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Finite Element Analysis of Stress Distribution in Alkali-Peroxide Treated Epoxy Composites with Various Woven Cotton Structures

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ABSTRACT

The poor surface properties of woven epoxy-cotton composite structures have limited their use in industrial applications. Existing solutions using single treatment processes have been developed to address the challenges but have recorded appreciable degrees of success. This study has introduced a novel and synergistic alkali-peroxide treatment in addition to the use of five (5) variations of reinforcing woven structures (plain, matt, twill, herringbone, and satin) to develop the composites via the vacuum bagging molding process. This paper demonstrates the effectiveness of the dual treatment and different woven architectures in structure-related properties, particularly in the warp (machine) direction. The synergistic treatment showed a negative effect on the thermal stability of the resulting composites. The composite with the optimum weave structure in reinforcement capacity was validated using ANSYS FEA based on the numerical and experimental results, and the obtained results showed the possibility of simulating the tensile behavior of the composite structures.

摘要

编织环氧棉复合结构的较差表面性能限制了其在工业应用中的使用. 已经开发了使用单一处理工艺的现有解决方案来应对这些挑战，但取得了可观的成功. 除了使用五（5）种不同的增强编织结构（平纹、亚光、斜纹、人字形和缎面）通过真空装袋成型工艺开发复合材料外，本研究还引入了一种新型的协同碱过氧化物处理. 本文证明了双重处理和不同织造结构在结构相关性能方面的有效性，特别是在经纱（机器）方向上. 协同处理对所得复合材料的热稳定性产生了负面影响. 基于数值和实验结果，使用ANSYS FEA验证了具有最佳编织结构的复合材料的增强能力，所得结果表明了模拟复合材料结构拉伸行为的可能性.

KEYWORDS

Cotton fabric; epoxy-cotton woven composite structures; alkali-peroxide treatment; vacuum bagging infusion; mechanical and thermal properties; finite element analysis

关键字

棉织物; 环氧棉编织复合结构; 碱过氧化物处理; 真空袋装输液; 机械和热性能; 有限元分析

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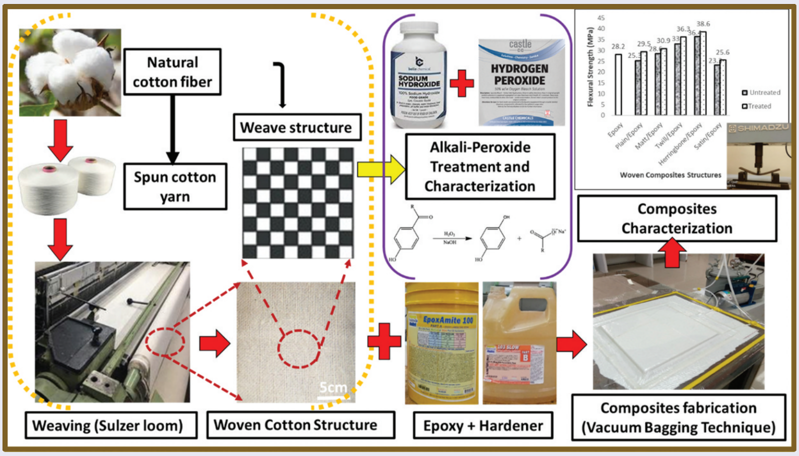

Synergistic impact of alkali-hydrogen peroxide AHP treatment techniques in enhancing the mechanical performance of cotton-epoxy woven composite structures for industrial applications

Introduction

In the domain of advanced materials, composite structures play a pivotal role in meeting the demanding requirements of various industrial applications. Epoxy-based composites, reinforced with natural fibers such as cotton, have garnered significant attention for their lightweight, environmentally friendliness, and their specific and cost-effective characteristics (Alsuwait et al. 2022; Khan et al. 2022). The mechanical properties of these composites, however, can be further optimized to meet the specific needs of diverse industries.

This research focuses on exploring novel surface treatment methodologies to enhance the mechanical performance of epoxy-cotton woven composites structures. Alkali treatment, recognized for its ability to modify fiber morphology and improve adhesion (Zidi and Miraoui 2024) and peroxide treatment, known for its role in enhancing polymer crosslinking (Al-Malaika, Riasat, and Lewucha 2017; González-Sánchez et al. 2016), are combined to investigate their synergistic effects on the overall composite structure. The intention is to develop a comprehensive understanding of how these treatments, when employed in tandem, influence key properties such as mechanical, thermal, and morphological behaviors.

The significance of this research lies in the potential to unlock new avenues for the design and production of composite materials with superior mechanical characteristics, thereby expanding their utility across a spectrum of industrial applications. By delving into the intricate interplay between alkali and peroxide treatments on epoxy-cotton woven composites, this study aims to contribute valuable insights that can inform the development of advanced materials capable of meeting the stringent performance requirements in fields ranging from automotive and aerospace to construction and manufacturing. Natural fibers are subjected to chemical treatment to improve their surface geometry, strength, and contact between the fibril and matrix, among other beneficial properties (Birniwa et al. 2023; Jagadeesh et al. 2021). The coupling agents aid in creating cross-linked interphase regions, eliminate weak boundary layers, create solid and flexible layers, improve polymer-substrate wetting, and produce covalent bonds (Samanth and Bhat 2023). This is achieved because the surface roughness and surface energy cause mechanical interlock at the interface which are primarily responsible for chemical and physical properties of natural fiber surfaces (Youbi et al. 2022). Hence, the surface of natural fibers ought to be modified by chemical treatments to improve adhesion at the fiber-matrix.

Cotton is a natural fiber of seed plant origin, known for its versatility, performance, and natural comfort and its strength and absorbency make it ideal for industrial products such as tarpaulins and tents (Basak et al. 2018; Maity, Singha, and Pandit 2023). Woven cotton (fabrics) are the most versatile, sophisticated, and aristocratic fabrics available with good strength, having different designs such as plain, twill, basket, and sateen (Jahan 2017). It can retain its characteristic properties against various effects during end use, determining the performance characteristics of the fabrics (Ala 2021). The structure of various weaves significantly influences fabric properties, with correlations often observed across different fabric aspects. Similar to how fiber structure impacts its mechanical properties, the characteristics of fabrics are shaped by their weave structures. This is particularly evident as the weave configuration plays a pivotal role in determining the mechanical properties of woven fabrics (Begum and Milašius 2022; Witczak, Jasińska, and Krawczyńska 2021).

The application of natural fibers in composite materials is often hindered by their hydrophilic nature, dimensional instability, incompatibility with certain matrices, and poor interfacial bonding. Additionally, natural fibers generally exhibit lower moisture resistance and mechanical strength compared to synthetic fibers, further limiting their usability in composite applications (Owen et al., 2022). Additionally, impurities on fiber surfaces exacerbate these limitations (Youbi et al. 2022). Hence, these challenges can be addressed by subjecting natural fibers to several treatment processes. Alkalization or mercerization is the mostly used conventional treatment method for surface modification of natural fiber in reinforcing thermoplastics and thermosets, and to improve interfacial bonding and lower surface tension because it is simple, economical, and effective (Mohammed et al. 2022). Alkali treatment increases fiber roughness and reduces fiber diameter by removing amorphous materials such as lignin, hemicellulose, and pectin. This process effectively increases the aspect ratio and fineness of the fibers (Beg, Pickering, and Gauss 2023). It has also been reported that alkali treatment increased thermal stability, impact strength, flexural strength, tensile strength, and elastic modulus of fibers (Samanth and Bhat 2023) while reducing the water absorption properties. The effect of alkaline treatments at different concentrations, temperatures, and times on the properties of cotton materials at lower concentrations of 0.75–2.25 M and temperatures of 70–100°C have been studied (Azeem, Mao, and Faisal 2019). Others reported improvement in the surface of recycled cotton fibers (Baccouch et al. 2020), surface modification of cotton weaves using 6% sodium hydroxide and 2% acetic anhydride (Enwerem et al. 2022), amongst other researchers. This treatment eliminates surface substances, decreases the fibers' hydrophilicity, and enhances fiber crystallinity by hydrolyzing amorphous cellulose (Ling et al. 2017). However, research has demonstrated that natural fibers, even after alkalization, remain hydrophilic (Montreuil et al. 2024), hence, the need for the use of improved or combined treatment methods to further decrease the hydrophilicity of fibers is of high significant interest.

Peroxide treatment has garnered attention from researchers for its ability to enhance adhesion in cellulose-based composites. This treatment, which includes methods using oxygen, chlorine, chlorine dioxide, hypochlorite, and hydrogen peroxide, can vary significantly in its environmental impact (Beg, Pickering, and Gauss 2023). Notably, hydrogen peroxide bleaching is favored for its environmental sustainability, as it avoids the use of chlorine-based chemicals. This method improves the interfacial adhesion between natural fibers and the polymer matrix, decreases water absorption, and increases the thermal stability of the fibers (Mohammed et al. 2022). Peroxide treatment also results in an increase in absorbency and levelness of pretreatment (Ferdush et al. 2019). Hydrogen peroxide usage was reported as the most used oxidative treatment agent for cotton and its blends, accounting for more than 90% of all the hydrogen peroxide agents (Fu et al. 2022) (Ferdush et al. 2019). explored the impact of various hydrogen peroxide concentrations on cotton fabric. A 30% peroxide treatment yielded optimal results, potentially reducing the costs of the surface treatment process, as many industries typically use higher concentrations of H_2O_2. In another study, Hasan et al. (2021) worked on combined peroxide-enzymatic treatment processes on stretch denim fabric to investigate the changes in dimensional stability and mechanical properties. Traditionally, these processes have involved the use of high concentrations of harsh chemicals such as alkaline and hydrogen peroxide, extreme temperatures, and significant volumes of water. The associated costs extend beyond the chemicals and energy to include the expense of treating wastewater to eliminate residual by-products. Therefore, treatments that will help reduce the aforementioned challenges while significantly improving the composite properties are worthy of deeper investigation.

Few studies have reported the use of combined chemical treatment of fibers, including alkali-alkaline self-treatment (Suwan et al. 2022), alkaline-silane treatment (Asumani, Reid, and Paskaramoorthy 2012; Huda et al. 2008a, 2008b; Owen et al. 2018; Youbi et al. 2022), alkali-resin surface coating treatment (Chen et al. 2024; Montreuil et al. 2024, Owen et al., 2023a, 2023b, 2023c; Rashid, Simončič, and Tomšič 2021), silane-surface coating treatment (Owen, Achukwu, and Md Akil 2022), alkaline-peroxide (Akindoyo et al. 2023; Beg, Pickering, and Gauss 2023; Ding et al. 2024; Sukmawan et al. 2022; Verma and Goh 2021) and alkali-benzoyl chloride or benzoic anhydride (benzoylation) treatment (Samanth and Bhat 2023) have shown most advantageous outcomes with notable improvement. The combined treatments were effective in eliminating components from the fiber that contribute to a weak interface, such as hemicellulose, wax, lignin, and oil thereby decreasing the fiber diameter and facilitating stronger adhesive bonding between polymer matrix and lignocellulosic fibers when compared to single alkali treatment. Additionally, the implementation of these combined chemical treatment of natural fiber have shown to resolve the compatibility challenge between hydrophilic fibers and hydrophobic polymer properties by facilitating mechanical interlocking between the fiber and the matrix (Verma and Goh 2021) and improving the overall performance of natural fiber reinforced composites. Peroxide treatment, when combined with alkali treatment, is an effective chemical process that enhances the chemical bonding between natural fibers and polymer matrices (Getme and Patel 2020). Zou et al. (2021) explored a combined treatment of alkaline-hydrogen peroxide impregnation and two-step mechanical refining to enhance the cellulose accessibility and specific surface area of pondcypress *(Taxodium ascendens)* fibers. Their study revealed that the molecular structure of the fibers was synergistically improved through the combined application of NaOH and H_2O_2. This treatment enabled the fibers to dissociate effectively under shear stress and friction, while consuming relatively low energy (1637 kW h/t). As a result, the fibers achieved an ultrahigh cellulose accessibility of 77.07% and a high surface-active hydroxyl content of 2.164×10^{-3} mol/g, following the exposure of the S2 cell wall with 16% H_2O_2 and 17.5% NaOH treatment. These findings confirmed that impregnation and mechanical refining are effective methods for dissociating fibers, paving the way for broader application of lignocellulosic fibers in cellulose-based composite materials. Akindoyo et al. (2023) investigated the performance of polylactic acid (PLA) matrix composites with varying levels of digested alkali-peroxide bleached harakeke fibers. When compared to alkali digestion alone, they found that the combination of alkali digestion and hydrogen peroxide bleaching treatment enhanced the reinforcing capabilities of natural fibers in polymer composites by improving fiber distribution and strengthening interfacial bonding. It was observed that combined alkali digestion-peroxide bleaching treatment removed larger amount of non-cellulosic components from the fiber, which increased intermolecular cellulose hydrogen bonding in the alkali digested-bleached fiber. This resulted in higher cellulose content and increased thermal stability of the combined alkali digested-peroxide bleached fiber composites compared to the alkali digestion treated sample fibers. It was determined that incorporating combined alkali-digested and peroxide-bleached harakeke fiber into PLA resulted in superior mechanical and thermomechanical performance compared to the digested fiber alone. This enhancement is attributed to stronger interfacial interactions between the PLA and the fiber. Youbi et al. (2022) assessed the impact of combined chemical treatments on the surface modification of Raphia vinifera fibers. The fibers were subjected to varying concentrations of alkaline (1%, 5%, and 10%) and silane (1% and 5%) solutions over different durations. The findings indicated that the chemical structure and thermal degradation of the fibers were altered after undergoing the combined treatment with silane and NaOH. The study determined that applying silane and 1% NaOH treatments significantly improved the surface energy of the fibers over time. In their study, Ding et al. (2024) obtained an improved interfacial property, and about 30.1% to 56.9% increased mechanical properties of bamboo fabric (BF)/epoxy (EP) composites by modifying woven bamboo fabric with the combination of 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO) and N-hydroxyphthalimide (NHPI) oxidation systems.

Furthermore, other studies have shown that treatments such as alkali-peroxide, alkali-silane, and peroxide-enzymatic processes can significantly improve fiber-matrix adhesion, mechanical properties, and thermal stability. For example, Zou et al. (2021) reported on the combined alkaline-hydrogen peroxide impregnation and two-step mechanical refining to treat pondcypress fibers, resulting in enhanced cellulose accessibility and increased specific surface area. Similarly, Akindoyo et al. (2023) found that the combination of alkali digestion and hydrogen peroxide bleaching improved the reinforcing ability of natural fibers in polymer composites. Other studies, such as those by Youbi et al. (2022) and Ding et al. (2024), have demonstrated the effectiveness of combined chemical treatments in improving the interfacial properties and mechanical performance of natural fiber composites. These advancements highlight the potential of combined chemical treatments in overcoming the limitations of single-treatment processes, thereby enhancing the overall performance of natural fiber-reinforced composites.

In addition, Ameer et al. (2017) investigated the impact of various surface treatments on the mechanical properties of jute fiber-reinforced composites and it was established that chemical treatments of alkali and silane significantly improved the flexural and tensile characteristics of the composites. Their findings also aligned with the current study on the synergistic effects of alkali-peroxide treatment in improving the mechanical performance of epoxy-cotton woven composites. Ali et al. (2018) reviewed hydrophobic treatments of natural fibers and their composites, emphasizing the significance of surface modifications in enhancing the moisture resistance and mechanical properties of composites. They concluded that hydrophobic treatments can significantly reduce the moisture absorption of natural fibers, thereby improving the durability and mechanical performance of the composites.

Some other systematic studies of different cotton woven structures, weave parameters, and their impacts on thermal resistance & conductivity, mechanical properties were reported by (Khan et al. 2022; Limeneh 2022; Prakash et al. 2021; Timothy and Pragasam 2018; Vimal, Murugan, and Subramaniam 2016). Umair et al. (2021) also explored how weave architecture and the percentage of glass microspheres influence the low-velocity impact response of hemp/green epoxy composites. They discovered that both the weave design and the inclusion of glass microspheres notably affect the impact properties of the composites. Specifically, composites with satin woven reinforcement displayed the highest impact force, and those containing 5% glass microspheres demonstrated increased resilience and stiffness. Safdar et al. (2024) studied the effect of fillers and weave architecture hybridization on the impact performance of 3D woven composites. Their findings indicated that the hybridization of weave architecture and incorporation of fillers substantially enhanced the impact performance and overall mechanical properties of the composites. Abbas et al. (2020) investigated how glass microspheres and fabric weave structure impact the mechanical performance of polymer composites. They established that the incorporation of glass microspheres and the optimization of weave structure can lead to significant enhancements in the mechanical properties of the composites, such as tensile strength and impact resistance (Karahan and Karahan 2013). investigated the influence of weaving structure and hybridization on the tensile properties of woven carbon-epoxy composites. They determined that the geometric properties of carbon fabrics produced with different weaving structures significantly affect the mechanical properties of the resulting composites. The study revealed that hybridization and the type of weaving structure used can impact the Young's modulus and tensile strength of the composites. Their findings suggest that optimizing the weaving structure and hybridization of natural fiber composites could similarly enhance their mechanical properties, making them more suitable for high-performance applications.

Despite the aforementioned studies, there is still a lack of systematic investigations on the combined alkali-peroxide surface treatment effects on woven cotton structures. Specifically, the impact of such combined treatments on the properties of reinforced cotton-epoxy polymer composites has not been reported in the literature to the best of our knowledge.

Finite element analysis (FEA) is an effective technique for predicting the mechanical properties of composite materials (Balasubramanian, Rajeswari, and Vaidheeswaran 2020). Chinta, Ravinder Reddy, and Prasad (2022) and Tiwari et al. (2021) reported the use of FEA to predict and validate properties and performance composites reinforced with natural fibers in comparison with the experimental results. The fiber composites specimen was mechanically characterized as per appropriate ASTM standards, then followed by simulation and modeling software was constructed via 2D and 3D models of the specimens, and finally subjected to similar testing conditions by FEA software. The results from the FEA closely matched those obtained from experimental analysis. They concluded that FEA can be utilized to accurately predict the mechanical behavior and properties of natural fiber reinforced composite when the actual composite has regular and symmetrical fiber arrangements. Hariprasad, Dharmalingam, and Raj (2013) investigated the properties of banana coir hybrid composites using both experimental methods and finite element modeling (FEM) techniques. They utilized ANSYS 11.0 to simulate tests, while the 3D model of the specimen was created using modeling software. Their results demonstrated that the FEA outcomes were closely aligned with experimental data, affirming the utility of FEM in predicting the mechanical behavior of fiber composites. Similarly, Monzón et al. (2019) analyzed and simulated the mechanical behavior of woven banana fiber reinforced composites, which involved fibers extracted from the pseudostem and subjected to enzymatic treatment. Specimens adhered to the respective ISO dimensions for tests on three different types of technical textiles (plain, basket, and twill). A 3D model was developed for simulation purposes, and its results displayed minimal divergence from experimental outcomes, further validating the capability of simulations to accurately predict the mechanical behavior of reinforced fiber composites.

Therefore, the aim of this study is to determine the combined effect of alkali and peroxide treatment and finite element analysis on the mechanical properties of epoxy-cotton composite with different weave structures (plain, matt, twill, herringbone, and satin weaves) for industrial applications. FEA is employed to validate the observed changes in the mechanical properties of various woven cotton fiber composite structures with respect to synergistic impact of combined alkali-peroxide treatment. The material properties observed through experimentation, including unidirectional Young's modulus, Poisson's ratio, and ultimate tensile strength, were incorporated into the material model to determine the properties of complex three-dimensional shapes. This study is born out of the fact that no systematic study has been found for mechanical properties of cotton fabrics of different weave structures as reinforcement in epoxy system, where the combined alkali-peroxide treatment effects has been extensively investigated.

Experimental

Materials

Five (5) different gray fabric weaves were used as reinforcing materials for the study. The fabrics which were made from 100% cotton with their construction details determined as in Table 1, were woven and supplied by Nichemtex PLC, a textile manufacturing industry located in Lagos, Nigeria. Analytical grade of caustic soda (NaOH) (Merck, Germany), hydrogen peroxide (H_2O_2) (JT. Baker), and sodium carbonate (Na_2CO_3) (Sigma-Aldrich) were used for the combined alkali and peroxide treatment techniques. EpoxAmite 102 medium curative hardener with EpoxAmite 100 resin, used as the matrix component in the composites, was procured from Smooth-On, Inc., located in Macungie, PA, USA.

Weaving of cotton fabric structures

Cotton fabric structures were woven using Sulzer loom dobby projectile weaving machines. Each fabric was constructed with identical specifications: yarn count, warp densities (ends per centimeter), and weft densities (picks per centimeter), though they featured various intricate weave patterns, as

Table 1. Fabric construction parameters for the various weaves.

Weave	Weft Count (Ne)	Warp Count (Ne)	Pick/cm	Ends/cm	Fabric Areal Density (g/m^2)
Plain	20	20	20	18	156
Matt	20	20	20	19	158
Twill	20	20	20	19	165
Herringbone	20	20	20	19	160
Satin	20	20	20	19	158

detailed in Table 1. The areal densities of each fabric were taken and labeled. The samples were finally conditioned for 24 hours at temperature of 27°C.

Combined alkali-hydrogen peroxide treatment of woven cotton structures

All the fabrics underwent alkali-peroxide treatment under laboratory conditions. The alkali pretreatment, using a 6% concentration of sodium hydroxide (NaOH) was performed at 75°C for 45 minutes according to Sukmawan et al. (2022) on the fabric immersed in NaOH solution with weight ratio of 20:1, and then alkali pretreated fabrics were removed after pretreatment, then followed by hydrogen peroxide (H_2O_2) treatment, at a concentration of 5% for 60 minutes at 80°C. The H_2O_2 solution-to-cotton weight ratio was 40:1 under constant agitation till the completion of the peroxide treatment process. Then the samples were rinsed in cold water and dried.

Characterization of woven cotton structures

Tensile strength tests were performed on both untreated and alkali-peroxide treated samples, along the warp and weft directions, using an Instron tensile machine (model 1026). This machine was equipped with a 300 kg capacity load cell and operated at a speed of 250 mm/min. Tests were conducted under standard atmospheric conditions of 27 ± 2°C and 60 ± 2% RH, adhering to the ASTM-D5035 standard test method. The mean breaking load and elongation at break were measured with sample dimensions of 140 mm x 50 mm.

Composites fabrication

The epoxy-cotton woven composite structures were fabricated utilizing a vacuum bagging technique following an initial hand lay-up. Woven cotton fabrics with dimensions of 300 mm x 300 mm x 3 mm, featuring various weaves including plain, matt, twill, herringbone, and satin, served as reinforcement, with epoxy matrix within the composite system. The matrix was formulated from EpoxAmite 100 resin (Part A) and EpoxAmite 102 medium curative hardener (Part B) in a mass ratio of 100:28.4. Initially, the components were manually mixed in a glass beaker and subsequently stirred mechanically for about 10 minutes. After drying in an oven at 80°C for 3 hours to remove moisture and prevent void formation, the fabrics were manually saturated (hand lay-up) by applying epoxy mixtures to both surfaces. Subsequently, they were positioned in a vacuum bag mold under atmospheric pressure. This process removed excess air and resin residues via the vacuum outlet valve with the use of a vacuum pump, and also pulls the epoxy resin through the reinforced cotton substrates. This process produced a high-quality composite with insignificant defects. The epoxy-cotton composite laminates, incorporating both untreated and treated fabrics, were initially cured at ambient temperature (27℃) for 48 hours and subsequently post-cured at 100°C for 5 hours. After curing, the composite structures were precisely cut into specimens measuring 200 mm in length, 25 mm in width, and 3.0 mm in thickness with a laser precision cutting machine. These specimens were prepared in accordance with the ASTM D3039 (2008) standard for mechanical characterization.

Characterization of composites

Impact, tensile, and three-point bending tests

The impact resistance of the composites was evaluated using an Izod impact testing device (model: XC-50 Pantec, with a 22 J hammer pendulum), adhering to the ASTM D256 (1900) standard test method. Each specimen was notched with a 45°C V-notch, 2.54 mm deep, using a Pantec Iz/Ch-50 single-tooth carver. Five specimens, each measuring 60.25 mm in length, 12.7 mm in width, and 10 mm in thickness, were vertically positioned with the notch facing the pendulum on a sample fixture to measure average energy absorption.

Tensile properties of both untreated and alkali-peroxide treated epoxy-cotton composite structures were assessed using a SHIMADZU Autograph Precision Universal Tester (model AG-X Series, Japan). Testing was conducted at 23 ± 2°C and 65 ± 2% RH, following the ASTM D3039–76 standard. Five specimens, each with dimensions of 200 mm x 25 mm x 3 mm, were tested at a crosshead speed of 5 mm/min.

Flexural properties were determined through a three-point bending test using the same SHIMADZU Autograph Precision Universal Tester under normal laboratory conditions (50% RH and 23°C) as per ASTM D790–07 (2007). The test involved five specimens, each with a gauge length of 200 mm, a width of 25 mm, and a thickness of 3 mm, tested at a crosshead speed of 2 mm/min.

Microstructural analysis

The microstructural analysis of all epoxy-cotton composite samples, both untreated and alkali-peroxide treated, was performed using a Hitachi 3400 SEM (Chiyoda, Tokyo, Japan). This analysis focused on examining the mechanisms of tensile fracture surfaces and the interface adhesion within the epoxy-cotton laminated composite structures. To prevent charging during analysis, the specimens were sputter-coated with gold using an accelerated voltage of 1 kV.

Thermogravimetric analysis (TGA)

The thermal properties of neat epoxy, untreated, and alkali-peroxide treated epoxy-cotton composite structures were analyzed to evaluate the impact of alkali-peroxide treatment on the composites' thermal behavior. Thermogravimetric analysis (TGA) was performed using a NETZSCH TG 209 F3 Tarsus model, in accordance with ASTM D3850 standard procedures. This thermo-analytical technique was utilized to determine the onset of degradation and decomposition temperatures of the composite specimens. The TGA was performed over a temperature range of 30–600°C at a heating rate of 10°C/min, in a nitrogen gas environment, with each sample weighing 5 mg. All data analysis was conducted using the integrated Proteus software.

Finite element analysis via ANSYS R23.2 workbench

ANSYS R23.2 was utilized to estimate the tensile stress developed in each woven composite structure by applying the average maximum load determined from the tensile tests of the materials. Material properties such as Poisson's ratio and Young's modulus, derived from these tensile tests, were inputted into the model. The same average maximum loads were then used in the modeling and simulation processes to accurately replicate the stress conditions encountered during testing. The equivalent stress results, derived from ANSYS R23.2 simulations, were subsequently displayed to provide a detailed analysis of the stress distribution within the woven composite structures while the comparison of ultimate tensile stress of woven cotton-epoxy composites structures from ANSYS R23.2. vs tensile stress obtained from tensile tests of composite specimens was made.

Finite element analysis (FEA) model parameters

The Finite Element Analysis (FEA) conducted by means of ANSYS software was to simulate the mechanical behavior of alkali-peroxide treated cotton-epoxy woven composites focused on critical model parameters such as mesh size, boundary conditions, and specific assumptions to ensure accurate and reliable simulation results.

A key aspect of the FEA model is the mesh size, which directly impacts the accuracy and computational efficiency of the simulation. A fine mesh, with tetrahedral elements averaging 0.5 mm in size, was utilized to capture the intricate details of the woven composite structure. This specific mesh size was determined through a mesh convergence study, which systematically refined the mesh until the resulting stress and deformation values stabilized within an acceptable tolerance range of 5%. This process ensured a balance between computational cost and the precision of the simulation results.

Accurate simulation of the real-world behavior of the composite materials necessitated the application of appropriate boundary conditions. A fixed support was applied to one end of the composite specimen to simulate clamping, restricting all translational and rotational degrees of freedom. At the opposite end, a uniform tensile load was applied, evenly distributed across the surface, to mimic the conditions of tensile testing. To further optimize computational efficiency, symmetry boundary conditions were employed along the plane of symmetry of the woven structure, assuming the composite material behaves symmetrically about this plane.

Several assumptions were incorporated into the FEA model to simplify the analysis without compromising accuracy. The material properties of the cotton fibers and epoxy matrix were considered isotropic and homogeneous, with values for Young's modulus, Poisson's ratio, and tensile strength derived from experimental data and literature. The model assumed perfect bonding interface between the cotton fibers and the epoxy matrix, indicating no interfacial slip or debonding during loading. The analysis also assumed linear elastic behavior for both the fibers and matrix material within the applied load range, providing insights into the initial mechanical response of the composite. Additionally, geometric nonlinearity was accounted for to consider large deformations and rotations, ensuring accurate stress and strain distributions under tensile loading.

The combination of these parameters and assumptions enabled the ANSYS FEA model to accurately simulate the mechanical behavior of alkali-peroxide treated cotton-epoxy woven composites. The model's results were validated against experimental data, demonstrating good agreement and confirming the model's predictive capability.

Results and discussion

Characterization of woven cotton structures

Impact of alkali-peroxide treatment

The tensile strength and extension-at-break results for alkali-peroxide treated woven cotton structures in plain, matt, twill, herringbone, and satin weaves are presented in Table 2. The fabrics treated with the combined alkali-peroxide method demonstrated a 5.7% increase in tensile strength and a 20% improvement in extension-at-break compared to the untreated cotton fabric. These enhancements are attributed to the effectiveness of the alkali-peroxide treatment in modifying the properties of the raw cotton fabrics. The alkali-peroxide treated fabrics with plain and matt weave structures showed maximum tensile strength of 22.8 MPa and 23.9 MPa, and maximum extension-at-break of 9.8% and 9.7% respectively. The observed improvement in the alkali-peroxide treated cotton fabrics can be attributed to the denser packing and increased presence of cellulose crystals, along with a higher overall cellulose content. This enhancement results from the effective removal of lignin and other non-cellulosic components during treatment, which increases the cellulose ratio per unit mass of the fiber. Additionally, the elimination of hemicellulose and lignin frees up cellulose chains, facilitating the formation of hydrogen bonds. This leads to a rearrangement and increased crystallinity of the fibers,

Table 2. Tensile properties of untreated and alkali-peroxide treated cotton fabric structures.

Fabric structures	Untreated						Alkali-peroxide treatment (5% Conc.)					
	Tensile strength (MPa)		Extension at break (%)		Crimp (%)		Tensile strength (MPa)		Extension at break (%)		Crimp (%)	
	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft
Plain	21.5 ± 0.5	17.8 ± 0.4	7.9 ± 0.2	6.5 ± 0.3	0.4	0.6	22.8 ± 0.3	18.7 ± 0.1	9.7 ± 0.1	8.4 ± 0.1	0.2	0.2
Matt	22.7 ± 0.6	19.8 ± 0.8	7.8 ± 0.3	6.4 ± 0.2	0.6	0.4	23.9 ± 0.2	21.8 ± 0.2	9.8 ± 0.2	8.6 ± 0.2	0.4	0.4
Twill	17.4 ± 0.9	14.9 ± 0.4	5.8 ± 0.6	5.3 ± 0.3	1.2	0.6	18.5 ± 0.4	15.7 ± 0.1	6.9 ± 0.3	6.7 ± 0.4	0.6	0.8
Herringbone	19.8 ± 0.7	14.8 ± 0.5	6.3 ± 0.9	5.4 ± 0.1	1.8	0.2	21.3 ± 0.5	15.3 ± 0.1	9.4 ± 0.2	5.4 ± 0.3	0.4	0.3
Satin	16.8 ± 1.3	15.4 ± 0.4	7.8 ± 0.4	4.9 ± 0.3	0.8	0.6	17.3 ± 0.2	15.9 ± 0.3	9.3 ± 0.1	6.3 ± 0.2	0.2	0.4

consequently enhancing their overall strength (Akindoyo et al. 2023). The tensile strength and breaking extension of all woven cotton structures displayed higher values in the warp direction compared to the weft direction for both untreated and alkali-peroxide treated fabrics. This suggests that the alkali-peroxide treatment significantly influences the strength behavior of cotton fabrics across various architectures. An optimal 5% concentration of alkali-peroxide treatment was found to effectively enhance fabric properties. This improvement occurs through the removal of non-cellulosic components and other impurities such as dirt, natural oils, and waxy substances from cotton fiber. These impurities can hinder the adhesion between fiber and matrix by impairing the exposure of hydroxyl groups to the resin, crucial for effective bonding in composite materials (Owen 2014). Ding et al. (2024) observed a relatively smooth surface with untreated fabric with less undulating after a combined treatment with two oxidation systems, in which the oxidation also led to a change in the crystallinity and surface morphology of the fiber during the oxidation process. However, the strength of treated fabric was 176.8% higher than that of untreated.

Table 2 also shows the results of alkali-peroxide treatment impact on the extension-at-break of various woven cotton structures for all the fabrics. The alkali-peroxide treatment also enhanced the extension-at-break of the different weave structures. What appeared to have a dominant effect is the architecture of the weave structure over the treatment. The maximum extension was 7.9% found with plain woven fabric, followed by matt and satin weave structures both having same extension of 7.8% respectively. The extension-at-break values for all alkali-peroxide treated fabrics were higher in the warp (longitudinal) direction compared to the weft (transverse) direction, surpassing those of the untreated fabrics. This increase in extension along the warp direction can be attributed to the presence of sizing agents, such as starch, applied to the warp yarns during preparatory weaving processes. The alkali-peroxide treatment likely enhanced these effects by removing existing impurities, thereby improving the fabric's elongation properties. Conversely, the lower extension values observed in the weft direction may be due to the higher crimp percentages in the weft yarns, which inherently limit their elongational capacity (Owen and Achukwu 2016).

Furthermore, the mechanical performance of cotton fabric composites is significantly influenced by the yarn crimp percentage within the woven fabric structures. Yarn crimp refers to the waviness of the yarns resulting from the interlacing of weft and warp yarns during the weaving process. High crimp levels can lead to increased fiber undulation, which reduces the load-bearing capacity and mechanical properties of the reinforced composites. The obtained results, as shown in Table 2, indicate that the tensile properties of untreated and alkali-peroxide treated cotton fabrics are affected by the yarn crimp characteristics. The untreated cotton fabric exhibited higher yarn crimp values, leading to a more pronounced undulation of the fibers. This increased crimp negatively impacted the tensile strength and modulus of the composites. In contrast, the treated cotton fabrics showed a reduction in yarn crimp due to the removal of non-cellulosic components such as pectin, lignin, wax, and other impurities. This treatment improved fiber alignment and reduced crimp, thereby enhancing the tensile properties of the cotton-epoxy composites (Figures 2 and 3).

Karahan and Karahan (2013) reported that the mechanical properties of woven composites are closely related to yarn crimp. Their study demonstrated that higher yarn crimp values result in lower tensile strength and modulus due to increased fiber undulation and reduced load-bearing capacity. Conversely, reducing yarn crimps through optimized weaving techniques or treatments can enhance the mechanical performance of the composites. Hence, the tensile test results obtained in the current study indicate that the alkali-peroxide treatment of cotton fabrics effectively reduces yarn crimp, thereby improving the tensile properties of the composites. This finding aligns with the observations made by Karahan and Karahan (2013), emphasizing the vital influence of yarn crimp on the mechanical performance of woven fabric composites.

Impact of weave structures

The impact of weave structure on the tensile properties of untreated woven fabrics for plain, matt, twill, herringbone, and satin weaves are shown in Table 2. The tensile strength across all weave structures was consistently higher in the warp direction compared to the weft direction. The matt (basket) weave showed a maximum tensile strength of 22.7 MPa, followed by plain with a strength of 21.5 MPa, while herringbone, twill, and satin weaves showed a tensile strength of 19.8 MPa, 17.4 MPa, and 16.8 MPa respectively. The behavior of the matt weave is as expected because it has a more balanced weave structure (a derivative of plain weave) obtained by grouping warps and/or ends in the cloth at intervals, in this case, the two or more warp and/or wefts operate as one. The pre-weaving yarn sizing and the orientation of testing along the machine (warp) direction significantly contributed to the enhanced tensile strength observed in the samples. Although, the tensile properties (strength & extension-at-break) of combined alkali-peroxide treated fabrics are generally higher as compared to untreated cotton fabrics. Observation at the weave structural point of view show that the matt and plain cotton weaves structures gave the maximum tensile strengths of 22.7 MPa and 21.5 MPa, and maximum extension-at-break of 6.4% and 6.5% respectively which might be due to its balanced thread interlacement structures and fiber orientations (Owen et al., 2023a). This was closely followed by herringbone and twill woven fabrics, which exhibited strength values of 19.8 MPa and 17.4 MPa, respectively. This performance is attributed to their structural characteristics, specifically the more pronounced warp ends along the diagonal axes of the fabrics. The satin weave cotton fabric showed the least tensile strength of 16.8 MPa which might be attributed to its loose structural characteristics due to less interlacing points and drapability, hence, is less durable when compared to plain and twill weaves.

Composite characterizations

Impact properties

Figure 1 presents the synergistic impact of combined alkali-hydrogen peroxide treatments in enhancing the impact strength of cotton-epoxy woven composite structures as well as the effects of weave structures for the epoxy composites reinforced with woven cotton fabrics. The impact properties of untreated woven cotton composite structures were assessed to understand the influence of various weave structures. The combined alkali-peroxide treatment, along with the specific weave patterns of the cotton structures, was instrumental in determining the impact strength of the composites. Notably, all alkali-peroxide treated woven composite structures exhibited higher impact strength compared to the untreated composites, with variations in strength across different weave patterns due to the effects of the alkali-peroxide treatment on the reinforcing fabrics. The maximum impact strength value of all composites with treated fabric is 27.4 and 27.0 KJ/mm^2 with over 8% improvement, hence, suggesting that the combined alkali-peroxide treatment has displayed the capabilities and effectiveness to improve the interfacial bonding between the epoxy matrix and the reinforcing cotton substrates.

Regarding the impact of different cotton weave structures on reinforced epoxy composites, the findings indicate that composites with plain and matt weave cotton structures demonstrated the highest impact strength, recording 27.4 KJ/mm^2 and 27.0 KJ/mm^2, respectively. These were followed by twill and herringbone weaves, which showed values of 26.24 KJ/mm^2 and 26.2 KJ/mm^2, respectively, and satin weaves, which exhibited an impact strength of 24.2 KJ/mm^2. The results suggest that the higher impact strength observed

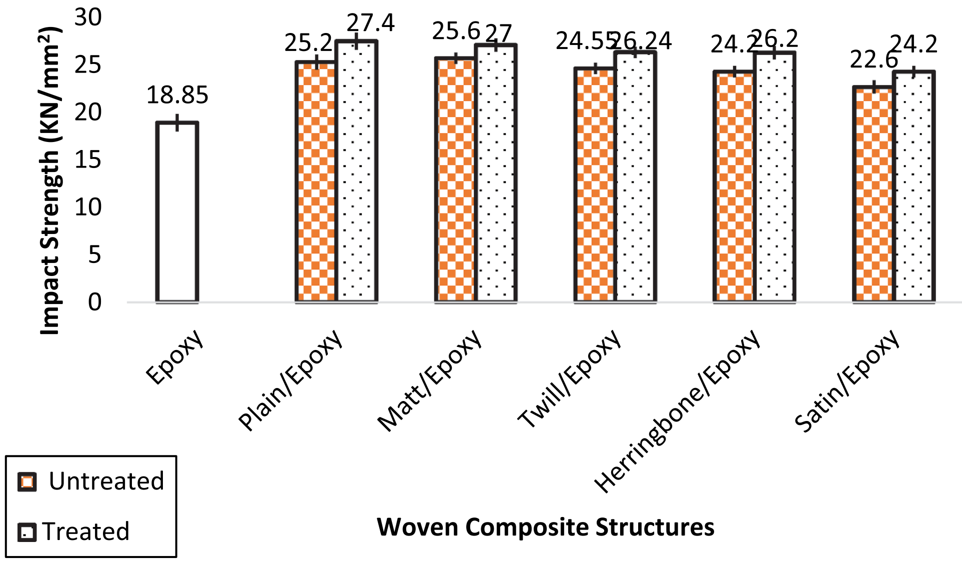

Figure 1. Impact strength of alkali-peroxide treated cotton-epoxy composites with different weave structures.

in all alkali-peroxide treated woven composites indicates effective stress transfer from the matrix to the reinforcing treated fiber and improved interfacial adhesion, which together contribute to enhanced impact strength of the composites. Plain woven structures are reported to exhibit superior impact performance due to the orderly interlacement of warp and weft yarns, which enhances the transverse strength of the composites. Additionally, the plain weave structure features a higher number of binding points and a greater cover factor, contributing to its enhanced mechanical properties (Achukwu et al., 2015b; Aisyah et al. 2021; Owen et al., 2023a). The results also indicated that the unreinforced neat epoxy matrix exhibited brittle behavior, leading to a diminished capacity to withstand higher impact loads as a standalone composite. This suggests that the weave design and the properties of the resin significantly influence the impact toughness of the composites. Each weave structure, whether plain, twill, satin, or other configurations, is systematically examined to reveal the nuanced effects of alkali-peroxide treatment on the material's capacity to absorb and dissipate impact energy. The obtained impact results have demonstrated enhanced impact resistance of composite materials for industrial applications, including transportation, sports equipment, and structural components. The findings, as illustrated in Figure 3, show that the combined alkali-peroxide treatments, when optimized with specific weave structures, can significantly improve the impact performance of composite materials. Although the impact properties of the developed cotton-epoxy composites are not as high as those of other natural fiber composites, they still provide adequate reinforcement. For instance, jute-epoxy composites exhibited impact strengths of up to 20 kJ/m^2, whereas the cotton-epoxy composites demonstrated impact strengths of around 10 kJ/m^2. The lower impact resistance of cotton-epoxy composites can be attributed to the inherent moderate strength and lower toughness of cotton fibers. Despite this, cotton fabrics offer sufficient reinforcement for epoxy composites and present advantages in terms of availability, cost, and environmental impact. Therefore, cotton-epoxy composites remain suitable for applications where moderate mechanical performance is acceptable.

Tensile properties

Figures 2 and 3 illustrate the synergistic effects of combined alkali-hydrogen peroxide treatments and cotton weave structure on enhancing the tensile strength and modulus of cotton-epoxy woven composite structures, respectively. The tensile modulus and tensile strength of all alkali-peroxide treated composite samples are superior compared to their untreated counterparts. This improvement

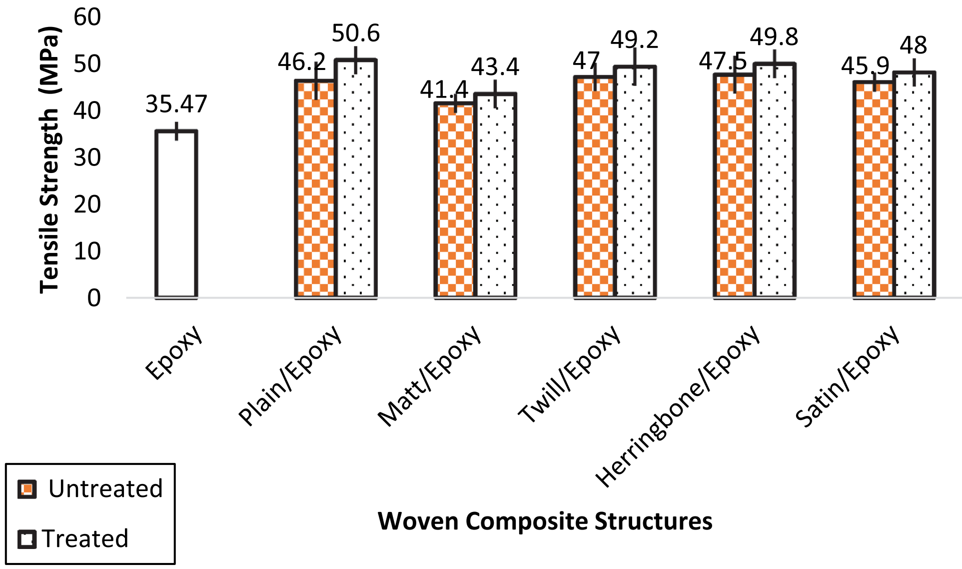

Figure 2. Tensile strength of alkali-peroxide treated cotton-epoxy woven composites with different weave structures.

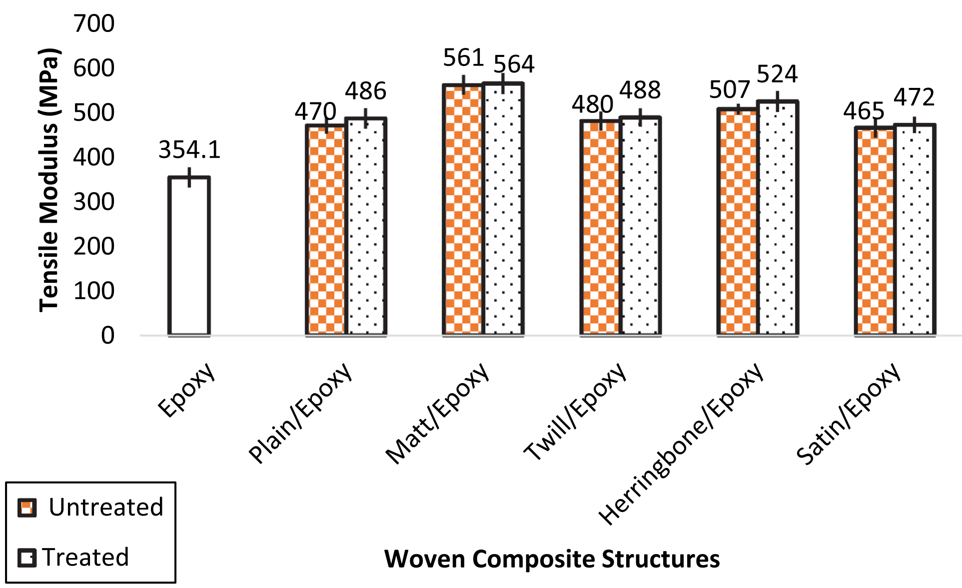

Figure 3. Tensile modulus of alkali-peroxide treated cotton-epoxy woven composites with different weave structures.

is attributed to the alkali-hydrogen peroxide treatment's effectiveness in improving the bond between the woven cotton fabrics and the epoxy matrix, as well as enhancing the overall tensile properties of the composites.

The maximum tensile strength value is 40.6 MPa with a 12.2% improvement compared to the composites without treatment. Additionally, both treated and untreated composites showed significant improvements in tensile strength and modulus relative to pure epoxy. Regarding weave effects, herringbone and twill-woven composite structures displayed slightly higher strength, with values of 37.5 MPa and 37.0 MPa, respectively, compared to plain and satin woven composite structures, which had tensile strength values of 36.2 MPa and 35.9 MPa, respectively. This signifies that the properties of the fabrics were not fully reproduced in the composite probably because of the matrix-fabric interactions and alignment. A similar observation was reported by (Ismail et al. 2018), who noted maximum strength in twill woven kenaf composite structures, attributing this to the fabric structural characteristics, such as higher binding points and a greater cover factor in plain weaves. The enhanced strength in twill, herringbone, and plain composite structures may also stem from the large contact surface area between the reinforced fabrics and the epoxy matrix within the composite system, facilitating effective surface interactions. Furthermore, the presence of more pronounced or elongated floating warp ends along the diagonal lines of the fabric surfaces in these woven composite structures likely contributes to this phenomenon. Additional contributing factors include improved fabric coverage, increased fabric density (thickness), and greater mass per unit area, all of which are characteristic features of plain, twill, and herringbone weaves (Owen et al., 2023a). The strength values observed for twill and herringbone composites (37.0 MPa and 37.5 MPa, respectively) showed a slight variance, likely due to the balanced twills in both weaves, featuring equal warp and weft floats. These results are consistent with the fact that all fabric structures were woven under uniform weaving conditions. This resulted in comparably limited contact surface areas between the fibers and the matrix, as seen in plain, twill, and herringbone composite structures. Such configurations are characterized by a high number of binding points (thread interlacements) that contribute to increased composite strength.

A similar trend is observed in the tensile modulus (Figure 3). However, the treated matt and herringbone weave composite structures demonstrated superior tensile moduli, with values of 564 MPa and 524 MPa, respectively, this suggests that the alkali-peroxide treatment has effectually improved the surface area, chemical bonding, and interface adhesion between the matrix and the natural fibers, leading to enhanced tensile properties of the composites. Wang et al. (2019) also observed maximum tensile modulus in alkali-treated jute fabric-reinforced epoxy composites, attributed to the effects of alkali treatment. In Figure 3, when considering untreated cotton composites with respect to weave structures, the matt and herringbone woven composites exhibited the highest modulus values of 561 MPa and 507 MPa, respectively. These were followed by twill and plain-woven composites, with modulus values of 480 MPa and 470 MPa, respectively. Notably, these values improved when the composites were reinforced with treated woven fabrics. Achukwu et al. (2015a) also reported improvements in elongation at break and tensile strength of cotton fabrics, as well as in the overall properties of cotton fabric/polyester composites featuring various fabric architectures constructed with 4-plied yarns. The various weave structures of plain, matt, twill weave, herringbone, and satin weave configurations, have demonstrated that the interplay between the combined alkali-peroxide treatment and weave structural patterns can be optimized for specific industrial applications. The obtained tensile results (Figures 2 and 3) have further provided insights for material design considerations and thereby contributing to the broader narrative of tailoring composite materials for superior tensile properties.

In comparison with other natural fiber reinforced composites, the tensile strength and modulus of the cotton-epoxy composites were found to be lower than those of jute-epoxy and hemp-epoxy composites but comparable to flax-epoxy composites. Specifically, the tensile strength of the cotton-epoxy composite was observed to be approximately 15.5 MPa, while jute-epoxy composites reported tensile strengths exceeding 50 MPa (Ali et al. 2018). Similarly, hemp-epoxy composites exhibited tensile strengths of around 40 MPa, significantly higher than cotton-epoxy composites. The lower tensile properties of cotton can be attributed to its moderate inherent fiber strength compared to the higher strength of bast fibers such as jute and hemp.

While cotton fabrics provide adequate reinforcement for epoxy composites, their tensile properties are not as high as those of composites reinforced with stronger natural fibers such as jute and hemp. However, the performance of cotton-epoxy composites, which are considered moderate, can be attributed to the specific moderate strength of cotton fibers. Despite this, cotton-epoxy composites offer advantages in terms of availability, cost, and environmental impact, making them suitable for applications where moderate mechanical performance is essential. Hence, the tensile results obtained (Figures 2 and 3) provide an approach for design, and manufacturing of composite materials with improved tensile properties.

Flexural properties

The effects of combined alkali-peroxide treatment technique and woven structure on the flexural strength and modulus of cotton-epoxy woven composites are illustrated in Figures 4 and 5 respectively. The untreated woven cotton composite structures were used to evaluate the influence of different weave structures on the bending properties of the resulting composites.

Figure 4 illustrates the flexural strength characteristics of alkali-peroxide cotton-epoxy woven composites, highlighting the influence of various cotton woven structures on this critical mechanical property. Flexural strength, a measure of a material's resistance to deformation under bending, is a key parameter in determining the composite's structural performance and its suitability for applications where bending forces are prevalent. The results serve as a significant reference for understanding the synergistic effects of alkali-peroxide and woven structures on flexural strength, guiding the optimization of composite materials for specific industrial applications that demand superior bending resistance. There was improvement in strength for all alkali-peroxide treated composites compared to the untreated samples. Maximum flexural strength after alkali-peroxide treatment was obtained by the herringbone woven cotton-epoxy composites with a value of 38.6 MPa which was a 5.7% improvement from 36.4 MPa for the untreated fabrics. Typically, the treatments display improved composite's properties when compared to their untreated counterparts. In respect to the synergistic effects of the different woven structures on composite's flexural strength, Herringbone, twill and matt cotton woven composite structures showed flexural strength values of 36.4 MPa, 33 MPa and 28 MPa respectively with herringbone exhibited maximum bending strength (36.4 MPa) as compared to the unreinforced epoxy. Achukwu et al. (2015c) recorded an increase of 20–47% in the flexural strength of polyester composites reinforced with NaOH-treated plain woven cotton fabrics. Enwerem et al. (2022) also reported improvements of

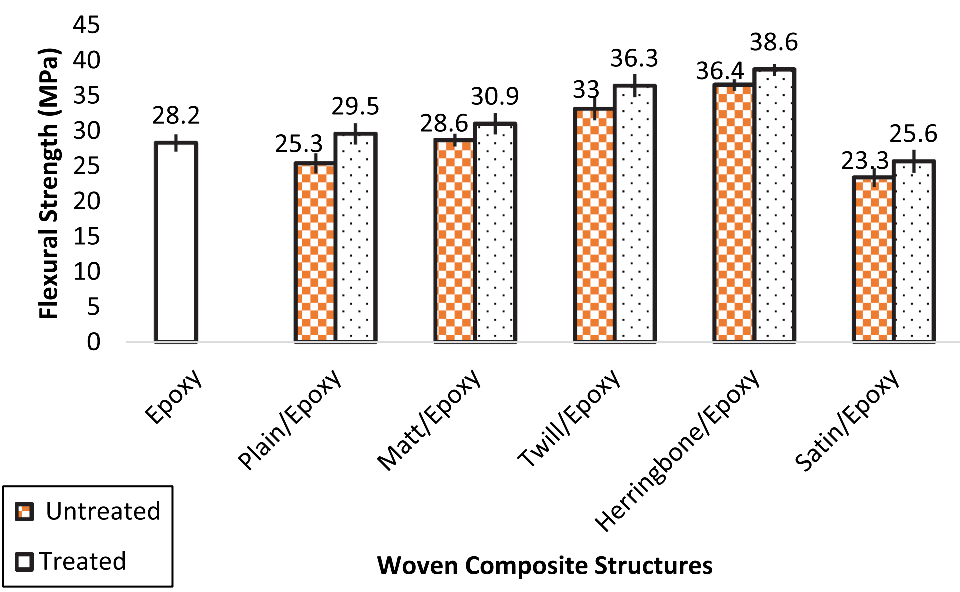

Figure 4. Flexural strength of alkali-peroxide treated cotton-epoxy woven composites with different weave structures.

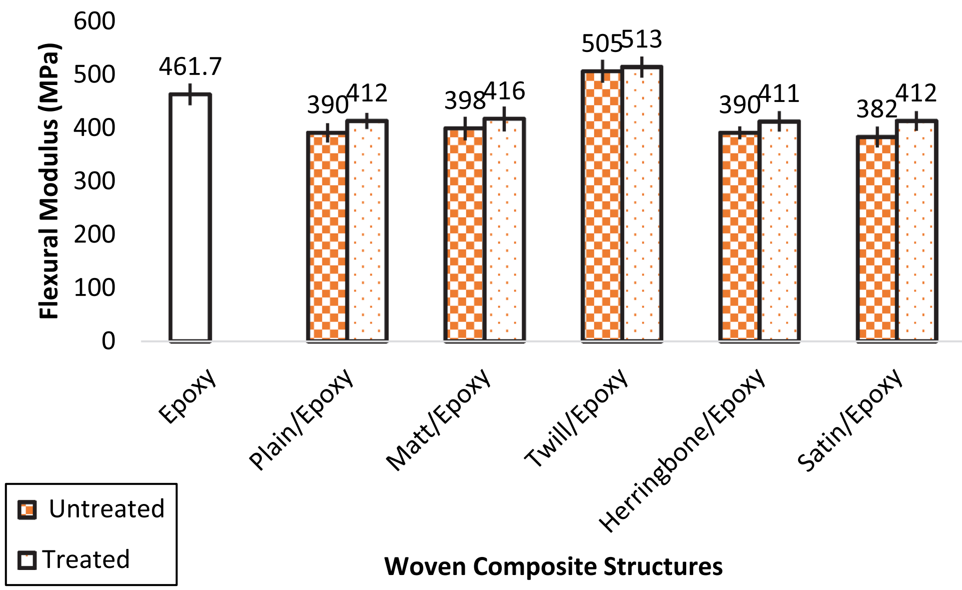

Figure 5. Flexural modulus of alkali-peroxide treated cotton-epoxy woven composites with different weave structures.

44.4–49% for acetic anhydride and 17–39.7% for sodium hydroxide-treated woven cotton structures in their polyester composites.

In Figure 5, which presents the flexural modulus, it was noted that all alkali-peroxide treated composites exhibited higher flexural modulus values compared to their untreated counterparts. The highest value recorded was 513 MPa for the alkali-peroxide treated twill cotton-epoxy composite. Eliminating surface impurities from natural fibers likely improves adhesion between the matrix and the fiber, resulting in stronger adhesion and mechanical interlocking as more hydroxyl groups are exposed to the resin. Consequently, the strength and modulus of the resulting composites are influenced by factors such as filler content, filler distribution, fiber wetting by the matrix, and fiber-matrix interfacial adhesion. Similarly, Owen (2014) reported that alkali-treated woven jute fabrics in epoxy composites exhibited higher flexural strength and modulus values compared to untreated fabrics and pure epoxy. This enhancement is attributed to the woven jute-reinforced epoxy composites being stronger and stiffer than the unreinforced neat epoxy. Morris et al. (2020) also noted that cotton-reinforced epoxy composites achieved the highest flexural modulus in their comparative analysis of woven silk, cotton, lyocell, and bamboo epoxy-based composites. Furthermore, it was observed that the twill weave composite structure exhibited the highest modulus at 505 MPa, followed by the matt weave at 398 MPa, while the plain and herringbone weave composite structures both showed a modulus of 390 MPa. The results consistently demonstrated that alkali-hydrogen treatment enhanced the flexural modulus and strength relative to both untreated samples and pure epoxy. The combined alkali-hydrogen peroxide treatment imparts ester functionality to the surface of natural fibers, which enhances the mechanical properties of the composites. This improvement is due to stronger interfacial adhesion and mechanical bonding between the epoxy and the alkali-bleached fabrics.

In comparison with other natural fiber reinforced composites, the cotton-epoxy composites demonstrated moderate performance in terms of flexural strength. The flexural strength of the cotton-epoxy composites was found to be around 40 MPa, which is lower than the flexural strength of jute-epoxy composites (approximately 80 MPa) and hemp-epoxy composites (around 70 MPa) as reported in previous studies. The flexural modulus of the cotton-epoxy composites was also lower compared to jute and hemp composites, indicating that while cotton fabrics provide some reinforcement, they do not match the stiffness and strength provided by other natural fibers.

The comparative analysis indicates that while cotton fabrics provide adequate reinforcement for epoxy composites, their flexural properties are not as high compared to those of composites reinforced with other natural fibers such as kenaf, sisal, jute, and hemp, due to the inherent moderate strength of cotton fibers. However, cotton-epoxy composites still offer advantages in terms of availability, cost, and environmental impact. These composites are suitable for applications where moderate mechanical performance is required.

Microstructural properties

To determine the microstructural properties of the composites, the tensile fractured composites with superior property (untreated, and alkali-peroxide treated fabrics) were considered. The SEM micrographs were captured at 50× and 100× magnifications (Figure 6), providing a detailed view of the composites structural changes induced by surface treatments in comparison with the untreated counterparts. The SEM images of untreated woven cotton-epoxy composites (Figure 6a,b) showed visible woven cotton pull-out (protruding yarn strands) and significant interfacial debonding. This is attributed to compatibility issues between the hydrophilic woven cotton structure and the hydrophobic epoxy matrix within the composite system, which likely contributed to the reduced impact, tensile, and flexural properties observed in Figures 1–5. Akindoyo et al. (2023) observed an increased number of pull-out holes on the fractured surfaces of composites, attributing this to inadequate wetting of the fiber by the matrix and diminished fiber-matrix interaction in PLA and harakeke composites with 30 wt% fiber content. This poor interfacing was identified as the cause of the observed decline in the mechanical strength of the composite. The SEM fracture images of the raw cotton weave

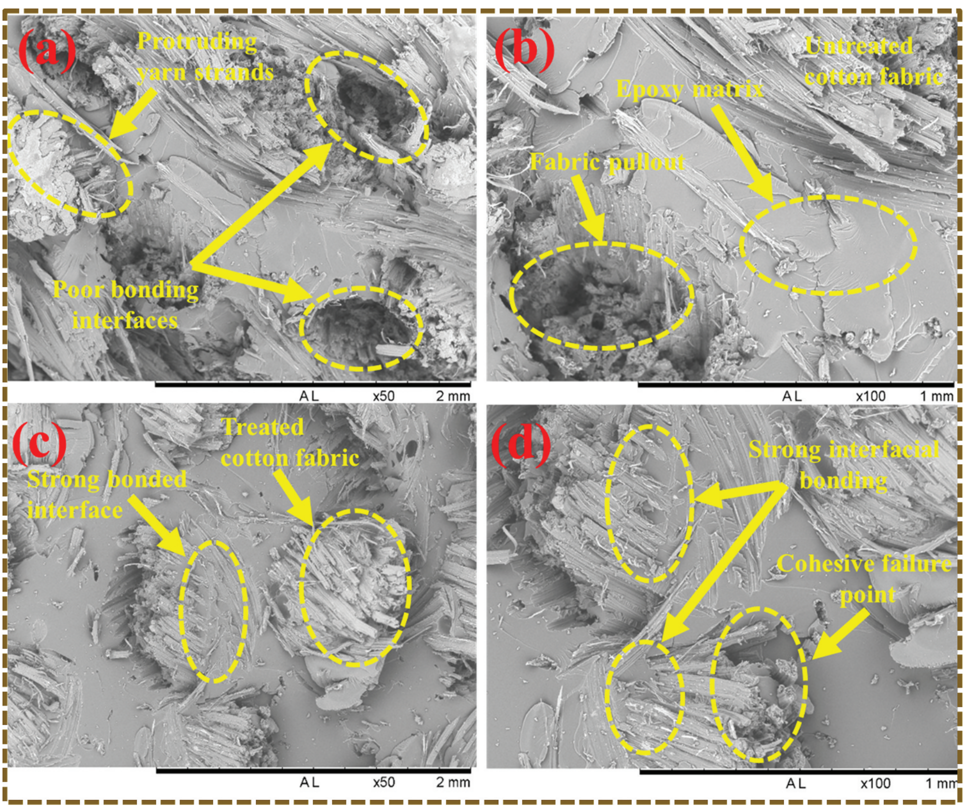

Figure 6. SEM micrographs of (a and b) untreated woven cotton-epoxy composite fractured surfaces, and (c and d) alkali-peroxide treated cotton-epoxy woven composite fractured surfaces viewed at 50x and 100x magnifications.

fabric composites further revealed smooth-like surfaces due to the presence of cementing substances which tend to shield the fiber pores. These cementing substances are impurities such as pectin, waxes, dirt particles, and other soluble substances.

In contrast, Figure 6(c,d) present the SEM micrographs of combined alkali-peroxide treated cotton-epoxy woven composites at the same magnifications respectively, revealing the microstructural alterations induced by alkali-peroxide treatments on the composite surface. The intention is to highlight any improvement in fiber-matrix adhesion, dispersion, or other structural modifications that contributed to the enhanced mechanical.

Figure 6(c,d) demonstrate that the alkali-peroxide treated woven cotton-epoxy composite structures exhibited better interaction than the untreated epoxy composites. The micrograph displayed evidence of cohesive failure points, which indicates effective fiber/matrix compatibility and a strong interfacial bond between the alkali-peroxide treated cotton woven structures and the epoxy matrix within the composite system. This robust interaction contributed to the enhanced impact, tensile, and flexural strength of the alkali-peroxide treated composites, as shown in Figures 1, 2 and 4, respectively. This emphasizes the critical importance of a strong fiber-matrix interface for the performance properties of composites, as noted by (Owen, Dauda, and Semo Ishiaku 2015).

The SEM images of treated composites showed smooth troughs near the fractured surface of the cotton-epoxy woven composite, indicating good wetting and a lack of voids. Significant portions of the reinforced alkali-peroxide treated fabrics remained adhered to the epoxy matrix, highlighting the effectiveness of the alkali-peroxide bleaching treatment. This treatment appears to facilitate the removal of cementing and binding structures from the fabric, thereby enhancing hydrogen bonding between the cellulose structures. As the cellulose structures rearrange and pack more densely, the fiber undergoes shrinkage, leading to a reduced diameter due to increased fibrillation. This process facilitates the opening of pores on the fabric surface, enhancing its reinforcing capability and improving fiber-matrix adhesion, which in turn contributes to greater composite strength (Jaiswal et al. 2022; Tiwari et al. 2021). In this study, the surface microstructural analysis revealed that failure predominantly occurred in the warp direction under longitudinal loading, suggesting uniform stress distribution along the warp axis. Figure 6c,d illustrate that the tensile fractured surface of alkali-peroxide treated composites exhibits uniform stress distribution between the fiber and matrix, which probably contributed to the superior mechanical properties observed in comparison to untreated composites. This improvement can be attributed to stronger cohesive forces between the woven cotton fabric structures and the epoxy matrix, coupled with minimal interlacing of fiber yarns in the warp and weft directions. Such configuration minimizes stress concentration between the yarns, allowing for uniform stress transfer across the specimen. Conversely, in untreated composites, non-uniform stress distribution along the warp and weft directions, influenced by the angle of twist, adversely affects the impact properties of the composites.

Thermogravimetric analysis (TGA)

Thermal studies were performed on selected samples, including neat epoxy, untreated cotton-epoxy, and alkali-peroxide treated cotton-epoxy woven composites, particularly those exhibiting superior properties. The results are summarized in Table 3. Figure 7a displays the TGA curve for neat epoxy, revealing an onset degradation temperature of 311.2°C and a maximum thermal decomposition temperature (DTG) of 343.8°C, with a residual mass of non-cellulosic components at 23.85%. Figure 7b compares the thermal behaviors of unreinforced epoxy and untreated cotton-epoxy composites, with the latter exhibiting higher onset degradation and maximum decomposition peak temperatures of 334.1°C and 362.1°C, respectively, compared to unreinforced epoxy.

In Figure 7c, the TGA curves of alkali-peroxide treated cotton-epoxy composites are compared with unreinforced neat epoxy. The treated composites exhibit a lower onset degradation temperature of 288.4°C, indicating faster degradation compared to the neat epoxy, which has a higher onset degradation temperature of 311.2°C. However, both the treated composite and neat epoxy

Table 3. TGA results for epoxy, untreated and alkali-peroxide treated cotton-epoxy composites.

Specimen	Onset Temp (°C)	Endset Temp (°C)	DTG Peak (°C)	Mass change (%)	Residual Mass (%)
Epoxy	311.2	371.4	343.8	68.70	23.85
Untreated cotton-epoxy	334.1	394.0	362.1	85.44	11.30
Treated cotton-epoxy	288.4	436.0	343.5	77.33	18.65

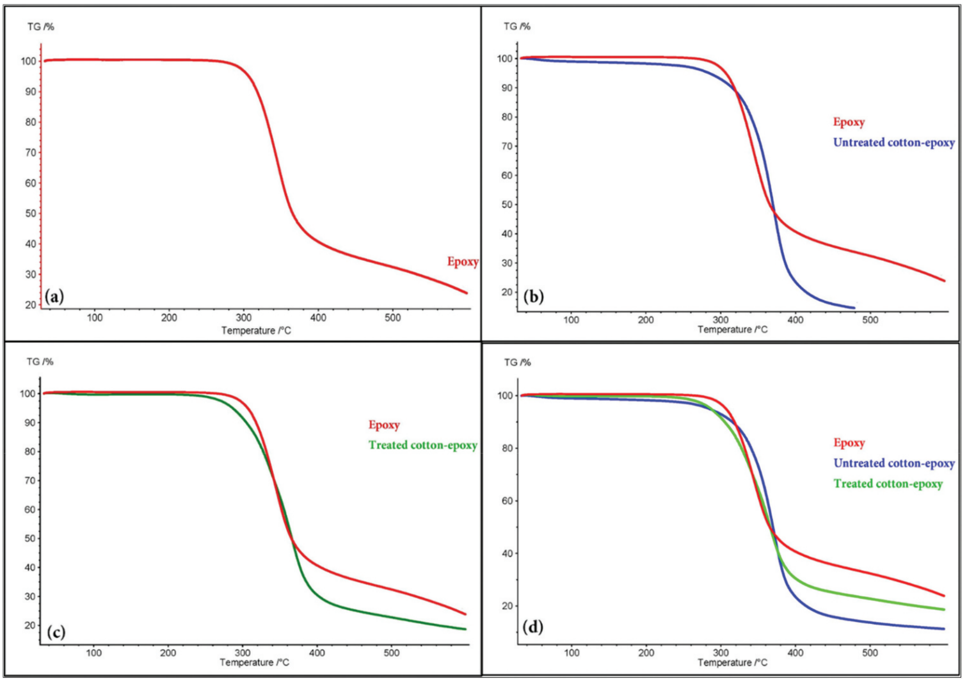

Figure 7. Combined TGA thermograms of (a) neat epoxy, (b) epoxy & untreated cotton-epoxy, epoxy & treated cotton-epoxy, (c) epoxy & untreated and (d) alkali-peroxide treated cotton-epoxy woven composites.

demonstrate thermal stability at 343.5°C and 343.8°C, respectively. The alkali-peroxide treated composites also showed a percentage mass residual of 18.65%, compared to the neat epoxy's mass residual of 23.85%.

Figure 7d presents the combined thermograms of the three considered composites. It is evident that all composite samples maintain thermal stability above 250°C. Among them, the untreated composite sample demonstrates the highest onset degradation temperature at 334.1°C, followed by neat epoxy at 311.2°C, with the alkali-peroxide treated sample exhibiting the lowest onset temperature at 288.4°C. This confirms that the combined alkali-hydrogen peroxide treatment effectively removes pectins and other cementitious materials from the woven fabrics, thereby making them more susceptible to heat and high temperatures.

Akindoyo et al. (2023) also observed a lower onset degradation temperature with digested alkali-peroxide treated harakeke fibers. The untreated cotton-epoxy woven composites exhibit the highest onset degradation and DTG decomposition temperatures at 334.1°C and 362.1°C, respectively, indicating that they degrade at higher temperatures. They also show the lowest percentage mass residual of 11.30%, compared to the treated cotton composites and neat epoxy. This could be attributed to the presence of complex lignin structures, which degrade at higher temperatures, as well as hemicellulose and other natural organic components in the reinforced woven cotton fabrics (Ameer et al. 2017).

In contrast, the treated cotton-epoxy woven composites exhibit an onset temperature of 288.4°C and a DTG degradation temperature of 343.5°C, indicating that these composites are thermally stable at lower temperatures compared to their untreated counterparts. This suggests that the alkali-peroxide treated cotton-epoxy composites decompose at lower energy levels due to the effectiveness of the alkali-peroxide treatment in significantly removing non-cellulosic components such as lignin, pectin, wax, oil, and other impurities from the cotton fibers (Ali et al. 2018).

This treatment enhances the bonding between the reinforced fibers and the epoxy matrix, thus requiring less energy to degrade. The treated composites exhibit an average thermal property and decompose faster than the untreated composites, which have higher decomposition temperatures. The treated composites also show a mass change value of 77.33%, compared to 85.44% for the untreated composites, and are higher than the neat epoxy with 68.7%. It is noteworthy that the alkali-peroxide treatment of cotton fabric in epoxy composite is a very effective method for surface modification of cellulose/hydrophilic natural fibers, facilitating good interfacial interaction with the hydrophobic polymer matrix (Zou et al. 2021).

The thermogravimetric analysis (TGA) results reveal that the alkali-peroxide treatment negatively affects the thermal stability of the composites, as indicated by the lower onset degradation temperature (288.4°C) compared to the untreated composites (334.1°C). This reduction in thermal stability can be attributed to the removal of non-cellulosic components, such as pectin, lignin, wax, and other impurities, during the alkali-peroxide treatment process. These components typically act as thermal insulators, and their removal increases the exposure of the cellulose fibers to thermal degradation (Ali et al. 2018). Despite the lower onset degradation temperature, the treated composites exhibit a comparable DTG peak temperature (343.5°C) to that of neat epoxy (343.8°C). Additionally, the higher residual mass of the treated composites (18.65%) compared to the untreated ones (11.30%) suggests an enhanced char formation ability, offering better protection during prolonged thermal exposure.

Furthermore, this treatment enhances fiber-matrix adhesion, resulting in improved mechanical properties, which are crucial for applications requiring both thermal and mechanical performance (Jabbar et al. 2015). The activation energies derived from the TGA data indicate favorable degradation kinetics for the alkali-peroxide treated composites, affirming their ability to maintain structural and mechanical integrity under operational conditions. In conclusion, while the alkali-peroxide treatment reduces the initial onset degradation temperature, the overall thermal stability, as evidenced by the DTG peak temperature and residual mass, remains robust. This treatment method effectively balances the trade-offs between mechanical enhancement and thermal performance, making the composites suitable for high-temperature applications (Safdar et al. 2024).

Recent advancements in the field of natural fiber composites have focused on the use of combined chemical treatments to enhance the properties of natural fibers and their composites. While the alkali-peroxide treatment has been shown to enhance the mechanical properties and thermal stability of cotton-epoxy composites, it is important to consider the environmental impact and sustainability of these chemical processes. For instance, (Jabbar et al. 2015 explored the mechanical performance of carbon fiber reinforced polymer composites subjected to various environmental conditions. They found that environmental factors such as humidity and temperature can significantly influence the tensile strength and modulus of the composites. This highlights the importance of considering environmental stability when developing natural fiber composites for practical applications.

The use of sodium hydroxide (NaOH) in alkali treatment can generate hazardous waste, posing risks to soil and water quality if not properly managed (Ali et al. 2018). Similarly, hydrogen peroxide (H_2O_2), although relatively environmentally friendly, can produce oxygenated byproducts that require careful handling and disposal to minimize environmental impact (Zou et al. 2021).

To address these concerns, sustainable practices such as recycling and reusing chemicals should be implemented. For instance, recovering NaOH from effluents can significantly reduce both the environmental footprint and associated costs. Exploring greener alternatives, such as enzymatic treatments, which use natural enzymes to modify fiber surfaces, offers a more sustainable approach. Enzymatic treatments are biodegradable, produce less hazardous waste, and operate under milder conditions.

Finite element analysis via ANSYS R23.2 workbench

Evaluation of tensile test results of cotton-epoxy woven composite structures in ANSYS R23.2

ANSYS R23.2 was used to estimate the tensile stress developed in each woven composite structure. The Young's modulus obtained from the tensile test, and Poisson's ratio obtained from the experiment were given as material properties in Table 4 while the equivalent stress obtained from ANSYS R23.2 is shown in Table 5. Figure 8 shows the comparison of ultimate tensile stress of woven cotton-epoxy composites structures from ANSYS R23.2. vs tensile stress obtained from tensile tests of composite specimens.

In Figure 8, it was observed that the maximum stress developed in the material slightly exceeds its ultimate strength, with only minimal variation noted. However, the experimental and ANSYS R23.2 values are in close variation. The finite element method, utilizing ANSYS R23.2, was successfully implemented to determine the equivalent stress developed in the cotton-epoxy composite structures. Similar observation of the changes in the tensile values of woven jute in the GFRP blade material obtained using ANSYS, was reported by other researchers (Chinta, Ravinder Reddy, and Prasad 2022).

Estimation of stresses developed for epoxy composites reinforced with different woven cotton structures in same boundary conditions

By applying average maximum load from the experimental values for all composite materials, the stresses developed in the material and deformation were observed with ANSYS R19.2 (Figure 9). The material properties used include the neat epoxy and woven cotton-epoxy composites of plain, matt, twill, herringbone, and satin weave structures. The stresses developed in the materials as listed in Table 5 and Figure 9 were found to slightly exceed their ultimate tensile strength but maintained similar trend as those from the experiment. So, based on the numerical approach and the tensile experimental test, it was recommended that the plain-woven cotton-epoxy composites have the best overall tensile performance among all woven cotton reinforced epoxy composites. Followed by herringbone and twill woven cotton-epoxy composites. This outcome from this numerical approach is in conformity with the tensile practical experimental result obtained in Figure 2, an indication that Finite element analysis (FEA) can effectively estimate the stress developed in the composite laminates.

Table 4. Tensile material properties for ANSYS R23.2 analysis.

Composite specimens	Young's modulus (MPa)	Poisson ratio (μ)
Neat epoxy	154.1	0.35
Plain woven cotton-epoxy	424	0.117
Matt woven cotton-epoxy	394	0.112
Twill woven cotton-epoxy	386	0.126
Herringbone woven cotton-epoxy	388	0.118
Satin woven cotton-epoxy	372	0.137

Table 5. Tensile stress obtained from tensile test vs ANSYS R23.2 results.

Composites specimen	Average Load (N)	Young's modulus (MPa)	Tensile strength (MPa) from tensile test	Tensile stress from ANSYS R23.2
Neat epoxy	2157.86	154.1	35.47	36.342
Plain woven Cotton-epoxy	3372.82	424	50.6	58.341
Matt woven Cotton-epoxy	3035.84	394	43.4	52.526
Twill woven Cotton-epoxy	3232.63	386	49.2	54.998
Herringbone woven Cotton-epoxy	3262.84	388	49.8	56.476
Satin woven Cotton-epoxy	3126.77	372	48.0	53.976

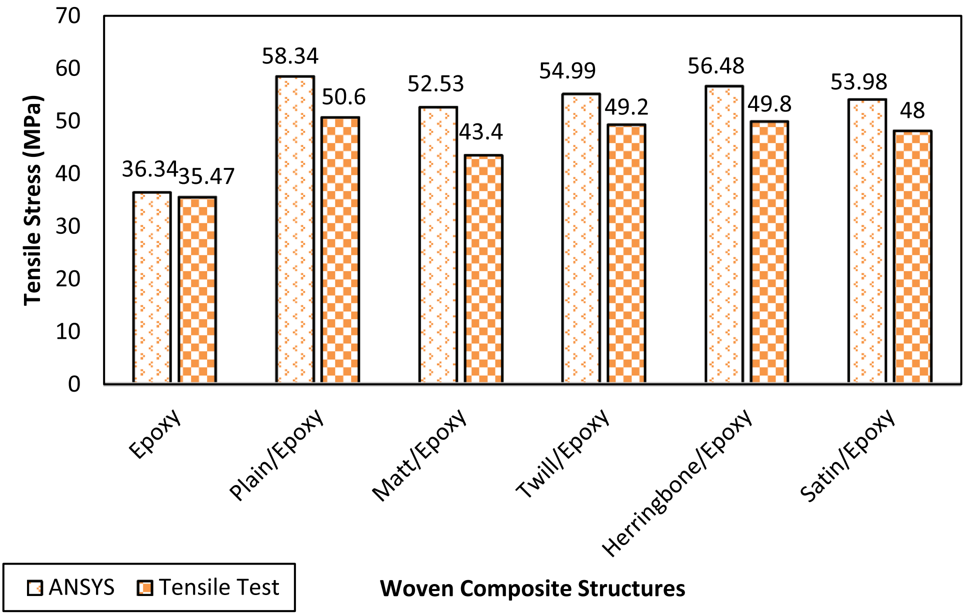

Figure 8. Tensile stress of woven cotton-epoxy composites structures from ANSYS vs tensile test.

In Figure 9 which illustrated the finite element analysis contour plots for stresses and deformation developed by applying maximum load obtained in the meshing of tensile test specimens. It is observed that the modeling of neat epoxy, alkali-peroxide treated woven cotton reinforced epoxy composite carried out using the ANSYS R23.2 workbench in comparison with practical experimental tensile tests showed interaction amongst epoxy matrix in reinforced condition. The obtained maximum stress of woven composites from ANSYS R23.2 followed approximately similar trend when equated with experimental results. The equivalent stresses obtained for neat epoxy was 36.34 MPa compared to the experimental value of 35.47 MPa showing a marginal difference of 2.4%. Other epoxy composites modeled with twill, plain, matt, satin, and herringbone had equivalent stress values of 54.99 MPa, 58.34 MPa, 52.53 MPa, 53.98 MPa, and 56.48 MPa (Figure 9(bi–fi)) respectively and their deformations (Figure 9(bi–fii)), which when compared to the experimental results had values of 49.2 MPa, 50.6 MPa, 43.4 MPa, 48 MPa, and 49.8 MPa (as shown in Table 5) with minimal variations. Similarly, Chinta, Ravinder Reddy, and Prasad (2022) reported very low variance in tensile values, and a closed flexural value for woven jute fiber reinforced hybrid composites specimen in comparison to the experimental results and FEA analytical simulated values which was considered as tolerance errors of machine. Tiwari et al. (2021) and Gupta et al. (2021) also showed close values when comparing simulated and experimental results, with observed trends that were reasonably consistent. They concluded that the results obtained by FEA agreed with the experimental test values under the same condition.

While the finite element analysis (FEA) model provides valuable insights into the mechanical behavior of alkali-peroxide treated cotton-epoxy woven composites. However, it has limitations that may affect the accuracy and reliability of its predictions. One key limitation is the assumption of isotropic and homogeneous material properties for cotton fibers and the epoxy matrix, which may not accurately reflect the anisotropic nature of natural fibers like cotton. Additionally, the model assumes perfect bonding between fibers and matrix, overlooking potential interfacial slip or debonding, which can lead to overestimation of the composite's stiffness and strength. The assumption of linear elastic behavior further simplifies the analysis but fails to capture nonlinear behavior and plastic deformation under higher loads.

Moreover, while the inclusion of geometric nonlinearity addresses large deformations, the model might not fully represent complex interactions and failure mechanisms such as fiber buckling or delamination. The mesh size, chosen through a convergence study, also presents

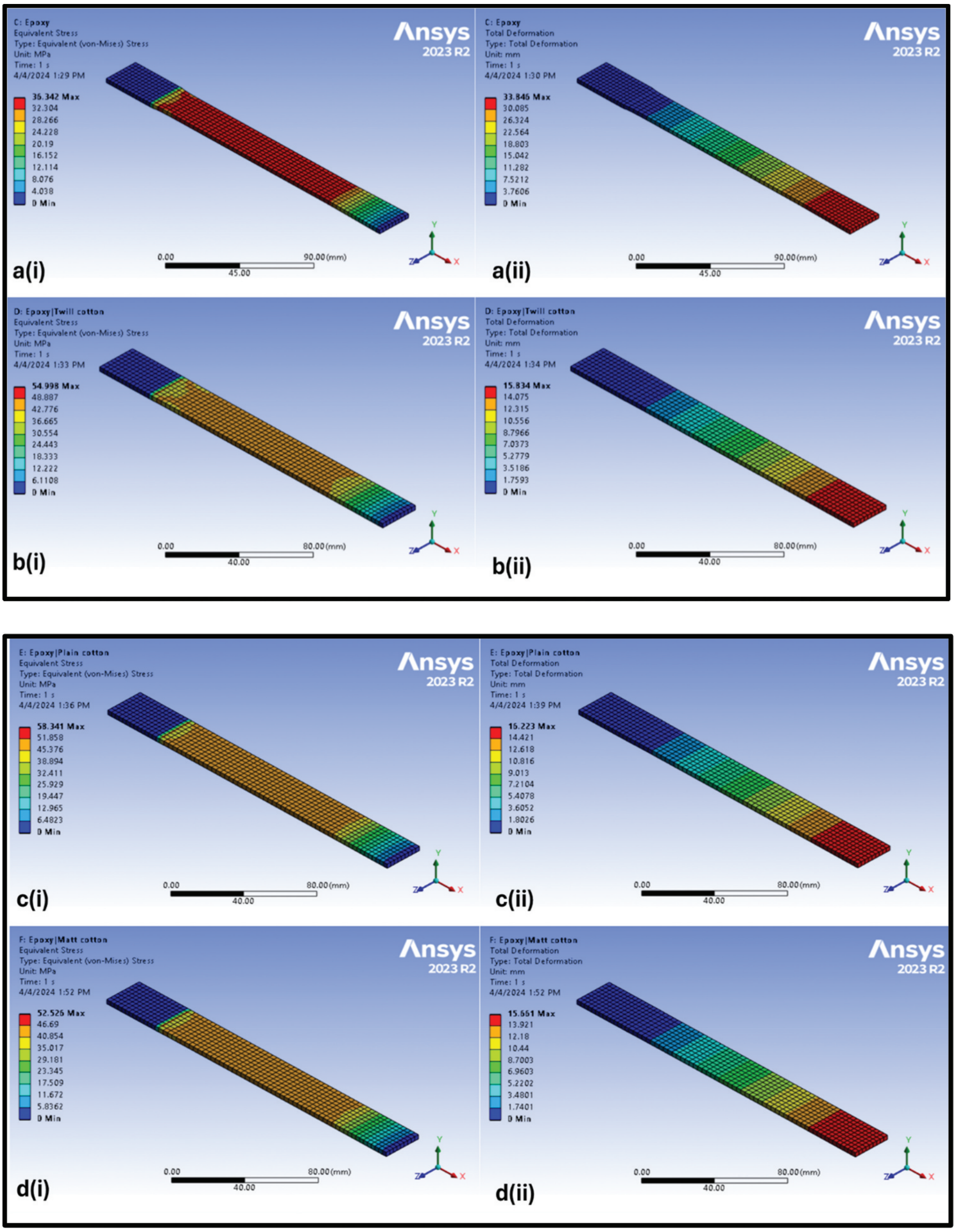

Figure 9a. Finite element analysis contour plots for equivalent stresses and deformation developed by applying maximum load obtained from the meshing of tensile test specimens.

a challenge; an improper balance can either miss critical details or increase computational costs unnecessarily. Finally, idealized boundary conditions and load applications may not perfectly mirror real experimental setups, potentially affecting the correlation between simulated and actual results. Despite these limitations, the FEA model remains a crucial tool for understanding the initial mechanical response and aiding the design of composite materials. Future efforts should focus on refining material models, incorporating interfacial behaviors, and validating simulations with comprehensive experimental data to enhance the model's predictive accuracy.

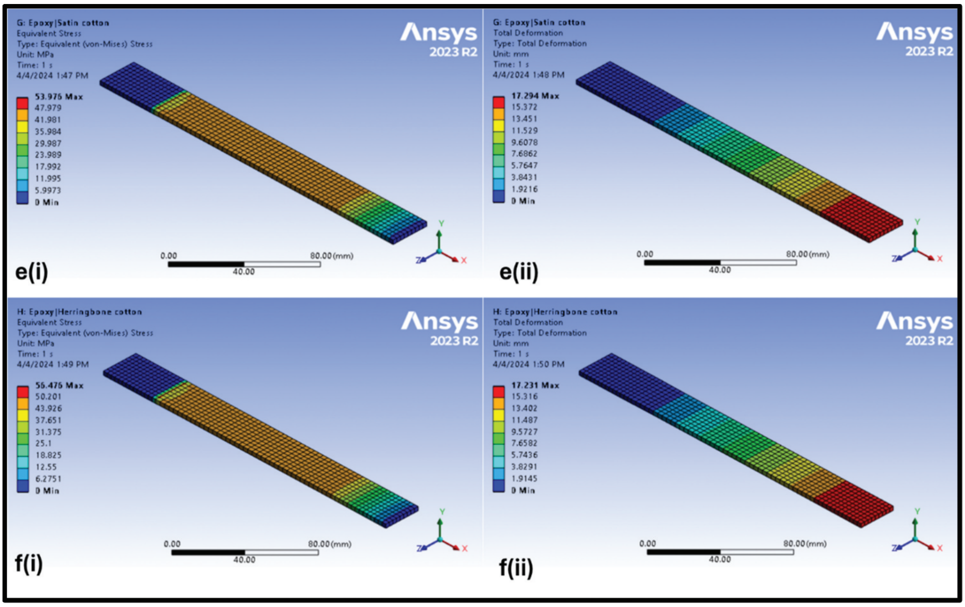

Figure 9b. Continued.

The alkali-peroxide treatment employed in this study have notable environmental implications that must be considered. Sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2) are effective in enhancing the mechanical and thermal properties of cotton-epoxy composites; however, their use presents certain environmental challenges. Sodium hydroxide, commonly used in alkali treatment, can generate hazardous waste if not managed properly. The effluents containing high levels of sodium salts can pose risks to soil and water quality, necessitating neutralization and treatment before disposal to mitigate environmental impact (Ali et al. 2018). Similarly, hydrogen peroxide, although relatively environmentally friendly, can lead to the formation of oxygenated byproducts that require careful handling and disposal to minimize potential environmental harm.

To address these concerns, it is essential to implement sustainable practices such as recycling and reusing chemicals. For instance, recovering NaOH from treatment effluents can significantly reduce both the environmental footprint and associated costs (Jabbar et al. 2015). Additionally, exploring greener alternatives like enzymatic treatments, which utilize natural enzymes to modify fiber surfaces, offers a more sustainable approach. Enzymatic treatments are biodegradable, produce less hazardous waste, and operate under milder conditions, making them an attractive alternative for future applications.

Conclusions

Finite element analysis of stress distribution in alkali-peroxide treated epoxy composites with various woven cotton structures was studied, and the results of this study indicated that:

- Alkali-peroxide-treated woven fabrics showed better tensile properties (strength and extension-at-break), and subsequently, the mechanical properties of all alkali-peroxide-treated woven cotton-epoxy composite structures improved significantly, with maximum tensile and flexural strengths of 40.6 MPa and 38.6 MPa, respectively, with 12% and 5.7% improvement.
- Woven cotton structures were superior in the warp direction than in the weft direction, and the plain and matt woven structures exhibited maximum tensile and impact properties with their

resultant composites, while herringbone and twill woven cotton-epoxy showed superior flexural properties.

- SEM images of alkali-peroxide-treated composites exhibit superior microstructural behavior with strong fabric-epoxy interfacial bonding, resulting in enhanced mechanical performance compared to untreated composites. The treatment improves fiber-matrix interaction, reduces voids, and creates a more homogeneous microstructure by enhancing fiber surface characteristics and promoting crosslinking and mechanical interlocking within the epoxy matrix.
- The woven cotton-epoxy composites were thermally stable above 250°C, with the alkali-peroxide-treated composites fast degrading at an onset degradation temperature of 288.4°C, and a DTG decomposition temperature of 343.5°C compared to the untreated cotton-epoxy composites.
- Tensile stress values developed and evaluated using ANSYS R19.2 finite element software were in good agreement and had a close variance with a low percentage variation when compared to the experimental tensile stress, showing that the properties of epoxy-woven cotton structures can be modeled for enhanced performance.
- The combined alkali and peroxide treatment approach represents a promising and innovative surface treatment route for enhancing the mechanical properties of woven cotton-epoxy composites, as these findings hold substantial promise for various industrial applications by providing a pathway for the development of advanced materials that meet the stringent requirements of diverse engineering applications. While the alkali-peroxide treatment is effective in enhancing composite properties, it is essential to consider and mitigate its environmental impact. Implementing chemical recycling, exploring greener alternatives, and conducting comprehensive environmental assessments are critical steps toward developing more sustainable chemical treatment methods for natural fibers.
- The produced woven cotton composite structures are suitable for use in technical textiles within industrial and automotive sectors, particularly for manufacturing components where lightweight and durable materials are essential.

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Highlights

- Combined alkali and peroxide treatment present an innovative surface treatment route for enhancing the mechanical properties of woven cotton, and cotton reinforced epoxy composites with significant improvement suitable for lightweight textile components in automotive and industrial applications.

- Different woven cotton structures (plain, matt, twill, herringbone, satin) significantly impact composite properties, with plain and matt weaves showing superior tensile and impact properties.
- Alkali-peroxide treated composites have better fiber-matrix adhesion, fewer voids, and superior mechanical performance compared to untreated composites.
- The reinforced woven cotton-epoxy composites are thermally stable above 250°C, with the alkali-peroxide-treated composites fast degrading at an onset degradation and DTG decomposition temperatures of 288.4°C and 343.5°C respectively.
- Validation with ANSYS R23.2 Finite Element Analysis (FEA) closely matches experimental data, confirming the reliability of FEA in predicting the behavior of epoxy-cotton composites and supporting effective modeling for enhanced performance.

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