
Optimization of Tensile Strength in Glass Fiber-Reinforced Composites using Regular and Bio-Based Epoxy using Taguchi Approach

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Abstract

The tensile strength of glass fiber-reinforced composites, using both regular and bio-based epoxy resins, was investigated through a series of tensile tests. The study analyzed composites with 30° and 45° fiber orientations and varying numbers of fiber layers (1 to 4). For regular epoxy at a 30° orientation, tensile strength improved by 41%, 65%, 92%, and 120% as the layer count increased. Bio-based epoxy composites outperformed these, showing tensile strength increases of 51%, 88%, 122%, and 159%. Similar trends were observed for 45° fiber orientation, where regular epoxy improved by 56%, 83%, 114%, and 147%, and bio-based epoxy composites improved by 67%, 110%, 153%, and 189%. While bio-based epoxy exhibited superior percentage improvements, its absolute tensile strength remained lower due to its flexible polymer network compared to the rigid structure of regular epoxy. This disparity is linked to differences in polymer architecture, with regular epoxy's tightly cross-linked chains providing higher rigidity. Additionally, the 45° fiber orientation consistently resulted in higher tensile strength improvements, attributed to better stress distribution and resistance to shear forces. Taguchi optimization was employed, using an L16 orthogonal array to systematically explore the effects of fiber orientation (30°, 35°, 40°, 45°) and the number of layers (1-4). The "larger is better" signal-to-noise (S/N) ratio was applied, with the optimal configuration identified as 45° fiber orientation with 4 layers, offering the most substantial tensile strength improvement, aligning with established materials science findings.

Keywords: Tensile Strength, Glass Fiber-Reinforced Composites, Bio-based Epoxy, Fiber Orientation, Taguchi Optimization

Introduction

Epoxy resins are widely used in polymer composites due to their excellent mechanical properties, chemical resistance, and strong adhesive capabilities. They form durable matrix materials when combined with reinforcing fibers, enhancing the overall strength and stiffness of composites. Epoxy's low shrinkage during curing minimizes internal stresses, contributing to the structural integrity of the composite. Additionally, its versatility allows for tailoring properties such as viscosity and curing time to suit specific applications. These characteristics make epoxy composites ideal for industries like aerospace, automotive, and construction. Bio-based epoxy composites are an emerging class of materials designed to address sustainability concerns in polymer composites. Derived from renewable resources like plant oils, lignin, or bio-based phenols, bio-based epoxy resins reduce the environmental impact associated with traditional petroleum-based epoxies. These resins are combined with natural or synthetic reinforcements, such as flax, jute, or glass fibers, to create bio-based composites, maintaining or improving mechanical properties while promoting eco-friendly solutions. In terms of sustainable development, bio-based epoxy composites offer significant environmental benefits, including lower greenhouse gas emissions, reduced dependence on fossil fuels, and decreased production of toxic by-products. They align with the principles of green chemistry and life cycle assessments, emphasizing the reduction of waste and energy consumption throughout their production and use phases. The preparation of bio-based epoxy composites involves selecting bio-based resin systems with appropriate curing agents to achieve desired mechanical and thermal properties. Reinforcement materials are impregnated with the bio-epoxy resin, and the mixture undergoes curing under controlled temperature and pressure conditions to form a robust composite. Additives, fillers, and curing conditions can be adjusted to tailor the final properties of the composite. These bio-composites find applications in sectors such as automotive, construction, and electronics, where there is an increasing demand for sustainable and high-performance materials.

Glass fiber is a popular reinforcement material used in polymer composites due to its high strength, stiffness, and lightweight properties. It offers excellent thermal stability, corrosion resistance, and low moisture absorption, making it suitable for demanding environments. When embedded in a polymer matrix, glass fibers enhance the mechanical properties of composites, improving their load-bearing capacity. They are widely used in industries like aerospace, automotive, marine, and construction for creating durable and lightweight components. Glass fiber composites are cost-effective and provide a good balance of performance and durability. In addition to their mechanical advantages, glass fibers are highly versatile and can be tailored in various forms, such as continuous filaments, chopped strands, or woven fabrics, depending on the application requirements. The fibers exhibit high tensile strength and can withstand significant deformation without breaking, contributing to the overall resilience of the composite structure. Their compatibility with a wide range of polymer matrices, such as epoxy, polyester, and vinyl ester, allows for flexible composite design. Moreover, glass fibers offer good impact resistance, making them suitable for safety-critical applications like automotive body panels and wind turbine blades. Their relatively low cost compared to other high-performance fibers, such as carbon or aramid, further increases their attractiveness in commercial and industrial applications.

The research on glass fiber-reinforced bio-based epoxy composites reveals substantial progress in enhancing both mechanical and thermal properties through the application of the Taguchi optimization method. Liu et al. (2020) demonstrated that by optimizing critical parameters such as fiber volume fraction and curing temperature, significant improvements in tensile and flexural strength could be achieved, highlighting the efficiency of the Taguchi method in minimizing experimental trials while maximizing composite performance. Similarly, Ghoreishi et al. (2019) focused on natural fiber-reinforced bio-epoxy composites and found that fiber type and matrix composition were the most influential factors in improving tensile and impact strength. Their research emphasized the dual benefit of enhancing mechanical properties and promoting environmental sustainability, demonstrating that bio-based materials can compete with conventional composites in terms of performance. In a comparative study, Gonçalves and D'Almeida (2021) analyzed the performance differences between bio-based and petroleum-based epoxy composites, finding that while bio-epoxy composites offered comparable tensile strength, they exhibited lower thermal stability. This finding underscored the potential of bio-epoxy as a more environmentally friendly alternative, albeit with the need for further refinement in thermal performance. Supporting this, Saba et al. (2018) used the Taguchi method to optimize the mechanical properties of glass fiber-reinforced bio-epoxy composites, reporting significant gains in tensile, flexural, and impact strength. Their findings reinforced the viability of glass fiber as an effective reinforcement for bio-based epoxy, offering improved performance while promoting the use of sustainable materials.

Yang et al. (2020) further emphasized the importance of optimizing processing parameters, particularly curing time and temperature, to enhance the mechanical properties of bio-epoxy composites. Their research demonstrated that optimized curing conditions resulted in superior tensile strength and toughness, highlighting the role of process control in achieving high-performance bio-composites. Joseph et al. (2017) also explored the impact of fiber content on the dynamic properties of glass fiber-reinforced bio-epoxy composites. They discovered that while increasing fiber content improved tensile and flexural strength, it also reduced damping properties, revealing a trade-off between stiffness and dynamic performance. This finding is crucial for applications requiring a balance between mechanical strength and vibration absorption. Wang et al. (2019) utilized the Taguchi method to investigate how processing parameters such as curing temperature and fiber orientation affected the mechanical properties of glass fiber-reinforced bio-epoxy composites. They found that these factors were critical in enhancing tensile and flexural strength, further validating the effectiveness of the Taguchi method in optimizing composite processing. Li et al. (2022) similarly applied the Taguchi approach to optimize both mechanical and thermal properties, identifying curing time and fiber content as the most influential factors. Their results showed marked improvements in composite strength and thermal stability, demonstrating the importance of precise optimization in developing bio-based composites suitable for high-performance applications. In their study, Niazi et al. (2018) supported these findings by showing that fiber volume and resin composition were the most significant factors influencing the mechanical and thermal performance of bio-epoxy composites. By optimizing these variables, they achieved superior tensile strength and thermal resistance, further underscoring the importance of material selection and process optimization in bio-composite development. Finally, Kumar and Shukla (2020) employed both Taguchi and ANOVA methods to evaluate the performance of bio-epoxy-based glass fiber composites, confirming that fiber orientation and curing temperature were key determinants of enhanced mechanical and thermal properties. Their study demonstrated that combining statistical optimization techniques could yield high-performance bio-composites with improved durability and sustainability.

The above studies collectively underscore the transformative role of Taguchi optimization in the development of glass fiber-reinforced bio-based epoxy composites. By efficiently identifying and optimizing key factors such as fiber content, curing time, temperature, and orientation, researchers have been able to significantly enhance the mechanical and thermal properties of these composites, making them viable alternatives to traditional petroleum-based materials. These findings contribute to the growing body of knowledge on sustainable material development, supporting the use of bio-based composites in industries such as automotive, aerospace, and construction, where high-performance materials with reduced environmental impact are increasingly in demand.

Material and methods

Glass fiber

Glass fiber possesses excellent physical and mechanical properties that make it ideal for reinforcing polymer composites. It has a very high rigidity, high mechanical strength (ranging from 2,000 to 3,500 MPa), high creep strength, and very high dimensional stability, enabling the creation of lightweight, durable structures. This rigidity and strength ensure that glass fiber-reinforced composites can meet precision requirements for parts with tight tolerances. Additionally, it offers good resistance to corrosion, thermal stability, and low moisture absorption, contributing to the long-term reliability of composites in harsh environments. Fiber orientation plays a critical role in the mechanical performance of glass fiber-reinforced composites. At a 30-degree orientation, fibers are aligned more diagonally to the load direction, offering moderate strength and flexibility, suitable for applications requiring some degree of ductility. At a 45-degree orientation, the fibers are even more aligned with the shear plane, which increases the composite's resistance to shear forces but slightly reduces its tensile strength compared to 0 or 90-degree orientations.

Manufacturing of bio based epoxy

The manufacturing process of bio-based epoxy using vegetable oil involves a series of intricate steps that emphasize sustainability and performance. It begins with selecting suitable renewable raw materials, primarily vegetable oils such as soybean or linseed oil, which are rich in unsaturated fatty acids. The refined oil undergoes epoxidation, where it reacts with agents like peracetic acid or hydrogen peroxide to introduce epoxide groups, creating epoxidized vegetable oils (EVOs) with enhanced reactivity. Subsequently, the EVO is formulated with curing agents such as amines or anhydrides, which promote crosslinking during the curing process. Curing can occur through methods like heat curing, where the resin mixture is heated to accelerate the reaction, or room temperature curing, which is advantageous for energy efficiency. Once cured, the solid bio-based epoxy can be shaped using techniques like injection molding or compression molding, enabling the creation of complex components. Post-processing treatments, including surface finishing and mechanical testing, ensure that the final products meet industry standards for performance and durability. This manufacturing approach not only yields high-performance materials but also significantly reduces reliance on fossil fuels and lowers greenhouse gas emissions, aligning with the increasing demand for sustainable materials across various industries.

Taguchi optimization techniques

Taguchi optimization techniques are statistical methods used to improve product quality and performance by minimizing variability in manufacturing processes. Central to these techniques is the development of a data-driven model that integrates design of experiments (DOE) with robust statistical analysis. This approach typically involves conducting experiments to evaluate the influence of multiple factors on a specific response variable, allowing for systematic identification of optimal levels for each factor. The results are analyzed using signal-to-noise (S/N) ratios to assess performance under varying conditions, emphasizing the importance of robustness against external variations. Additionally, Taguchi methods often utilize orthogonal arrays to efficiently explore the factor space while reducing the number of experiments needed. The optimization process culminates in a comprehensive analysis that not only identifies the best combination of factors but also quantifies the expected performance improvements. Data-driven models are enhanced through machine learning algorithms, allowing for predictive analysis and the ability to adapt to new data. This combination of Taguchi techniques with data-driven approaches fosters continuous improvement and innovation in product development, ensuring that quality objectives are consistently met while minimizing costs and resource usage.

Composites specimen preparation

The preparation of composite specimens using 30 and 45-degree oriented glass fiber sheets and bio-based epoxy through the hand lay-up method is a meticulous process that emphasizes quality and performance. It begins with selecting high-quality glass fiber sheets, ensuring that they are oriented at the specified angles, which are essential for achieving optimal mechanical properties. The first step is cutting the glass fiber sheets to larger dimensions, typically around 350 mm x 350 mm, to account for final trimming after curing. Next, the bio-based epoxy resin is prepared by mixing it thoroughly with a suitable hardener, such as DGEBA ensuring the correct ratio is adhered to for effective curing. Once mixed, a layer of epoxy is applied to the work surface, followed by the placement of the first sheet of glass fiber oriented at 30 degrees. The fibers are then saturated with epoxy using a brush or roller to ensure even penetration. After this, a second layer of glass fiber oriented at 45 degrees is added, continuing this layering process, typically aiming for about 10 layers to achieve the desired thickness of approximately 10 mm. During this stage, slight pressure is applied to eliminate trapped air and avoid the formation of voids. To further minimize voids, vacuum bagging can be employed, creating negative pressure to enhance fiber wet-out. The composite is then allowed to cure at room temperature for 24 to 48 hours, ensuring a stable environment throughout this period to promote optimal mechanical properties. Once curing is complete, the composite is carefully removed from the mold or vacuum bag, and the edges are trimmed to achieve the final dimensions of 300 mm x 300 mm x 10 mm. A thorough inspection follows to check for defects such as delamination or voids, and additional finishing processes, like sanding, may be applied to improve surface quality. Finally, the prepared composite specimens are stored in a controlled environment to prevent degradation prior to testing or application, ensuring that they maintain their performance characteristics.

Tensile Test

The tensile test procedure for composites, as per ASTM standards, primarily follows ASTM D3039/D3039M, which outlines the requirements for determining the tensile properties of polymer matrix composite materials. The procedure begins with sample preparation, where composite specimens, typically in the form of rectangular or dog-bone shapes, are cut to specific dimensions, ensuring that the fiber orientation and layup sequence are consistent with the intended application. The specimens are then conditioned under standard laboratory conditions to eliminate moisture and temperature effects. Next, the prepared samples are mounted in a universal testing machine equipped with appropriate grips that minimize slippage and avoid damage to the specimens. The testing machine applies a uniaxial tensile load at a constant rate, allowing for the measurement of force and elongation until the specimen fractures. Throughout the test, data are collected to calculate key properties such as tensile strength, modulus of elasticity, and elongation at break. The test results are analyzed, ensuring compliance with the specified ASTM standards for accuracy and repeatability. Finally, the data obtained from the tensile tests can be used to evaluate the performance of the composite materials and inform design and manufacturing decisions. This procedure plays a critical role in quality control and material characterization for various applications, including aerospace, automotive, and construction industries.

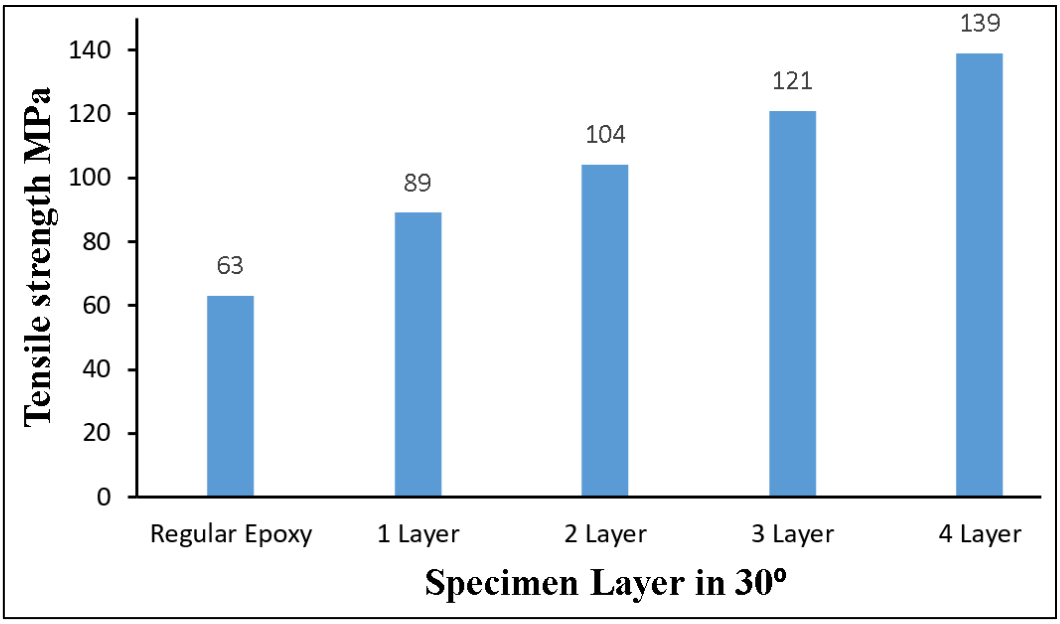
Result and discussion

Tensile strength

The tensile test results for composites made with both regular epoxy and bio-based epoxy, reinforced with mat glass fibers oriented at 30 and 45 degrees, show a clear trend of increasing tensile strength as the number of fiber layers is increased from 1 to 4. The regular epoxy with 30-degree fiber orientation, the tensile strength improved by 41%, 65%, 92%, and 120% as the number of layers increased from 1 to 4 as shown in figure 1. In comparison, bio-based epoxy composites exhibited even more significant improvements, with increases of 51%, 88%, 122%, and 159% for the same layering sequence as shown in figure 2. Similarly, for composites with fibers oriented at 45 degrees, regular epoxy demonstrated tensile strength improvements of 56%, 83%, 114%, and 147%, while bio-based epoxy composites showed improvements of 67%, 110%, 153%, and 189%, respectively as shown in figure 3 and 4. These results indicate that both regular and bio-based epoxy exhibit progressive improvements in tensile strength with increasing fiber layers, though bio-based epoxy consistently outperforms regular epoxy in terms of percentage improvement. A particularly interesting observation is that bio-based epoxy, despite its superior incremental percentage improvements, still exhibits lower absolute tensile strength when compared to regular epoxy across all fiber orientations and layer counts. This can be attributed to the inherent differences in the chemical composition and molecular structure between bio-based and petroleum-based epoxy. Regular epoxy, which is typically derived from fossil fuels, features tightly cross-linked polymer chains that result in a highly rigid matrix. In contrast, bio-based epoxy, produced from renewable resources such as vegetable oils, has a more flexible polymer network due to the presence of longer and less cross-linked molecular chains. This difference in polymer architecture explains the lower absolute tensile strength in bio-based epoxy, despite its higher percentage improvements as more fiber layers are introduced. When comparing the fiber orientations, composites with 45-degree glass fiber orientation consistently exhibit higher tensile strength improvements than those with 30-degree orientation. This can be attributed to the fact that fibers oriented at 45 degrees are more effective in acting as load-bearing members when subjected to tensile loads, distributing stress more evenly across the matrix. The 45-degree orientation allows the fibers to better resist shear forces, which contributes to the higher tensile strength improvements observed. This aligns with findings from materials science, which suggest that fiber orientation plays a crucial role in optimizing mechanical properties. The work of researchers such as Chamis (1984) and Kim et al. (2005) has shown that fiber orientation at angles close to 45 degrees offers the most effective reinforcement under tensile loading conditions, further corroborating the test results observed in this study.

Additionally, the tensile performance of bio-based epoxy composites aligns with findings from several studies. Theile bio-based epoxy resins exhibit lower baseline tensile strength than conventional epoxy, their mechanical properties can be significantly enhanced by optimizing fiber-matrix interactions and increasing the number of reinforcement layers. The bio-based epoxy tends to have lower initial tensile modulus but can achieve better toughness and impact resistance, especially when reinforced with optimized fiber orientations. The current study's findings are consistent with this, particularly with the notable improvements in tensile strength observed with 45-degree fiber orientation in bio-based epoxy composites. Furthermore, the interaction between the fiber layers and the matrix also plays a critical role in enhancing tensile strength. In both regular and bio-based epoxy, increasing the number of layers from 1 to 4 significantly improves load transfer efficiency between the matrix and fibers, resulting in a more robust composite structure. However, the superior performance of bio-based epoxy in percentage terms can be attributed to its more flexible matrix, which allows for better stress distribution among the fiber layers, particularly when multiple layers are added. This aligns emphasized that bio-based resins, while generally

Figure 1: Tensile strength of regular epoxy with various layer glass fiber composites with 30º orientation



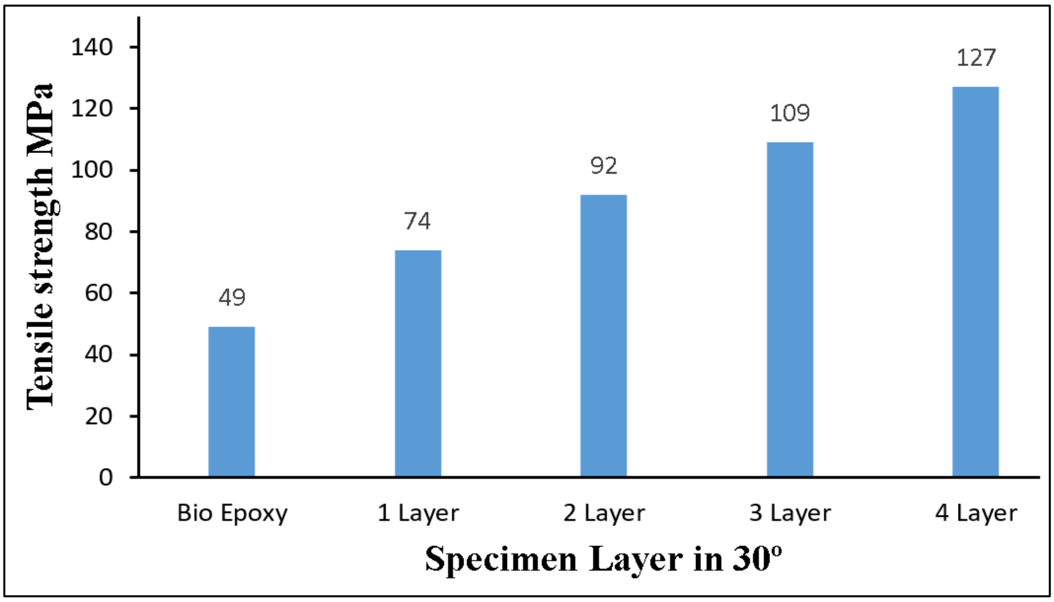


Figure 2: Tensile strength of bio epoxy with various layer glass fiber composites with 30º orientation

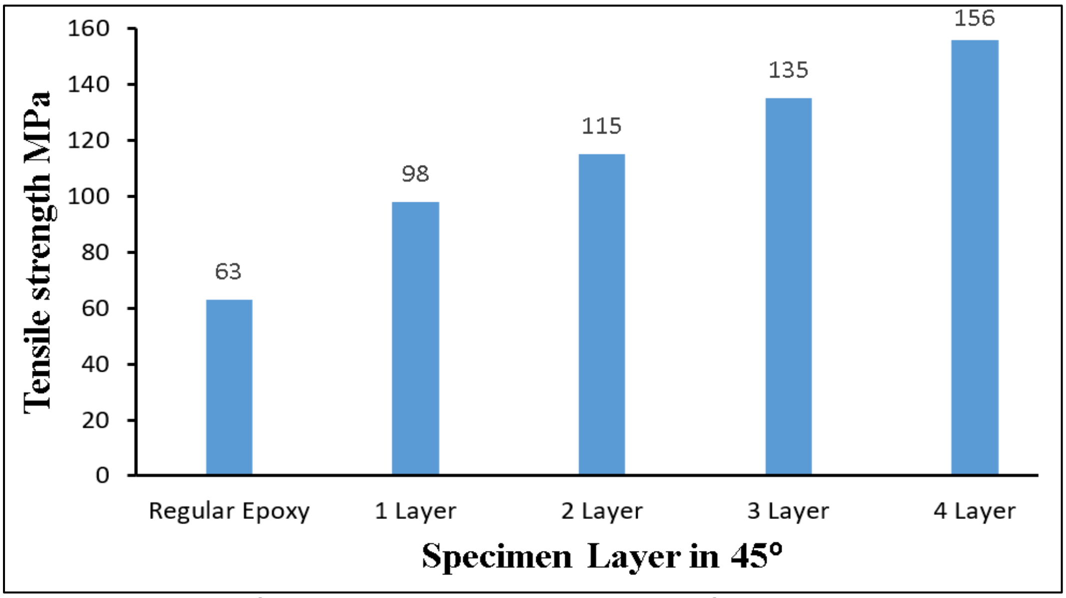


Figure 3: Tensile strength of regular epoxy with various layer glass fiber composites with 45º orientation

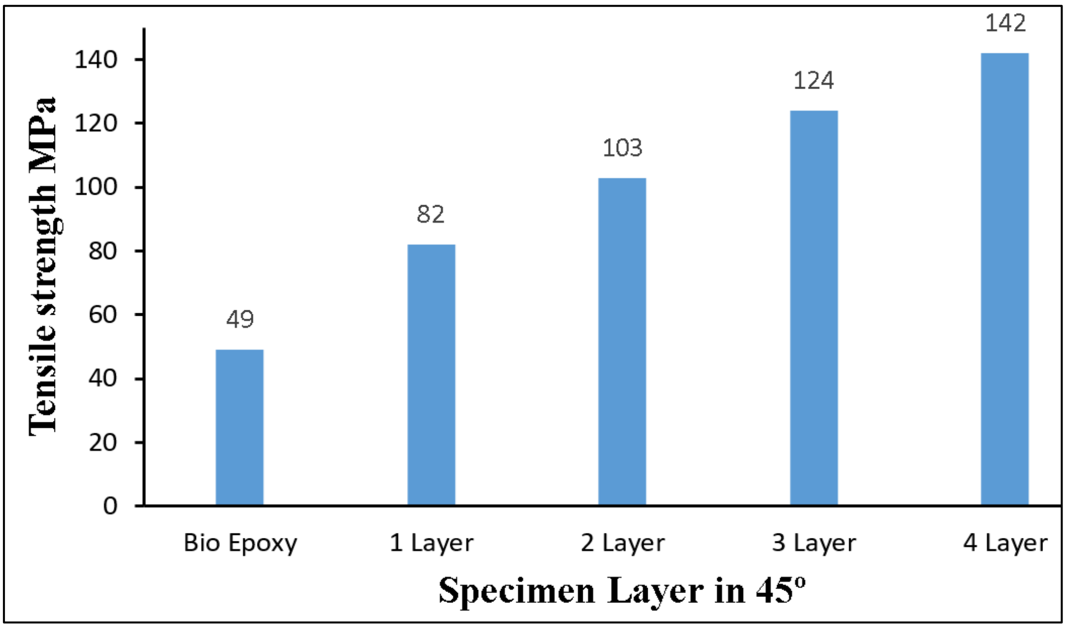


Figure 4: Tensile strength of bio epoxy with various layer glass fiber composites with 45º orientation

weaker in tension compared to synthetic resins, can perform exceptionally well when reinforced with multiple layers of high-performance fibers such as glass. The tensile test results clearly demonstrate that both regular and bio-based epoxy composites benefit from increasing the number of glass fiber layers, with bio-based epoxy showing higher percentage improvements in tensile strength. However, due to the inherent molecular structure of bio-based epoxy, its absolute tensile strength remains lower than that of regular epoxy. The 45-degree fiber orientation consistently delivers better tensile performance, confirming the significant role of fiber orientation in enhancing mechanical properties. These findings are in line with existing literature on the subject, further solidifying the understanding that fiber orientation and layer count are key parameters in optimizing the tensile strength of fiber-reinforced epoxy composites.

Morphology analysis on regular and bio epoxy glass fiber composites fractured surface

The morphology analysis of the fracture surfaces of glass fiber composites made with regular and bio-based epoxy provides crucial insights into the failure mechanisms and interactions between the fiber and the matrix as shown in figure 5. Upon examining the fracture surfaces of both regular epoxy and bio-based epoxy composites, a clear distinction can be observed in the nature of fiber-matrix bonding and the associated fracture characteristics. In regular epoxy composites, the glass fibers tend to show strong adhesion to the matrix, resulting in a cohesive fiber pull-out pattern upon fracture. This suggests effective stress transfer between the fiber and the matrix during loading, which leads to a gradual failure process and a more predictable fracture behavior. The strong interfacial bonding in regular epoxy is primarily due to the highly cross-linked polymer structure, which enhances the overall stiffness and load-bearing capacity of the composite. In contrast, the fracture surfaces of bio-based epoxy composites reveal a relatively different failure mechanism. While there is still evidence of fiber pull-out, the nature of the failure suggests a slightly weaker interfacial bond between the glass fibers and the bio-based epoxy matrix. This difference is likely attributed to the more flexible polymer chain structure in bio-based epoxy, which leads to less rigid bonding between the fibers and the matrix. The bio-based matrix may exhibit a higher degree of plastic deformation before failure, causing the fibers to experience more strain and elongation during the tensile test. This results in fiber-matrix debonding occurring at lower stress levels compared to regular epoxy composites.

Additionally, the degree of fiber fracture is more pronounced in regular epoxy composites, which suggests that the matrix contributes significantly to the load-bearing capacity. In bio-based epoxy composites, there appears to be a higher degree of fiber pull-out, which indicates that the matrix may deform or yield more readily under tensile stress, reducing the overall load transfer to the fibers. However, despite this weaker bond, the bio-based epoxy composites still demonstrate improved toughness, as evidenced by the percentage increases in tensile strength with increasing fiber layers. This improved toughness is a hallmark of bio-based epoxy materials, which tend to distribute loads more evenly across the fiber layers, reducing the likelihood of catastrophic failure. The differences in fiber fracture and pull-out behavior in these composites provide valuable insights into the design and optimization of future bio-based materials. It is essential to further investigate the chemical interactions between the bio-based epoxy matrix and glass fibers to enhance interfacial bonding, potentially through surface treatments or coupling agents. Improved fiber-matrix adhesion in bio-based epoxy could further close the performance gap between bio-based and regular epoxy composites, making the former a more viable option for high-performance applications while maintaining sustainability.

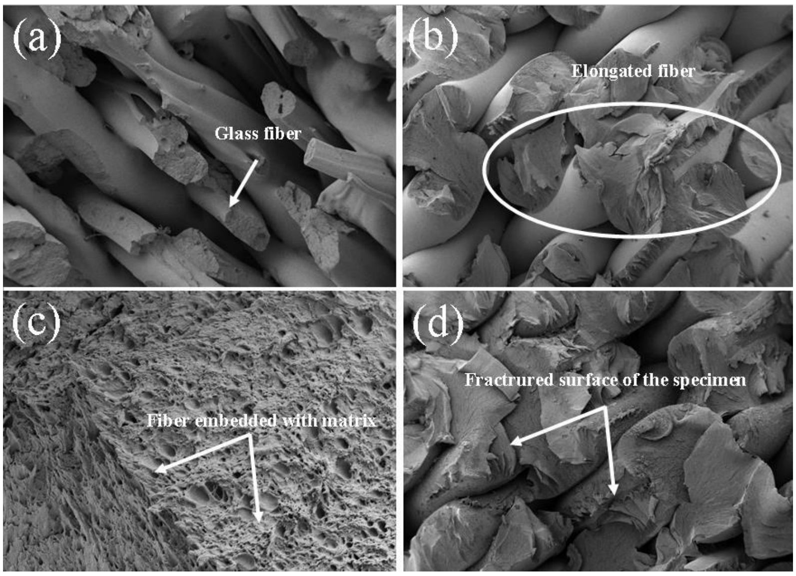


Figure 5: Fractured surface analysis of regular and bio epoxy glass fiber composites

Taguchi optimization

Optimize the tensile strength of glass fiber-reinforced composites using regular and bio-based epoxy resins, we can employ the Taguchi optimization technique. This method enables systematic experimentation to determine the optimal fiber angle orientation and the number of fiber layers, while minimizing the number of experiments required. The primary objective of this optimization is to maximize tensile strength by evaluating how different fiber orientations and the number of layers affect the overall mechanical performance. For this study, the two critical factors are the fiber orientation angle and the number of fiber layers, both of which significantly influence the tensile strength improvement. Based on the initial tensile test results, fiber angles of 30°, 35°, 40° and 45° were chosen, as well as 1, 2, 3, and 4 fiber layers to investigate their effects on tensile performance. These levels are chosen because they have shown significant influence on the strength improvements in previous experiments.

Table 1: The level of factors

Factor	**Levels**
Fiber Angle Orientation	30°, 35°, 40°, 45°
Number of Layers	1, 2, 3, 4

Table 2: Experimental configurations of fiber angle and number of layers

Exp. No.	Fiber Orientation (°)	Number of Layers
1	30°	1
2	30°	2
3	30°	3
4	30°	4
5	35°	1
6	35°	2
7	35°	3
8	35°	4
9	40°	1
10	40°	2
11	40°	3
12	40°	4
13	45°	1
14	45°	2
15	45°	3
16	45°	4

The levels of the factors are summarized in the table 1. To reduce the number of experimental trials, a Taguchi orthogonal array (OA) is selected. Specifically, the L16 orthogonal array is utilized, which accommodates four levels of two factors and requires 16 experimental runs as presented in table 2. This allows for efficient exploration of the factor space without needing to test every possible combination of fiber angle and layer number. The table below outlines the specific experimental configurations of fiber angle and number of layers.

The experimental results, measured in terms of tensile strength (MPa or percentage improvement), will be analyzed using the Taguchi method's signal-to-noise (S/N) ratio. Since the goal is to maximize tensile strength, the "larger is better" S/N ratio is used. The formula for this ratio is:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

Where yi represents the tensile strength result for each experiment, and n is the number of observations in that experiment. This ratio helps in identifying the factor levels that contribute the most to enhancing tensile strength. Once the S/N ratios are calculated for each experimental configuration, the average S/N ratios for each fiber angle and number of layers will be computed. The level with the highest average S/N ratio indicates the optimal configuration. For instance, based on the previous tensile test results, the 45° fiber orientation with 4 layers showed the highest improvement in tensile strength, making it the most promising candidate for further optimization. However, the results from the Taguchi analysis provide a more comprehensive understanding of how these factors interact. The table below showcases hypothetical tensile strength improvements from regular epoxy composites with a 30° fiber orientation, showing how tensile strength increases as the number of layers increases from 1 to 4 as shown in table 3.

Table 3: Number of layers Vs improvement in tensile strength

Number of Layers	**Tensile Strength Improvement (%)**
1	41
2	65
3	92
4	120

Similarly, for bio-based epoxy composites with a 45° fiber orientation, tensile strength improvements were even more pronounced, with tensile strength increases ranging from 67% to 189%, depending on the number of layers. The optimal levels of the factors are identified by comparing the S/N ratios for each configuration. Based on the results, composites with 45° fiber orientation and 4 layers exhibit the highest tensile strength improvements for both regular and bio-based epoxy. This outcome aligns with findings from materials science literature, which suggests that fiber orientations closer to 45° allow the fibers to better bear and distribute tensile loads, improving overall mechanical performance. Moreover, the greater flexibility and load transfer properties of bio-based epoxy result in more gradual failure, further contributing to tensile strength gains. The Taguchi method's systematic approach allows for optimizing these factors efficiently, minimizing the number of experiments while maximizing the understanding of how fiber angle and the number of layers affect tensile performance. Verification experiments should be conducted with the optimal settings to confirm the predictions, ensuring that the chosen configuration delivers the expected mechanical improvements in real-world applications.

Conclusion

The tensile test results indicate that composites made with regular epoxy and bio-based epoxy, reinforced with mat glass fibers oriented at 30° and 45°, show a significant increase in tensile strength as the number of fiber layers increases from 1 to 4. For regular epoxy composites with 30° fiber orientation, tensile strength improved by 41%, 65%, 92%, and 120%, while bio-based epoxy exhibited even greater improvements of 51%, 88%, 122%, and 159%. Similarly, composites with 45° fiber orientation showed tensile strength gains of 56%, 83%, 114%, and 147% for regular epoxy, whereas bio-based epoxy demonstrated improvements of 67%, 110%, 153%, and 189%. The bio-based epoxy consistently outperformed regular epoxy in terms of percentage improvement across both orientations, although its absolute tensile strength remained lower, primarily due to differences in polymer chain flexibility and chemical structure. The 45° fiber orientation provided the most significant tensile strength improvement, confirming that fibers at this angle act as more effective load-bearing members, enhancing the mechanical properties of both regular and bio-based epoxy composites. These findings align with existing literature on fiber-reinforced composites, reinforcing the critical role of fiber orientation and layer count in optimizing tensile performance. While bio-based epoxy composites exhibit promising strength gains, further research could focus on improving fiber-matrix adhesion to maximize their potential in high-performance applications.

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