/10%	0.856	20.183	0.088	301.056
135 ± 5mm/4%	0.647	15.108	0.23	66.749
135 ± 5mm/7%	0.641	14.679	0.176	87.164
135 ± 5mm/10%	0.476	11.228	0.226	50.487

The data presented in Table 1 are derived from torsion testing and provide detailed outcomes for strain, stress, and torsional modulus for each tested specimen. The variability in results across different samples can primarily be attributed to variations in fiber density, fiber size, and the density of the matrix material within each specimen. For specimens with a fiber length of 10 mm, the results indicate that a fiber composition of 7% yielded the highest average torque of 0.755 Nm and a significant shear stress of 17.784 MPa. Interestingly, the maximum shear strain was observed in specimens with a higher fiber content of 10%, recording a strain of 0.492.

In specimens with a 20 mm fiber length, the highest torque value was recorded at 1.418 Nm in those with 7% fiber content, which also exhibited a moderate shear stress of 29.348 MPa. Notably, the highest strain for this fiber length was found in specimens with the lowest fiber content (4%), which had an average strain of 0.126. For the 25 mm fiber length, the 10% fiber content specimens showed the highest average torque of 1.134 Nm and a shear stress of 26.716 MPa, with an average strain yield also at 0.126. In contrast, specimens with a much longer fiber length of 135 ± 5 mm demonstrated the highest torque at a 10% fiber composition, measuring 0.988 Nm and achieving the greatest shear stress of 23.841, while the largest strain was observed at a 4% fiber composition, with a value of 0.230.

These variations across different fiber lengths and compositions underscore the complex interplay between material properties and structural performance in composite materials. The differences in mechanical behavior highlight the critical influence of fiber content and length on the torsional resilience and integrity of the composites.

3.2. Fibre content effect

The analysis of torsional test results from Table 1 indicates a clear pattern: shorter fibers consistently exhibit superior torsional strength compared to longer fibers. As the fiber content increases from 4% to 10%, there is a notable decrease in torsional strength among the longer fibers. This reduction can be attributed to a decline in the quality of the interfacial bonding between the fibers and the resin matrix with increasing fiber length and content.

Supporting this observation, research by Bagir & Pradana (2008) found that the mechanical properties of water hyacinth fibers are negatively impacted by increased fiber loading, particularly in compression strength tests, where added fiber weight exacerbated the weakening of the composite structure [8]. These findings are analogous to the decreases in torsional strength noted in our study, particularly at higher fiber percentages.

Further analysis reveals that for fibers measured at 10 mm and 20 mm in length, torsional strength was higher than those at 25 mm. This suggests that beyond a certain fiber length, the efficiency of the bonding process diminishes significantly, adversely affecting the torsional strength. This is evident from the performance discrepancies observed between different fiber lengths—10 mm and 20 mm fibers maintain better structural integrity under torsion than the 25 mm fibers.

Moreover, the comparison between fibers of different lengths (10 mm, 20 mm, and 25 mm) at varying content percentages (4%, 7%, and 10%) showed that changes in fiber percentage did not significantly alter the torsional strength across these dimensions. This indicates that while fiber length has a pronounced effect on torsional strength, variations in fiber percentage within this range do not lead to significant differences in performance, underscoring the predominant influence of fiber length over percentage in determining the torsional strength of the composite.

3.3. Microscopic and macroscopic analyses

Following the torsion testing, the specimens typically exhibit either brittle or flexural fracture types. Detailed microscopic and macroscopic analyses are performed on these fractures to uncover the underlying mechanisms, as shown in Figure 1. Observations reveal that the predominant cause of failure is debonding, which is the detachment of the interfacial bond between the water hyacinth fibers and the epoxy resin. This occurs when the applied load leads to the fibers peeling away from the resin matrix. Microscopic views provide insights into the microscale mechanisms such as fiber pull-out and matrix cracking, highlighting how these contribute to the overall fracture behavior. Conversely, macroscopic views offer a broader perspective, illustrating the general distribution and alignment of fibers within the matrix and identifying larger-scale defects and paths of fracture propagation. These combined observations help in understanding the material's mechanical behavior under stress and the structural vulnerabilities of the composite.

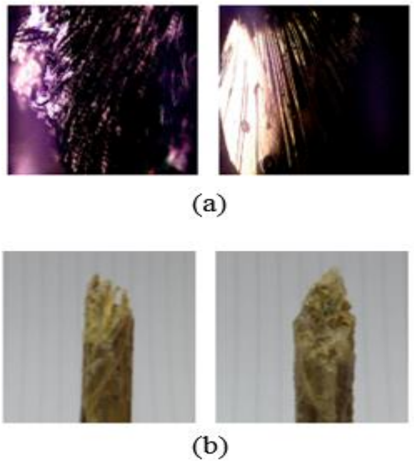

Figure 1. Morphology in micro (a), and macroscopic (b) view

3.4. Result of regression method

The regression analysis, conducted to determine the relationship between fiber length and torsional strength, has yielded predictive equations that illustrate how fiber characteristics impact the mechanical properties of the composite. Utilizing Microsoft Excel for statistical analysis, we developed regression models that express torsional strength, strain, stress, and shear modulus as functions of fiber length and content [15].

The derived equations are instrumental in predicting the torsional strength based on varying lengths and contents of water hyacinth fibers reinforced with epoxy resin. These models provide a mathematical representation of how changes in fiber dimensions and concentrations influence the mechanical behavior of the composites under torsional load. This approach allows for a quantitative assessment and visualization of the impact of fiber adjustments, offering valuable insights into optimizing composite material properties for specific engineering applications. The regression models thus serve not only as a tool for understanding existing data but also for predicting outcomes of new composite formulations.

Table 2 and Figures 2 and 3 detail the regression equations for 4% fiber content analyzing shear stress, shear strain, and shear modulus. Remarkably, the coefficient of determination (R^2) for these models is 1.00, indicating a perfect fit where the regression model explains all the variability of the response data around its mean. This high level of accuracy suggests that the third-order polynomial regression accurately captures the complex relationships between fiber length and mechanical properties at this fiber content level. For composites with 7% fiber content, the regression models as depicted in Figures 4 and 5 show coefficients of determination of 0.99, 0.95, and 0.99, respectively.

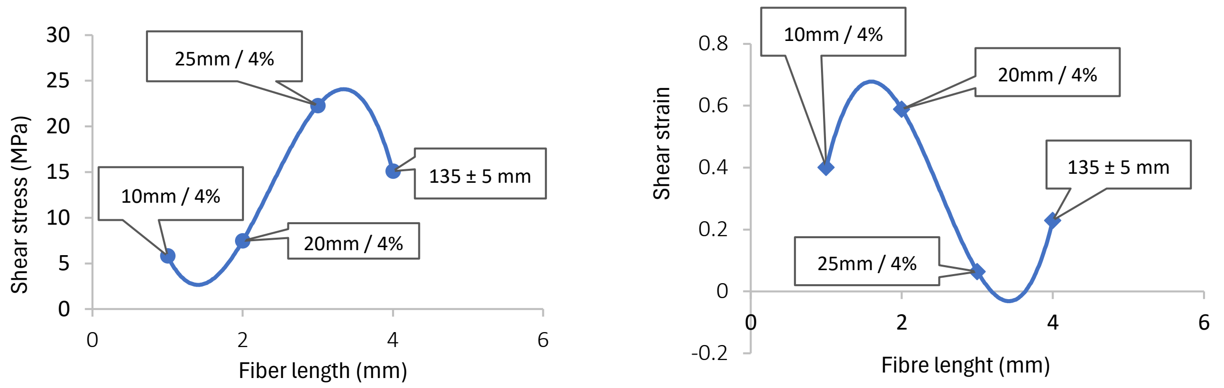

Figure 2. Fiber length vs. tension curve (Left); and fiber length vs. strain curves (Right) with 4% fiber content

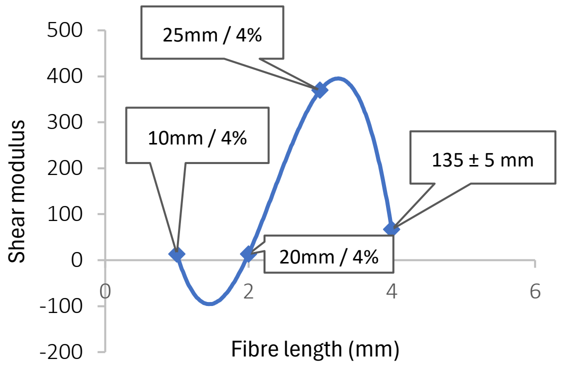

Figure 3. Fiber length vs. shear modulus curves (4% fiber content)

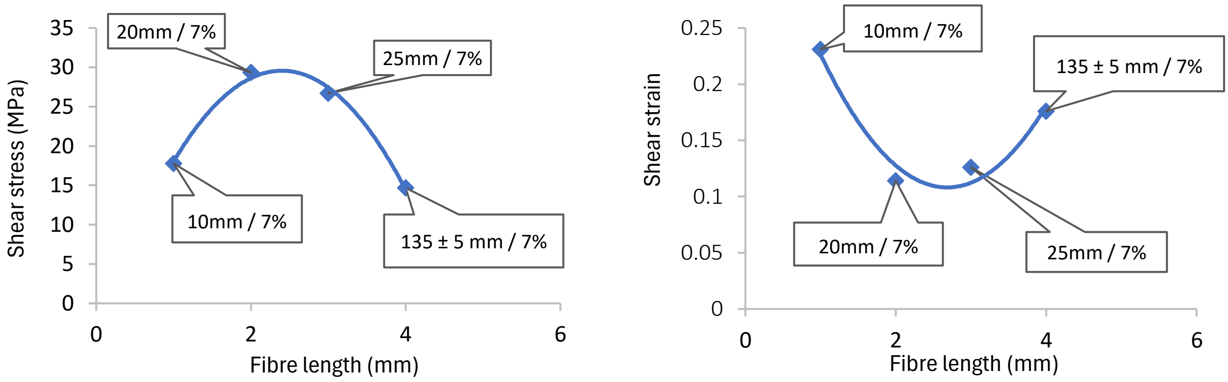

Figure 4. Fiber length vs. tension curve (Left); and fiber length vs. strain curves (Right) with 7% fiber content

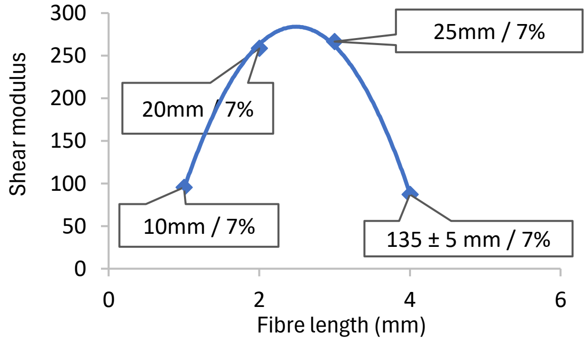

Figure 5. Fiber length vs. shear modulus curves (7% fiber content)

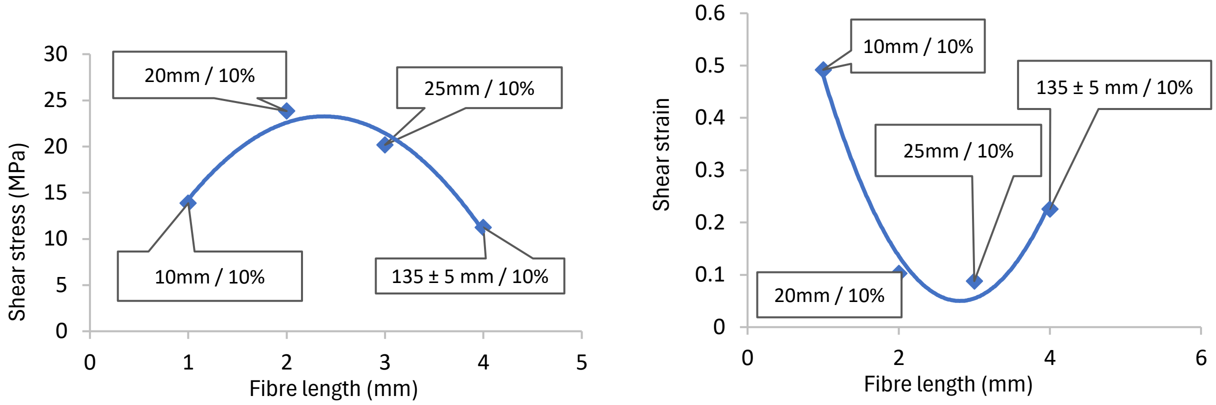

Figure 6. Fiber length vs. tension curve (Left); and fiber length vs. strain curves (Right) with 10% fiber content

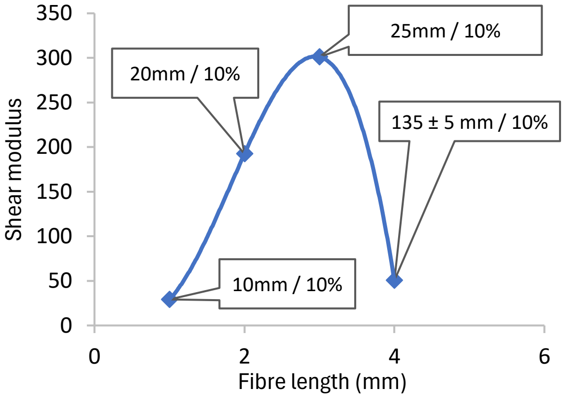

Figure 7. Fiber length vs. shear modulus curves (10% fiber content)

Table 2. Results of regression method

Fiber	Detail	Regression Formula	R^2
4%	Fiber length and tension	$y = 5.862\,x^4 + 1.758\,x^3 - 82.5938\,x^2 + 52.514\,x$	1
4%	Fiber length and strain	$y = 0.234\,x^3 - 1.7605\,x^2 + 3.8315\,x - 1.904$	1
4%	Fiber length and shear	$y = 169.28\,x^3 + 1194\,x^2 - 2397.7\,x + 13865$	1
7%	Fiber length and tension	$y = 5.9003\,x^3 + 28.307\,x^2 - 4.3828\,x$	0.99
7%	Fiber length and strain	$y = 0.0418\,x^3 - 0.2241\,x^2 + 0.4088\,x$	0.95
7%	Fiber length and shear	$y = 638\,x^3 + 426.52\,x^2 - 247.09\,x$	0.99
10%	Fiber length and tension	$y = 4.7322\,x^3 + 22.504\,x^2 - 3.4878\,x$	0.96
10%	Fiber length and strain	$y = 0.1318\,x^3 - 0.7401\,x^2 + 1.0893\,x$	0.97
10%	Fiber length and shear	$y = 507.738\,x^3 + 277.35\,x^2 - 313.481\,x$	0.97

These values, consistently above 95%, denote an excellent fit, supporting the use of second-order polynomial regression to model the relationships between fiber length and the mechanical properties of shear stress, shear strain, and shear modulus. The high R^2 values imply that these models can reliably predict the mechanical behavior of the composite material under varying conditions.

Further, for the 10% fiber content, the results shown in Figures 6 and 7, with R^2 values of 0.96, 0.97, and 0.97, respectively, also support the use of second-order polynomial regressions. These consistently high coefficients of determination indicate that the regression models provide a precise fit and effectively capture the essential dynamics of how increased fiber content influences the composite's mechanical properties. Overall, these regression analyses demonstrate that the polynomial regression models, whether second or third order, are highly effective in predicting the mechanical behavior of the composite material as a function of fiber length and content. The consistency of high R^2 values across different models and fiber contents highlights the substantial impact of fiber variables on the composite's mechanical properties and supports the reliability of these models for future predictive tasks.

4. Conclusions

Torsion testing on water hyacinth fiber-reinforced epoxy resin composites revealed that fiber length and content significantly influence torsional strength, with shorter fibers demonstrating superior strength due to more effective fiber-resin bonding. Notable results include the highest torque of 1.418 Nm and shear stress of 29.348 MPa at a fiber length of 20 mm with 7% fiber content, while the greatest shear strain of 0.589 and shear modulus of 369.40 were observed at the same length but with 4% fiber content. Regression analysis, employing a third-order polynomial model, achieved a coefficient of determination (R^2) of 0.99, indicating high accuracy in predicting material behavior. Specifically, the model formulas $y=0.234x^3-1.7605x^2+3.8315x-1.904$, $y=0.234x^3-1.7605x^2+3.8315x-1.904$, and $y=0.234x^3-1.7605x^2+3.8315x-1.904$ proved perfect fit ($R^2 = 1$), underscoring their efficacy in forecasting shear strain and modulus based on fiber adjustments. These findings underscore the potential of tailored fiber dimensions and compositions in optimizing the mechanical performance of sustainable composite materials for engineering applications.

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