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SUSTAINABLE INNOVATIONS: MECHANICAL AND TRIBOLOGICAL ADVANCEMENTS IN CARBON AND KEVLAR REINFORCED EPOXY COMPOSITES

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Abstract: The study of technical textiles and their composites is crucial for material selection in performance-driven applications. This research investigates the mechanical and abrasion behavior of plain-woven Kevlar and carbon fiber fabrics and their epoxy-based composites under various environmental conditions. Tensile tests and Martindale abrasion tests were performed in warp and weft directions, following ASTM D3039, ISO 105-E04:2013, and ISO 12947-3:1998 standards. Samples were tested in dry conditions, after immersion in water, and in a salt solution simulating human sweat. Dry fabrics exhibited the highest tensile strength, with Kevlar fabric outperforming carbon fabric due to its denser weave and resistance to moisture-induced degradation. However, carbon/epoxy composites showed superior mechanical properties, owing to better fiber–matrix adhesion and stiffness. Hybrid Kevlar-carbon composites offered a balanced mechanical response, particularly in the warp direction. Abrasion tests revealed lower mass loss in Kevlar fabrics compared to carbon, with damage intensifying under wet conditions especially in sweat simulations due to salt-induced weakening. This behavior is linked to fiber structure, fiber–matrix bonding, and abrasive wear mechanisms. Sweat simulation testing reflects realistic service conditions found in protective clothing and aerospace applications. The results support the development of durable, lightweight composites for environments involving moisture or salt exposure. While statistical consistency was ensured using sample averaging, future studies will include detailed statistical analyses. To mitigate wet-condition degradation, future work will explore the use of surface treatments or coatings. This study contributes to sustainable material design by enabling longer service life, reduced material waste, and optimized hybrid fiber configurations. Further research will explore bio-based matrices and nano-enhanced hybrids to expand eco-friendly performance solutions.

Key words: tensile testing, martindale test, abrasion resistance, sustainable, kevlar textiles, carbon textiles

1. INTRODUCTION

Fabrics have become an integral part of everyday life and are used for clothing, upholstered furniture and technical textiles. Kevlar and carbon fabrics are particularly important. Kevlar, a synthetic para-aramid fiber, is known for its high strength, tensile strength-to-weight ratio, stiffness, heat resistance and abrasion resistance. Carbon fibers, which consist of thin, strong crystalline carbon filaments, are characterized by a high strength-to-weight ratio, stiffness and resistance to temperature and corrosion. Composites of Kevlar and carbon fibers combined with resins such as epoxy offer exceptional strength, stiffness and light weight, making them ideal for applications in the automotive, aerospace and protective clothing industries. Analyzing the mechanical properties of these materials, such as strength, stiffness and elongation, provides insight into how composition affects mechanical behavior. Many researchers have studied the mechanical properties of Kevlar and carbon composites and their hybrids. Rajesh et al. [1] investigated the tensile strength of a four-ply Kevlar composite produced by hand lay-up and found it to have high tensile strength, making it suitable for various engineering applications. Suthan et al. [2] studied Kevlar fiber-epoxy composites, focusing on their tensile and flexural properties, and found them to be superior to aluminum composites. Yeung et al. [3] examined Kevlar-49 reinforced composites with different thermoplastic matrices and found that composites with a SAN matrix exhibited higher tensile strength than those with ABS, polyester, and polyethylene matrices. Agarwal et al. [4] compared the mechanical, wear, and thermomechanical properties of epoxy composites reinforced with glass, Kevlar, and carbon fabrics. They found that increasing the fabric content initially improved the properties, but excessive loading reduced them. Carbon fabric composites performed better overall than glass and Kevlar composites. Al-Qrimli et al. [5] investigated carbon/epoxy fabric composites produced by hand lay-up and found that they exhibited good elastic properties, with similar behavior in both warp and weft directions, and comparable shear and Poisson's ratios. Channabasavaraju et al. [6] studied the tensile and flexural properties of polymer composites reinforced with glass, graphite, and Kevlar fibers and concluded that both the type and thickness of the fiber affect these properties, with greater thickness leading to improved performance. Hybrid composites are materials made by combining different types of fibers or materials to achieve improved properties. They can be developed using synthetic, natural, and metallic fibers, resulting in enhanced strength, stiffness, and a high strength-to-weight ratio [6]. Furthermore, Kumar et al. [7] investigated the effects of hybridization on the properties of synthetic fibers using 3 mm thick laminates:

Kevlar49-E-glass, pure Kevlar49, and Kevlar49-carbon. The Kevlar-E-glass hybrid retained 90% of the strength of Kevlar, the carbon-Kevlar hybrid exhibited higher strength, and Kevlar showed higher impact strength. In another study, Hashim et al. [8] examined the tensile properties of carbon/Kevlar hybrids with different fiber orientations (0°, 45°, and 90°). The highest tensile strength was observed when the fibers were oriented in the direction of the carbon fibers (0°). Recently, Khaddour et al. [9] studied carbon, glass, and Kevlar fabrics, as well as epoxy hybrid composite laminates. Increasing the number of carbon layers increased the modulus of elasticity and tensile stress while reducing the elongation at break. The stacking sequence had no significant effect, except for a central Kevlar layer, which reduced the tensile properties. Priyanka et al. [10] also found that the hybridization pattern and the orientation of the carbon yarn in the carbon-Kevlar hybrid fabric significantly affected the modulus and strength, while the weaving pattern had no effect on mechanical performance. Plain woven fabrics resulted in stiffer laminates under loading. In addition, Hossain et al. [11] showed that CK/epoxy composites exhibited better mechanical properties compared to other matrices. Furthermore, Karthik et al. [12] investigated the tensile properties of hybrid composites with different stacking sequences and found that the carbon-Kevlar-carbon-Kevlar-carbon (C-K-C-C-C-C) sequence exhibited the highest tensile strength. Recent advancements in composite materials have emphasized sustainability, durability, and performance optimization under variable environmental conditions. Studies have explored the development of eco-friendly and high-strength polymer composites using bio-fillers, hybrid reinforcements, and water treatment applications to enhance material performance and longevity [13-16]. Innovations in textile-reinforced composites, including the integration of carbon and Kevlar fibers, have shown promising results in mechanical and tribological improvements [17-20]. Moreover, the role of surface treatments, hybrid stacking, and environmental resistance has been critically examined to address durability challenges in aggressive environments [20].

This study focuses specifically on plain-woven technical textiles, as woven fabrics are commonly used in structural composite applications due to their predictable mechanical behavior. The study hypothesizes that the mechanical and abrasion properties of Kevlar and carbon fiber fabrics, as well as their composites, are significantly influenced by environmental conditions, fiber type, and fabric orientation. It is expected that dry conditions will enhance tensile strength and reduce material loss during abrasion testing, while wet conditions, including exposure to water and salt solutions, will negatively affect performance. Additionally, hybrid composites combining Kevlar and carbon fibers are anticipated to provide balanced mechanical behavior by utilizing the strengths of both materials. The main objective of this research is to investigate the mechanical response of these fabrics and their composites under varying environmental conditions. The study includes tensile and abrasion testing of the materials in both dry and wet states, and compares the performance of Kevlar, carbon, and hybrid composites considering fiber orientation and stacking sequence. The findings aim to inform material selection for sustainable, high-performance applications in fields such as aerospace, automotive, and protective equipment.

2. MATERIALS AND METHODS

In this research, two types of fabrics were used: plain weave Kevlar fabric (0.24 mm thickness, 200 g/m² surface density) and plain weave carbon fabric (0.28 mm thickness, 200 g/m² surface density). In this experimental study, the fabrics and their composites were tested under various conditions using tensile and abrasion tests. Tensile tests were carried out on a Universal Testing Machine for both the fabrics and the composites, while abrasion tests were conducted using a Martindale Abrasion Tester.

2.1. Tensile Test on Fabrics

The most common mechanical test performed on textiles is the tensile strength test. It measures how a fabric responds when subjected to a stretching force along its length. The test works on the basic principle of holding the sample at two or more points and pulling it until it breaks [21]. In this study, tensile tests were carried out on fabric samples under different conditions: dry, after being soaked in water for 24 hours, and after being soaked in a saltwater solution for 24 hours to simulate human sweat. According to ISO 105-E04:2013 [22], the artificial sweat solution consists of 5 grams of sodium chloride (NaCl) dissolved in 1 liter of distilled water. All tests were conducted in both the warp and weft directions to examine any differences in performance under each condition. The samples, made of Kevlar and Carbon fabrics, measured 25 mm × 250 mm and were cut using a laser cutting machine. Aluminum plates (25 × 50 mm) were attached to the ends of each sample and bonded with epoxy to ensure smooth tensile loading and to prevent slipping from the jaws of the testing machine. The tensile strength tests were performed using a Zwick Roell Z600 tester with hydraulic grips, operating at a speed of 2 mm/min.

2.2. Tensile Test on Composite Fabrics

A tensile test is a widely used method for evaluating the mechanical properties of materials, including composite fabrics. These fabrics consist of two or more components—typically reinforcing fibers and a matrix material. In this study, three types of composite materials were prepared: Kevlar/epoxy, Carbon/epoxy, and a hybrid Kevlar-Carbon/epoxy composite. The Kevlar and Carbon specimens each contained six layers of fabric (referred to as 6K and 6C, respectively), while the hybrid composite was made by alternating three layers of Kevlar and three layers of Carbon in a KCKCKC sequence. The epoxy resin and hardener were mixed in a recommended weight ratio of 10:6. The composites were then fabricated using the hand layup method, by layering fabric and resin alternately in an open mold. The samples were left to cure at room temperature for at least 24 to 48 hours to ensure the resin dried completely. Tensile tests were carried out using a Zwick Roell Z600 material testing machine in accordance with the ASTM D3039 standard [23], at a test speed of 2 mm/min for all composite samples. Three specimens were prepared for each fabric type in both the warp and weft directions, with dimensions of 250 mm × 25 mm, a thickness between 2.0 and 2.5 mm, and a gauge length of 150 mm. The average values of the results were recorded. Samples were cut using an abrasive water jet machine. To ensure a smooth tensile process and prevent slippage from the grips of the testing machine, aluminum tabs (25 mm × 50 mm) were securely bonded to the ends of each specimen using epoxy. Tensile loading was applied in both the warp and weft directions. Mechanical properties such as tensile strength, tensile modulus, elongation at break, and maximum force were evaluated.

2.3. Abrasion test on Fabrics

The wear behavior of fabrics involves examining how different materials respond to mechanical stress and environmental conditions over time. This includes evaluating their resistance to abrasion, pilling, tearing, and other types of wear. Abrasion testing is one of the key methods used to assess the durability and wear resistance of fabrics. Abrasion refers to the mechanical damage caused by rubbing the fabric against another surface. Over time, this can lead to the loss of performance properties—especially strength—and negatively affect the fabric's appearance [24]. Abrasion resistance is evaluated by measuring changes such as loss of mass, reduction in strength, increased air or light permeability, decrease in thickness, and alterations in surface structure (e.g., broken yarns or holes). These surface changes often reflect modifications in the fabric's physical properties and internal structure [25]. Several techniques are used to test abrasion resistance. All of them involve rubbing the sample fabric against an abrasive surface, another fabric, or emery paper, either for a set duration or a certain number of strokes, often following a Lissajous pattern of movement [18]. The Martindale abrasion test is the most commonly used method. In this test, circular fabric samples are rubbed against a standard abradant under a specific load. One advantage of the Martindale test is that it exposes the sample to wear from multiple directions. Common abrasives used in the test include silicon carbide paper or woven worsted wool [26].

In the current study, abrasion tests were conducted on 100% Kevlar and 100% Carbon fabrics using a Martindale abrasion tester (Fig. 1). Three types of sandpaper with different grit levels were used: Silicon Carbide Paper P1000 and P500 from STRUERS, and Micro Cloth Paper P1200 from BUEHLER. Tests were carried out for 25, 50, and 75 cycles. The abrasion resistance was evaluated based on ISO 12947-3:1998, which outlines the procedure for determining fabric mass loss using the Martindale method [27] . While this standard served as a reference, the testing conditions were adapted to suit different scenarios, but all procedures were conducted in a consistent and controlled manner. Experiments were performed under both dry and wet conditions for each cycle count and sandpaper type. Three fabric samples were tested for each case, and the average mass loss was recorded. Samples were cut into 80 mm diameter circles using a laser cutting machine, ensuring each circular piece included both warp and weft yarns. All samples were labeled and coded for clarity, with "S" referring to Kevlar and "C" to Carbon samples. Figure 2: Kevlar and Carbon fabric samples cut into 80 mm diameter circles using a laser cutter, shown placed in holders prior to abrasion testing using the Martindale abrasion tester. Each sample includes both warp and weft yarns to ensure uniform exposure to abrasion during testing. The wet condition tests were conducted using two methods: immersion in pure water and immersion in a simulated sweat solution. The sweat solution, based on ISO 105-E04:2013 [22] contained 5 grams of sodium chloride (NaCl) dissolved in 1 liter of water. Samples were soaked in each solution for 24 hours before testing and were weighed on a precision scale both before and after abrasion testing. In all test cases, the samples were abraded against sandpaper using the Martindale abrasion tester. The process began under dry conditions, with tests conducted using P500 sandpaper for 25, 50, and 75 cycles. After each cycle set, the samples were carefully removed from the holder to prevent damage or displacement of the yarns, then weighed to calculate mass loss. This procedure was repeated for the 50- and 75-cycle tests. The same sequence was followed for the tests conducted under pure water and simulated sweat conditions.

All tests were carried out under consistent conditions, with the sandpaper replaced at each stage—whether in dry or wet testing. Abrasion resistance was determined by calculating the mass loss of each sample before and after each test cycle (25, 50, and 75), and the results were expressed as percentages for comparison.

Fig. 1. Martindale abrasion tester

3. RESULTS AND DISCUSSIONS

3.1. Fabric Tensile Test Results and Discussions:

Tensile strength is a key mechanical property of woven materials, representing the force required to break multiple yarns simultaneously in either the warp or weft direction. It measures the fabric's ability to withstand tension or pull forces without breaking or tearing. Table 1 presents the average tensile strength and maximum force for two fabrics—Kevlar and Carbon—in both warp and weft orientations, tested under three conditions: dry, immersion in water, and immersion in a water-and-salt solution to simulate human sweat. "K" refers to Kevlar fabric samples, while "C" refers to Carbon fabric samples.

It is well known that woven fabrics exhibit different mechanical properties depending on direction and environmental conditions. As shown in Figures 2a and 2b, the tensile strength in the warp direction is greater than in the weft direction. This is because warp threads are typically under higher tension during the weaving process, which tightens and aligns the yarns, making them more resistant to stretching or breaking in the longitudinal direction. In contrast, weft threads, which interlace with the warp yarns, experience less tension during weaving and generally exhibit lower tensile strength in the transverse direction. When comparing tensile strength across different conditions, the dry samples consistently showed higher strength than those immersed in water or the sweat solution. For Kevlar fabric (Figure 3a), the ultimate tensile strength (UTS) in the warp direction reached approximately 548.21 MPa, 546.44 MPa, and 527.45 MPa for the dry, water-immersed, and sweat-immersed samples, respectively—each surpassing their corresponding weft-direction values. A similar trend was observed for the Carbon fabric, where the warp direction generally exhibited higher UTS than the weft direction. However, an exception was noted in the C3 warp-direction sample, which reached 359.68 MPa—higher than the dry and sweat-condition samples. Further inspection revealed that this sample had more burned edges due to laser cutting, which may have increased its resistance compared to the other samples. It was also observed that tensile strength is influenced by multiple factors beyond yarn strength. These include the type of fiber or fiber blend, the degree and direction of twist, the number of yarns, the spinning system, the yarn's bending behavior, its frictional properties, as well as the fabric's geometry, thread density, and weave pattern. Additionally, testing conditions—such as temperature, humidity, loading duration, applied force, jaw spacing, and the specific testing procedures—can significantly affect fabric strength [28].

Tab. 1. Average results of Tensile test for Kevlar and Carbon fabric on different conditions

Average Results in Dry Conditions			
Fabric Code	Thickness (mm)	Tensile strength (MPa)	Fmax (N)
K1 (Warp)	0.24	548.21	3289.25
K2 (Weft)	0.24	512.19	3073.14
C1 (Warp)	0.28	340.33	2382.33
C2 (Weft)	0.28	149.38	1045.69
Average Results with Water Conditions			
K3 (Warp)	0.24	546.44	3278.64
K4 (Weft)	0.24	510.57	3063.43
C3 (Warp)	0.28	359.68	2517.74
C4 (Weft)	0.28	29.78	208.48
Average Results with Sweat Conditions			
K5 (Warp)	0.24	527.45	3164.71
K6 (Weft)	0.24	507.50	3045.01
C5 (Warp)	0.28	326.22	2283.51
C6 (Weft)	0.28	116.14	812.95

It has been observed that fabric strength is highest in the dry state compared to wet conditions. Furthermore, fabric submerged in water retains more strength than when submerged in a saltwater solution. In the dry state, fiber remains tightly packed and well-aligned, allowing them to bear loads and resist deformation more effectively. In wet conditions, fibers absorb moisture, which causes swelling and reduces their mechanical performance. When immersed in a saltwater solution, the presence of salt ions causes additional swelling and interacts with the fiber surface, disrupting intermolecular forces. These ionic interactions weaken the bonding between fibers, resulting in decreased overall textile strength. Salt ions interact with the fibre surface and interfere with intermolecular bonding, increasing the degree of fiber swelling and reducing structural cohesion. This leads to a greater reduction in tensile strength compared to pure water exposure. Due to differences in composition and structure, Kevlar fabric demonstrates more durable and consistent performance than Carbon fabric. Kevlar threads are more tightly interwoven, while the threads in Carbon fabric may not bind as effectively, leading to fiber separation or release. This contributes to greater variability and fluctuations in the performance of Carbon fabric, making it less reliable as a structural textile compared to Kevlar. Sweat simulation led to greater fabric mass loss than pure water immersion, indicating that salt content accelerates degradation.

3.2. Composites Fabric Tensile Test Results and Discussions:

The tensile test is a vital evaluation method for composite materials, offering critical insights into their mechanical performance under stress. It measures key properties such as strength, stiffness, and elongation by applying an axial load to a specimen until failure occurs. These data are essential for informed material selection and sustainable technical design in sectors such as aerospace, automo-tive, construction, and advanced manufacturing, where durability, performance, and resource efficiency are priorities. In this study, tensile tests were performed on three types of composite materi-als—Kevlar/Epoxy, Carbon/Epoxy, and a Kevlar-Carbon hybrid/Epoxy composite. Mechanical properties including tensile strength, Young's modulus (tensile modulus), elongation at break, and maximum force were determined to assess the structural integrity and performance potential of each material configuration.

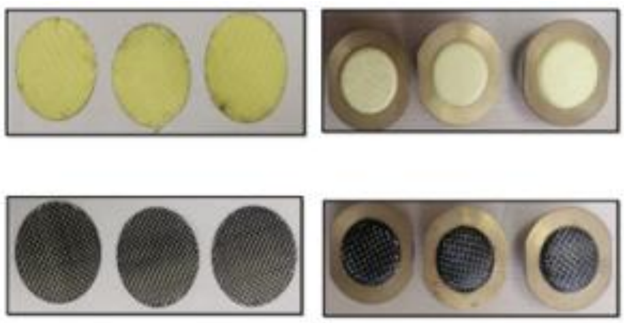


Fig. 2. Kevlar and Carbon fabrics samples after cutting in 80mm diameter from fabrics and in holders before test

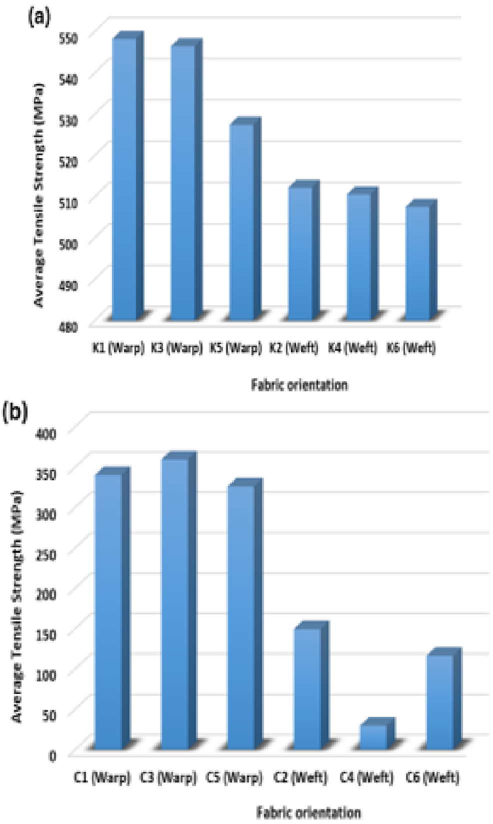


Fig. 3. Average results of Tensile strength in dry and wet cases for: a) Kevlar fabric , b) Carbon

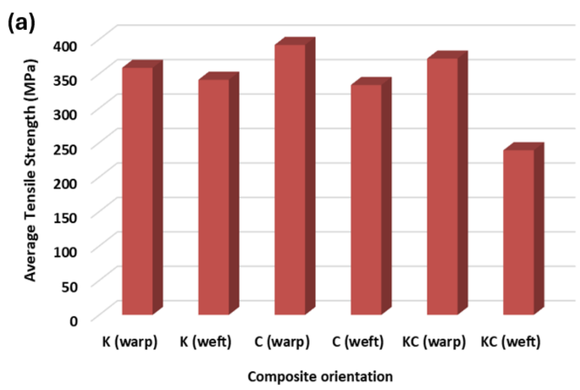
Table 2 and Figures 4a and 4b present the average mechanical results for the different composite types in both warp and weft orientations. The data reveal that Kevlar/Epoxy composites exhibit high tensile strength and strain in both directions, with notably higher Young's modulus and tensile strength in the warp direction. Similarly, Carbon/Epoxy composites demonstrate superior tensile strength and modulus in the warp direction, although with reduced strain compared to Kevlar/Epoxy. This indicates that Carbon composites offer higher stiffness and load-bearing capacity, while Kevlar composites provide more flexibility. The hybrid Kevlar-Carbon/Epoxy composites combine the mechanical advantages of both fiber types. In the warp direction, these hybrid materials show a balanced performance, with tensile strength and modulus values between those of pure Kevlar and Carbon composites. In the weft direction, however, the hybrid composites exhibit a compromise-lower tensile strength than either of the individual fiber composites, but a higher modulus than Kevlar/Epoxy, suggesting improved stiffness with some trade-off in strength.

Tab. 2. Average results of Tensile test for Kevlar and Carbon fabric on different conditions

for (Kevlar/Epoxy, Carbon/Epoxy, and K-C hybrid/Epoxy) in warp and weft directions					
Code	Thickness (mm)	Max Strain %	Tensile strength (MPa)	Fmax (kN)	E-Mod (GPa)
K (warp)	2.25	4.03	358.63	19.72	8.39
K (weft)	2.13	4.56	341.28	18.20	6.77
C (warp)	2.30	2.09	391.85	23.13	21.64
C (weft)	2.37	1.65	333.68	19.13	22.20
KC (warp)	2.17	2.31	372.04	20.06	16.07
KC (weft)	2.30	1.84	238.97	13.73	11.96
for both directions (warp & weft) for each composite (Kevlar/Epoxy, Carbon/Epoxy, and K-C hybrid/Epoxy)					
K	2.19	4.30	349.95	18.96	7.58
C	2.33	1.87	362.77	21.13	21.92
KC	2.23	2.08	305.51	16.89	14.01

As illustrated in Figure 4a, Kevlar/Epoxy composites in the warp direction achieve a tensile strength of 358.63 MPa, slightly lower than Carbon/Epoxy composites, which reach 391.85 MPa. This indicates that Carbon-based composites offer enhanced tensile strength compared to Kevlar-based ones. In the weft direction, the tensile strengths of Kevlar/Epoxy (341.28 MPa) and Carbon/Epoxy (333.68 MPa) are closely matched, suggesting that both materials perform comparably in the transverse orientation [29-31]. The Kevlar-Carbon hybrid composite in the warp direction achieves a tensile strength of 372.04 MPa—higher than Kevlar/Epoxy but still lower than Carbon/Epoxy. This demonstrates that the inclusion of Carbon fibers enhances the tensile properties of the hybrid compared to Kevlar alone, though not to the level of pure Carbon/Epoxy. In the weft direction, the hybrid composite shows a tensile strength of 238.97 MPa, which is lower than both Kevlar/Epoxy (341.28 MPa) and Carbon/Epoxy (333.68 MPa). This suggests that hybridization in the weft direction may lead to weaker fiber interactions and reduced load transfer efficiency, which impacts tensile strength. The hybrid composite achieved 372.04 MPa in warp direction, compared to 358.63 MPa for Kevlar/Epoxy, indicating improved tensile strength due to the reinforcing contribution of carbon layers. Overall, the results provide valuable data for the development of high-performance, fiber-reinforced composites with applications in sustainable design and lightweight structural components. Hybrid composites may offer a strategic balance between performance and material efficiency, contributing to the broader goals of sustainability through optimized resource use and extended material life cycles. Figure 4b illustrates that Carbon/Epoxy composites exhibit significantly higher Young's moduli in both the warp (21.64 GPa) and weft (22.20 GPa) directions compared to Kevlar/Epoxy composites, which recorded values of 8.39 GPa and 6.77 GPa in the warp and weft directions, respectively. These findings confirm that Carbon fibers impart superior stiffness and rigidity to composite materials. However, the hybrid Kevlar-Carbon composites demonstrate intermediate Young's moduli—16.07 GPa in the warp direction and 11.96 GPa in the weft direction—indicating a reduction in stiffness relative to pure Carbon/Epoxy composites, yet an improvement over Kevlar/Epoxy composites. This highlights the trade-off introduced by blending fibers: while Kevlar fibers enhance other properties such as flexibility, they reduce the overall stiffness of the hybrid composite. In terms of strain behavior, Kevlar/Epoxy composites display greater ductility compared to Carbon-based composites. Specifically, Kevlar/Epoxy composites exhibit strain values of 4.03% in the warp direction and 4.56% in the weft direction, compared to Carbon/Epoxy composites, which show 2.09% and 1.65% strain in the warp and weft directions, respectively. These results suggest that Kevlar-based composites can endure higher deformation under tensile loading, making them more suitable for applications where flexibility and impact resistance are critical. For the hybrid Kevlar-Carbon composites, strain in the warp direction is 2.31%, and in the weft direction, 1.84%. These values lie between those of the Kevlar and Carbon composites, indicating a synergistic behavior that combines some flexibility from Kevlar with the rigidity of Carbon. This behavior suggests the hybrid structure could offer a balanced mechanical response, which is advantageous for applications requiring a compromise between stiffness and flexibility.

As summarized in Table 2, the comparative performance of the composite types shows that Carbon/Epoxy composites consistently demonstrate higher tensile strength and stiffness, but lower strain, compared to Kevlar/Epoxy and hybrid composites. These characteristics may result from stronger interfacial bonding between the Carbon fibers and the epoxy matrix, which contributes to more efficient load transfer and improved mechanical performance. In contrast, Kevlar/Epoxy composites exhibit lower tensile strength and stiffness, likely due to weaker adhesion between the Kevlar fibers and the resin, but benefit from greater strain capacity. The hybrid Kevlar-Carbon composites exhibit a combination of the properties found in the individual materials, offering a viable compromise for multifunctional applications. From a sustainability perspective, such hybridization can contribute to material efficiency by optimizing mechanical performance while reducing dependency on high-cost or resource-intensive components like pure Carbon fibers.



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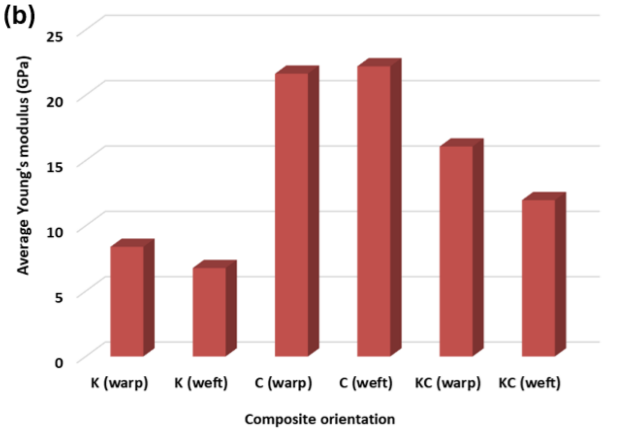
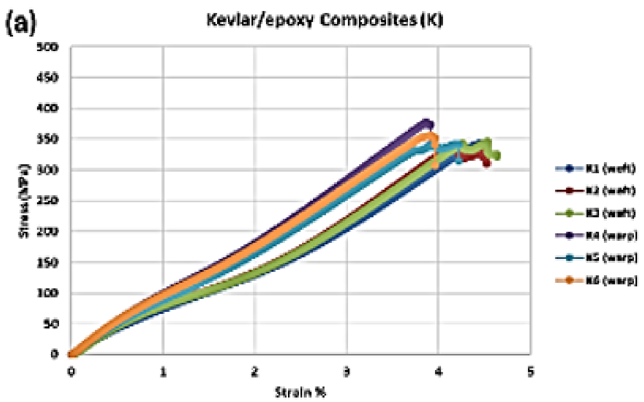
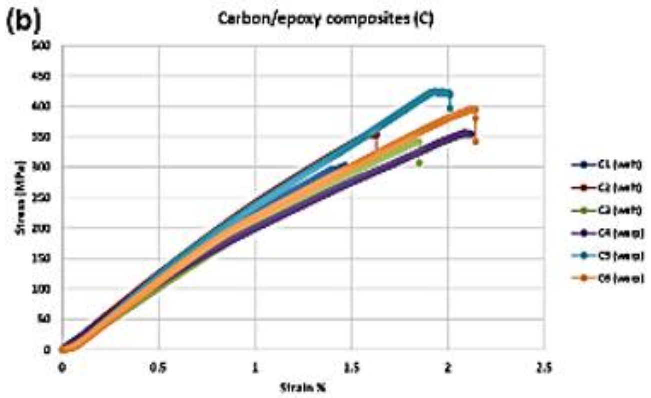


Fig. 4. Average mechanical properties for (Kevlar/Epoxy, Carbon/Epoxy, and K-C hybrid/Epoxy) in warp and weft directions for; a) Tensile strength, b) Young's modulus

These findings also reinforce the well-documented anisotropic nature of fiber-reinforced composites, in which mechanical properties vary depending on the direction of applied stress relative to fiber alignment. This directional dependence is a fundamental design parameter in sustainable composite engineering. By carefully selecting fiber types, orientations, and matrix combinations, designers and engineers can tailor composite materials to meet performance requirements while optimizing resource use and minimizing environmental impact. In summary, the results underscore the critical role of fiber selection, orientation, and material hybridization in achieving desirable mechanical performance and advancing sustainable material development for structural and engineering applications. The stress–strain curves of the composite materials, evaluated in both the warp and weft directions, exhibit an initial linear response up to the point of ultimate failure, which occurs suddenly and without significant plastic deformation. However, slight nonlinear behavior is observed prior to fracture, primarily due to matrix cracking and micro-damage accumulation, which introduces minor fluctuations in the curves, as illustrated in Figures 5a, 5b, and 5c. It is important to note that several factors influence the mechanical performance of composite materials. These include the fabrication technique, the type and quality of the matrix, fiber grade, thermal processing conditions, chemical treatments related to performance enhancement, and the degree of fiber–matrix interfacial adhesion. Optimizing these factors is essential not only for improving mechanical properties but also for advancing the development of more durable, resource-efficient, and sustainable composite systems [32-34].





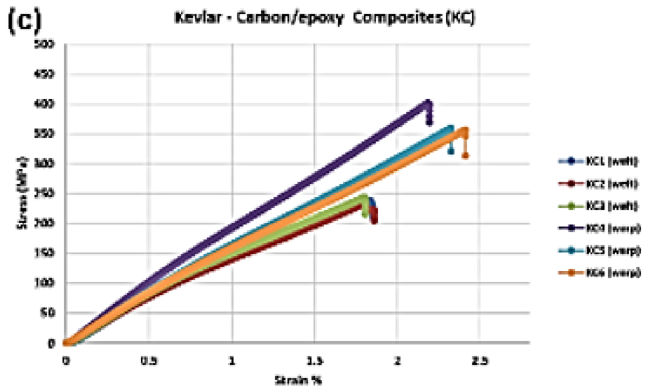


Fig. 5. Stress-Strain curve composites in warp and weft directions of: a) Kevlar/epoxy, b) Carbon/epoxy and c) Kevlar – Carbon /epoxy

Figure 6a illustrates the failure modes of the composite materials in both the warp and weft directions. As observed, the failures occur at the length of the specimens. The failure strength of a composite typically falls between the failure strengths of its fibers and matrix, with some fibers breaking at various points and others pulling out at regions where matrix-fiber adhesion fails [35, 36]. In Kevlar/epoxy composites, failure initiates with matrix cracking, where the epoxy resin matrix begins to crack under stress. This is followed by fiber/matrix interface debonding and fiber pull-out, indicating that the epoxy matrix is unable to effectively distribute and absorb the applied load, leading to localized failure. This failure mode is a critical consideration when designing composites for sustainability, as improving matrix-fiber bonding could enhance the longevity and durability of materials, reducing the need for frequent replacements and minimizing waste. For Carbon/epoxy composites, a simultaneous and complete cutting of both the matrix and Carbon fibers was observed. This suggests a strong interaction and bonding between the matrix and Carbon fibers, enhancing the material's stiffness and strength. The failure near the grips may be attributed to stress concentration at these points, but the efficient load transfer between matrix and fibers contributes to improved overall mechanical performance. The strong fiber-matrix bonding in Carbon composites also has sustainability implications, as it potentially leads to longer-lasting materials with lower environmental impact over their lifecycle. This anisotropy is attributed to the weaving process, where warp threads are subjected to higher tension, resulting in better alignment, tighter packing, and enhanced load transfer capabilities. In hybrid composites, consisting of both Kevlar and Carbon fibers in an epoxy matrix, a combination of failure modes is observed. Carbon layers exhibit complete cutting or failure, whereas Kevlar layers initially fail in the matrix, followed by fiber failure. Additionally, delamination between the Kevlar and Carbon layers occurs. This delamination suggests mismatched properties or interactions between the two materials, implying imperfect adhesion or bonding. Such issues are important in the context of sustainability, as delamination can reduce the overall strength and lifespan of the composite, leading to more frequent material replacement. Future efforts to optimize the adhesion and compatibility of hybrid materials could improve their performance and sustainability, contributing to the development of more efficient and environmentally friendly composite materials. While Kevlar fabric exhibits higher tensile strength than carbon fabric in isolation, the superior fiber–matrix adhesion and stiffness of carbon fibers enable carbon/epoxy composites to outperform Kevlar/epoxy composites overall.

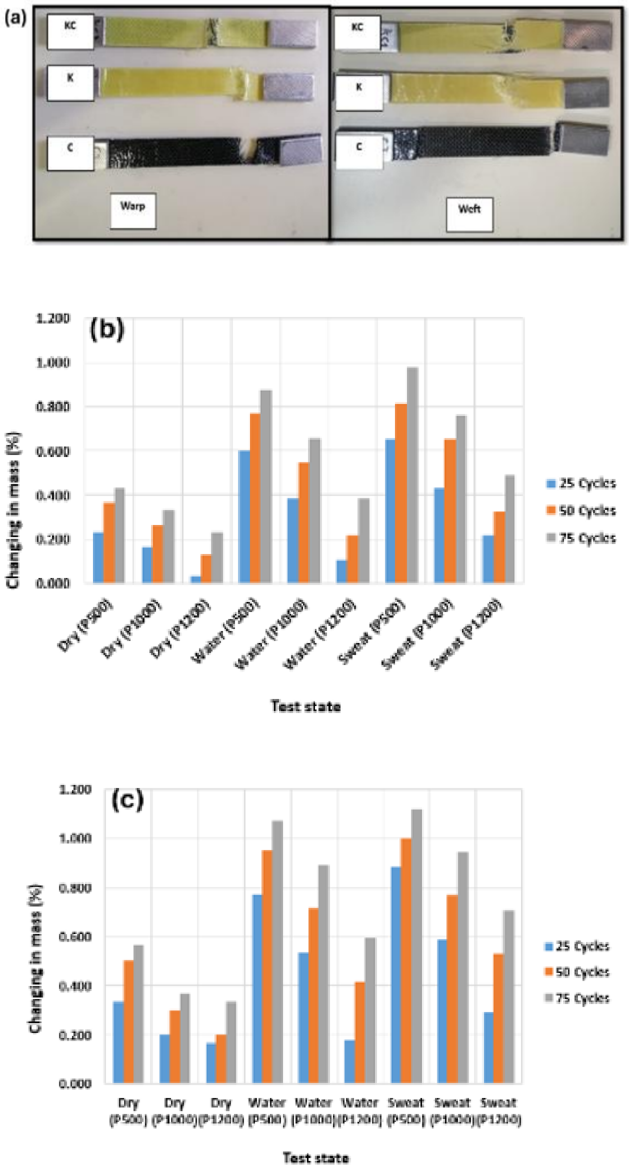


Fig. 6. The failures of the composite; a) (Kevlar/Epoxy, Carbon/Epoxy, and K-C hybrid/Epoxy), b) Kevlar fabric against sandpapers, c) Carbon fabric against sandpapers in warp and weft directions

3.3. Fabric Abrasion Test Results and Discussion

Fabric abrasion resistance was evaluated using the Martindale test, a widely recognized method for assessing textile durability. The results of abrasion resistance for the fabrics, tested against three types of sandpaper (P500, P1000, and P1200), are presented in Table 3 and expressed as a percentage of mass loss. Figures 6b and 6c illustrate the percentage of mass loss for all fabric specimens based on the number of abrasion cycles and different test conditions (dry and wet). These figures represent the average results of three samples evaluated for each abrasion cycle, where each sample was tested for each cycle against a sandpaper, and the average was computed. The abrasion testing results at 25, 50, and 75 cycles revealed varying levels of mass loss among the fabric samples under different sandpaper grits and test conditions (dry and wet). In dry conditions, Kevlar fabric exhibited less mass loss at all testing cycles against all sandpapers when compared to Carbon fabric, as shown in Figures 6b and 6c. For instance, under dry conditions with an abrasion cycle of 25 and sandpaper P500, Kevlar fabric experienced a mass loss of 0.2333%, whereas Carbon fabric exhibited a mass loss of 0.333%. As the number of abrasion cycles increased, the mass loss intensified, reaching 0.366% and 0.433% for Kevlar fabric at 50 and 75 cycles, respectively. Similarly, Carbon fabric demonstrated a mass loss of 0.5% at 50 cycles and 0.5667% at 75 cycles, as shown in Table 3. This trend persisted when testing with sandpapers P1000 and P1200, although the magnitude of mass loss varied depending on the sandpaper grit. The superior strength and endurance of Kevlar allow it to better withstand abrasion and wear than Carbon fabric. Moreover, the molecular structure of Kevlar provides remarkable tensile strength and toughness, making it highly resistant to abrasion and friction damage. In contrast, Carbon fabric, despite its strength, is less resistant to abrasion compared to Kevlar. The increased mass loss in carbon fabric is likely due to lower resistance to fiber breakage under mechanical abrasion, as well as differences in yarn bonding. Kevlar's high crystallinity and hydrogen bonding provide better abrasion resistance.

Tab. 3. Average results for Abrasion test samples in different conditions

Cycles	P500				P1000				P1200			
	Fabric code	Mass before (g)	Mass after (g)	%	Fabric code	Mass before (g)	Mass after (g)	%	Fabric code	Mass before (g)	Mass after (g)	%
in Dry case for Kevlar and Carbon fabrics												
25	S1	1	0.997	0.23	S4	1	0.998	0.16	S7	1	0.999	0.03
50	S2	1	0.996	0.36	S5	1	0.997	0.26	S8	1	0.998	0.13
75	S3	1	0.995	0.43	S6	1	0.996	0.33	S9	1	0.997	0.23
25	C1	1	0.996	0.33	C4	1	0.998	0.20	C7	1	0.998	0.16
50	C2	1	0.995	0.50	C5	1	0.9970	0.30	C8	1	0.9980	0.20
75	C3	1	0.994	0.56	C6	1	0.9963	0.36	C9	1	0.9967	0.33
with pure water case for Kevlar and Carbon fabrics												
25	S10	1.829	1.82	0.60	S13	1.83	1.82	0.38	S16	1.828	1.826	0.1094
50	S11	1.829	1.82	0.77	S14	1.83	1.82	0.55	S17	1.828	1.824	0.22
75	S12	1.828	1.81	0.88	S15	1.83	1.82	0.66	S18	1.828	1.821	0.38
25	C10	1.682	1.67	0.77	C13	1.68	1.67	0.54	C16	1.682	1.679	0.18
50	C11	1.682	1.67	0.95	C14	1.68	1.67	0.71	C17	1.682	1.675	0.42
75	C12	1.682	1.66	1.07	C15	1.68	1.67	0.89	C18	1.682	1.672	0.59
sweat simulation case for Kevlar and Carbon fabrics												
25	S19	1.841	1.829	0.6518	S22	1.841	1.833	0.4346	S25	1.841	1.837	0.2173
50	S20	1.839	1.824	0.8157	S23	1.841	1.829	0.6518	S26	1.840	1.834	0.3261
75	S21	1.841	1.823	0.9777	S24	1.841	1.827	0.7605	S27	1.841	1.832	0.4889
25	C19	1.698	1.683	0.8834	C22	1.698	1.688	0.5890	C25	1.698	1.693	0.2945
50	C20	1.698	1.681	1.0012	C23	1.697	1.684	0.7661	C26	1.698	1.689	0.5300
75	C21	1.698	1.679	1.1190	C24	1.698	1.682	0.9423	C27	1.698	1.686	0.7067

The observations indicate that the fabric's mass loss is greater in wet conditions (both pure water and sweat simulation) than in dry conditions for both Kevlar and Carbon textiles. As seen in the

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figures, the percentage of mass loss during water tests, using sandpaper P500 and an abrasion cycle of 25, was 0.6014% for Kevlar fabric and 0.7729% for Carbon fabric. Notably, as the number of cycles increased, a significant divergence between the two fabrics became apparent under identical water test conditions, as shown in Table 3. Furthermore, the mass loss percentage in the sweat simulation cases exceeded that observed in the water test. For instance, with sandpaper P500 and an abrasion cycle of 25, the mass loss for Kevlar fabric was recorded as 0.6518%, while Carbon fabric exhibited a higher mass loss of 0.8834%, as shown in Table 3. Additionally, the degree of mass loss increased with the number of abrasion cycles. Comparing the two wet test conditions, it is clear that the pure water test resulted in lower mass loss than the sweat simulation in all samples tested, including Kevlar and Carbon fabrics. This difference is attributed to the presence of particles such as salt in sweat, which can act as abrasive agents, increasing friction and accelerating the wear on the fabric surface. As a result, fibers exposed to the sweat solution experience more abrasion-induced mass loss than those exposed to pure water.

The difference in mass loss between wet and dry conditions can be attributed to the weaker and more brittle connections between the fabric's threads when exposed to moisture or immersed in water or sweat solutions, compared to their stronger bonds in dry conditions. In the dry state, the fibers and threads are typically tightly bound, creating resilient connections that provide structural integrity and strength. However, when exposed to wet or damp conditions, these connections weaken, making textiles more prone to breakage and distortion. Consequently, the threads and fibers become more susceptible to separation, breakage, or pull-out from the fabric surface, resulting in increased mass loss. Additionally, moisture absorbed by the fabric contributes to its weight, further increasing the overall mass loss. Visual comparisons of the fabric's appearance before and after testing reveal significant differences in mass loss, as shown in Figures 7(a, b, c, d, e, and f). These images display the fabric's state before and after 75 cycles of abrasion testing under various conditions, including dry and wet states, using different grades of sandpaper. Based on the images, it is evident that Carbon fabric experiences greater mass loss compared to Kevlar fabric. The images also illustrate the extent of damage and deterioration on the surface of the Carbon fabric in contrast to the Kevlar fabric. Furthermore, it is worth noting that mass loss is larger in the wet state compared to the dry state, with sweat testing resulting in higher mass loss than water testing. It should be emphasized that the abrasion resistance of textile materials is a complex phenomenon influenced by various factors, including fiber, yarn, fabric features, and finishing techniques. Some of these factors impact the fabric's surface, while others affect its internal structure [37].

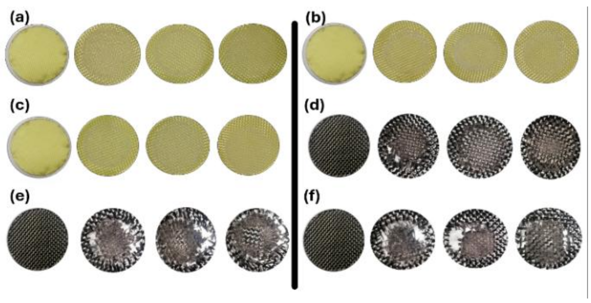

Fig. 7. The failure modes before and after 75 abrasion cycles for a) Kevlar dry, b) Kevlar pure water, c) Kevlar sweat, b) carbon dry, e) carbon pure water, f) carbon sweat

It has been observed that fabric samples tested with P500 sandpaper exhibited higher mass loss compared to those tested with P1000 and P1200, indicating increased abrasion damage. The higher mass loss observed with P500 sandpaper can be attributed to its coarser grit size. Coarser grits contain larger abrasive particles, which cause more fiber damage and material loss during the abrasion cycle. Conversely, finer grits (P1000 and P1200) have smaller abrasive particles, resulting in a gentler abrasion process with less fiber breakage and material loss. When comparing the differences in mass loss with the number of abrasion cycles, it is evident that the samples experience greater mass loss as the cycles increase. Cycles 50 and 75 show more mass loss than cycle 25, with cycle 75 showing the highest mass loss.

4. CONCLUSION

This study emphasizes the importance of understanding material behavior for advancing sustainability in industries such as aerospace, automotive, and protective clothing, where high-performance textiles are crucial. The results from tensile tests revealed that material orientation and environmental conditions significantly influence tensile strength. Specifically, dry conditions consistently yielded better results than wet conditions. For composite materials, Carbon/Epoxy exhibited superior strength and stiffness, with a tensile strength of 391.85 MPa in the warp direction, compared to Kevlar/Epoxy, which showed a tensile strength of 358.63 MPa in the same direction. Hybrid Kevlar-Carbon composites demonstrated a balanced performance, with a tensile strength of 372.04 MPa in the warp direction, combining the strengths of both Kevlar and Carbon fibers, making them suitable for applications requiring both strength and flexibility. Sweat simulation reflects realistic operational environments in applications such as military uniforms, firefighting suits, and aerospace seat structures, where body perspiration or saline air can degrade fabric integrity.

Furthermore, abrasion tests indicated that wet conditions led to increased mass loss for both fabric types. Under pure water conditions, Kevlar fabric showed a mass loss of 0.6014% at 25 abrasion cycles with P500 sandpaper, while Carbon fabric exhibited a higher mass loss of 0.7729% under the same conditions. In sweat simulation tests, the mass loss increased further, with Kevlar fabric showing a loss of 0.6518% and Carbon fabric 0.8834%. Kevlar consistently outperformed Carbon in terms of abrasion resistance, particularly in wet conditions, due to its superior strength and durability.

These findings highlight the importance of careful material selection and the consideration of environmental conditions in optimizing performance characteristics such as strength, stiffness, flexibility, and durability. Future research should focus on further exploring the impact of different environments, fabric structures, and textile treatments to enhance the sustainability and performance of materials across various applications, aiming to improve long-term material lifespan and reduce the environmental footprint of textile production and use. While triplicate samples were used to ensure consistency, further statistical analysis (e.g., ANOVA) will be applied in future studies to validate differences across environmental conditions. Future work should explore the use of hydrophobic coatings, fibre sizing agents, or nano-fillers to enhance moisture resistance and reduce the performance drop observed under wet conditions.

REFERENCES

1. Rajesh S, Ramnath BV, Elanchezhian C, Abhijith M, Riju RD, Kishan KK. Investigation of tensile behavior of Kevlar composite. Mater Today Proc. 2018; 5: 1156-1161.
2. Suthan R, Jayakumar V, Madhu S. Evaluation of mechanical properties of kevlar fibre epoxy composites: an experimental study. Int. J. Veh. Struct. Syst. 2018; 10: 389-394.
3. Yeung KH and Rao K. Mechanical properties of Kevlar-49 fibre reinforced thermoplastic composites. Polym Polym Compos. 2012; 20: 411-424.
4. Agarwal G, Johri N. Experimental investigations on mechanical properties and abrasive wear response of glass, kevlar and carbon fabric reinforced composites. Mater Today Proc. 2021; 46: 7966-7972.
5. AL-Qrimli HF, F. A. Mahdi FA, Ismail FB. Carbon/epoxy woven composite experimental and numerical simulation to predict tensile performance. Adv Mater Sci. 2015; 4:33-41.
6. Channabasavaraju S, Shivanand H, Santhosh K. Evaluation of tensile and flexural properties of polymer matrix composites. Int J Mod Eng Res. 2013; 3: 3177-3180.
7. Prabhuram T, Somurajan V, Prabhakaran S. Hybrid composite materials in Front Automot Mech Eng. 2010; 27-31.
8. Hashim N, Abdul Majid DL, Zahari R, Yidris N. Tensile properties of woven Carbon/Kevlar reinforced epoxy hybrid composite in Mater Sci Forum; 2017; 20-23.
9. Al Khaddour S, Ibrahim MB. Experimental Investigation on Tensile Properties of Carbon Fabric-Glass Fabric-Kevlar Fabric-Epoxy Hybrid Composite Laminates. J Compos Adv Mater; 2021; 31.
10. Priyanka P, Mali HS, Dixit A. Carbon–Kevlar intraply hybrid fabric polymer composites: mechanical performance. Iran Polym J. 2023; 32: 633-645.
11. Hossain MM, Khan M, Khan R, Siddiquee MAB, Islam T. Carbon/Kevlar reinforced hybrid composite: impact of matrix variation, in Proceedings of the Int Conf Mech Eng Renew Energy Chittagong. Bangladesh; 2015.
12. Karthik K, Rajamani D, Manimaran A, Udayaprakash J. Evaluation of tensile properties on Glass/Carbon/Kevlar fiber reinforced hybrid composites, Mater Today Proc. 2021; 39:1655-1660.
13. Lakshmaiya N, Surakasi R, Nadh VS, Srinivas C, Kaliappan S, Ganesan V et al. Tanning wastewater sterilization in the dark and sunlight using Psidium guajava leaf-derived copper oxide nanoparticles an and their characteristics. ACS Omega. 2023; 8: 39680-39689.
14. Velmurugan G, Chohan JS, Babu K, Paramasivam P, Maranan R. Biosynthesis of SiO2 nanoparticles from bamboo leaves for tanning wastewater treatment and mechanical properties of HMPC-SiO2 nanocomposite, Clean Technol Environ Policy. 2024; 1-20.
15. Natrayan L, Janardhan G, Nadh VS, Srinivas C, Kaliappan S, Velmurugan G. Eco-friendly zinc oxide nanoparticles from Moringa oleifera leaf extract for photocatalytic and antibacterial applications. Clean Technol Environ Policy. 2024; 1-13.
16. Velmurugan G, Chohan JS, Paramasivam P, Maranan R, Nagaraj M, Green marvel: Harnessing spinach leaves' power for enhanced photodegradation of various effluents with biogenic ZnO nanoparticles. Desalin Water Treat. 2024; 319: 100566.
17. Velmurugan G, Chohan JS, Babu K, Nagaraj M, Velumani A. Exploring the efficacy of biosynthesized cupric oxide nanoparticles from Jasminum Sambac flower extract in wastewater treatment: experimental investigations and potential applications. Desalin Water Treat. 2024; 319: 100570.
18. Velmurugan G, Chohan JS, Paramasivam P, Maranan R. Green synthesis of silver nanoparticles from southern Eucalyptus globulus: Potent antioxidants and photocatalysts for rhodamine B dye degradation. Desalin Water Treat. 2024; 320: 100687.
19. Natrayan L, Jayakrishna M, Shanker K, Muthu G, Kaliappan S, Velmurugan G. Green synthesis of silver nanoparticles using lawsonia inermis for enhanced degradation of organic pollutants in wastewater treatment. Glob NEST J. 2024; 26:10.30955.
20. Ganesan V, Shanmugam V, Alagumalai V, Kaliyamoorthy B, Das O, Misra M. Optimisation of mechanical behaviour of Calotropis gigantea and Prosopis juliflora natural fibre-based hybrid composites by using Taguchi-Grey relational analysis. Compos C Open Access. 2024; 13: 100433.
21. Jahan I. Effect of fabric structure on the mechanical properties of woven fabrics. Adv Res Text Eng. 2017; 2:1018.
22. ISO B. Textiles–tests for color fastness. Part E04: Colour fastness to perspiration; 2013 (BS EN ISO, 105-E04: 2013).
23. International A. Standard test method for tensile properties of polymer matrix composite materials: ASTM Int; 2007.
24. Kaynak HK, Topalbekiroğlu M. Influence of fabric pattern on the abrasion resistance property of woven fabrics. Fibres Text East Eur. 2008; 16: 54-56.
25. Radmanovac N, Ćirković N, Šarac T. The importance of the resistance to wear in the choice of fabrics for protective garments. Adv Technol; 2017; 6:81-87.
26. Özdil N, Kayseri GO, Mengüç GS. Analysis of abrasion characteristics in textiles. Abrasion Resist Mater. 2012; 2:119-146.
27. ISO E. Textiles–Determination of the Abrasion Resistance of Fabrics by the Martindale Method–Part 2: Determination of Specimen Breakdown; 1998.
28. Hossain MM, Datta E, Rahman S. A review on different factors of woven fabrics' strength prediction. Sci Res. 2016; 4: 88-97.
29. Abdellah MY, Alharthi H. Stress Analysis and Strength Prediction of Carbon Fiber Composite Laminates with Multiple Holes Using Cohesive Zone Models, Polym. 2025;17(1):124.
30. Mohamed AF, Abdellah MY, Hassan MK, Backar R. Advanced Prediction and Analysis of Delamination Failure in Graphite-Reinforced Epoxy Composites Using VCCT-Based Finite Element Modelling Techniques. Polym. 2025; 17(6): 771.
31. Sadek MG, Abdellah MY, Abdel-Jaber GT. A review on properties, applications and feasibility study of date palm fiber-reinforced polymer composites. SVU Int J Eng Sci Appl. 2024; 5: 50-61.
32. Mohammed Y, Hassan MK, Hashem A. Finite element computational approach of fracture toughness in composite compact tension specimen. Int J Mech Mechatron Eng. 2012; 12: 57-61.
33. Gamal M, Abdellah MY, Alharthi H, Abdel-Jaber G, Ahmed H. Backar, Characteristic Properties of Date-Palm Fibre/Sheep Wool Reinforced Polyester Composites, J Bioresour Bioprod. 2023, 8(4): 430-443.
34. Fahmy HS, Abdellah MY, Abdel-Jaber G, Hashem AM. Characteristic Properties of Glass Fiber Reinforced Sugarcane Bagasse Medium Density Fiber Board. Cienc Tecnol Mater. 2017; 29: 97–105.
35. Gelany A, Abdellah MY, Mohamed AF, Khoshaim AB, Protection of limestone Coated with Different Polymeric Materials. Am J Mech Eng. 2017; 5.
36. Abdellah MY, Hagag AAE, Marzok W, Hashem AF. Tensile and Fracture Properties of Chemically Treatment Date Palm Tree Fibre Reinforced Epoxy. Int J Mech Mechatron Eng IJMME-IJENS. 2019; 4: 40.
37. Fouad H, Moura AHI, Alshammari BA, Hassan MK, Abdellah MY, Hashem M. Fracture toughness, vibration modal analysis and viscoelastic behavior of Kevlar, glass, and carbon fiber/epoxy composites for dental-post applications. J Mech Behav Biomed Mater. 2020; 101: 103456.

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