Araştırma Makalesi / Research Article

INVESTIGATION OF PERFORMANCE CHARACTERISTICS OF CARBON, GLASS, BASALT HYBRID WOVEN FABRICS

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ABSTRACT*:* Hybrid textile composites reinforced with carbon, glass, and basalt fibers have gained significant attention due to their superior mechanical properties and lightweight nature. This study investigates the tensile and flexural behavior of hybrid composites produced using different fiber combinations. Basalt yarn (17 µm, 1200 tex) was used as the warp yarn in all samples, while 3K carbon, 12K carbon, E-glass (300 tex), and basalt (1200 tex, 17 µm) were used as weft yarns. The fabrics were woven in a plain weave structure and reinforced with an epoxy matrix using the hand lay-up method. Tensile and three-point flexural tests were conducted to evaluate the mechanical performance of the composites. The results showed that the glass/basalt hybrid composite exhibited the highest tensile strength in the warp direction, reaching 550 MPa, and the highest flexural strength at 740,4 MPa. In the weft direction, the 12K carbon/basalt hybrid composite achieved the highest tensile strength of 252 MPa, whereas the basalt/basalt composite had the highest flexural strength of 144 MPa. These findings indicate that fiber hybridization significantly affects the mechanical properties of composite materials, making them suitable for various engineering applications.

Keywords: Hybrid fabrics, composite materials, basalt fiber, carbon fiber, glass fiber, mechanical properties

KARBON, CAM, BAZALT HİBRİT DOKUMA KUMAŞLARIN PERFORMANS ÖZELLİKLERİNİN İNCELENMESİ

ÖZ: Hibrit tekstil kompozitleri, üstün mekanik özellikleri ve hafif yapıları nedeniyle giderek daha fazla ilgi görmektedir. Bu çalışmada, farklı lif kombinasyonları kullanılarak üretilen hibrit kompozitlerin çekme ve eğilme davranışları incelenmiştir. Tüm numunelerde çözgü ipliği olarak bazalt ipliği (17 µm, 1200 tex) kullanılmış, atkı ipliği olarak ise 3K karbon, 12K karbon, E-cam (300 tex) ve bazalt (1200 tex, 17 µm) iplikleri tercih edilmiştir. Kumaşlar bezayağı örgü yapısında dokunmuş ve el yatırma yöntemiyle epoksi matris ile güçlendirilmiştir. Kompozitlerin mekanik performansını değerlendirmek için çekme ve üç nokta eğilme testleri uygulanmıştır. Elde edilen sonuçlara göre, çözgü yönünde en yüksek çekme dayanımı 550 MPa ve en yüksek eğilme dayanımı 740,4 MPa ile cam/bazalt hibrit kompozitinde gözlemlenmiştir. Atkı yönünde yapılan testlerde ise 12K karbon/bazalt hibrit kompoziti en yüksek çekme dayanımına (252 MPa) sahip olurken, bazalt/bazalt kompoziti en yüksek eğilme dayanımını (144 MPa) göstermiştir. Bu bulgular, lif hibritizasyonunun kompozit malzemelerin mekanik özelliklerini önemli ölçüde etkilediğini ve çeşitli mühendislik uygulamaları için uygun hale getirdiğini göstermektedir.

Anahtar Kelimeler: Hibrit kumaşlar, kompozit malzemeler, bazalt lifi, karbon lifi, cam lifi, mekanik özellikler

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1. INTRODUCTION

Composite materials have been used across various industries, from automotive to aviation, since the 1940s [1]. Generally, composites consist of two main components: a matrix and a reinforcement. The primary source of strength in composite materials is the reinforcing fibers, which provide durability and flexibility. Additionally, these fibers distinguish composite materials from traditional options, such as steel, by offering significant lightness. The matrix material's primary role is to bind the fibers together [2,3]. Thermoplastic and thermoset matrices are the most widely used types of matrix materials. Thermoplastics, which have linear chain molecules, can be repeatedly melted or reprocessed, though they are limited by high expansion and viscosity [4]. As a result, thermoset matrices are more commonly used in many sectors [5]. Thermoset materials cannot return to their original forms once shaped. Examples of thermoset matrix materials include polyester, epoxy, high-temperature resins, phenolics, silicones, polyamides, polyurethanes, and cyanate esters. Textile-based composites have high strength, modulus, corrosion, and fatigue resistance. Additionally, textile-based composites facilitate the construction of complex geometric parts [1]. High-performance fibers such as carbon, glass, and basalt are used as reinforcement elements in composites.

Textile-based composites are a prominent category within composite materials due to their high strength-to-weight ratio, corrosion resistance, and fatigue resistance. Moreover, these composites facilitate the manufacturing of complex geometric components [1]. High-performance fibers such as carbon, glass, and basalt are commonly used as reinforcements in textile-based composites.

Carbon fibers have been utilized in polymer composites since the 1960s due to their exceptional mechanical properties, high thermal and electrical conductivity, and toughness [6]. Carbon fiber composites are widely used in aerospace, automotive, wind energy, construction, and marine applications. Carbon fibers can be derived from various precursors such as polyacrylonitrile (PAN), mesophase pitch, rayon, and other polymer-based materials [7]. The mechanical properties of carbon fibers obtained from various precursors are given in the table below.

Glass fibers are another widely used reinforcement due to their high tensile strength, good electrical insulation, non-flammability, and resistance to chemical degradation. E-glass fibers, the most used type, exhibit a tensile strength of 2700-3000 MPa, an elastic modulus of 72-76 GPa, and an elongation at break of 2.5% [8-10]. These properties make glass fiber composites suitable for aerospace, marine, automotive, and electronic applications.

Basalt fibers, produced by melting and spinning volcanic rock, have gained attention as an environmentally friendly alternative to synthetic fibers. Unlike glass fibers, basalt fibers do not require additives during production. They exhibit high tensile strength (3000-3400 MPa), a modulus of 86-90 GPa, and an elongation at break of 3.2% [9-12]. Basalt fibers offer excellent thermal and chemical stability, high resistance to weathering, and superior sound and heat insulation. Although basalt fibers are denser and more expensive than glass fibers, they are more cost-effective than carbon fibers, making them a viable alternative in composite applications, including aerospace, automotive, construction, and fire-resistant materials.

Hybrid composites integrate different types of fibers within a single matrix to achieve enhanced mechanical properties while optimizing cost-effectiveness. Hybridization can be achieved through various configurations, including interlayer, intralayer, and intra-yarn hybridization. The interlayer configuration involves stacking different fiber layers, whereas the intralayer method incorporates different yarns within a single layer. Intra-yarn hybridization blends multiple fibers within a single yarn structure [13,14]. Numerous studies have investigated the mechanical performance of hybrid composites with various fiber combinations. For example, El-Baky et al. (2022) studied flax/basalt/E-glass hybrid composites, while Guo et al. (2021) examined the effect of interlayer and intra-yarn hybridization on carbon/glass fiber-reinforced composites [14,15]. Similarly, Chen et al. (2019) analyzed the bending performance and cost efficiency of carbon/basalt/glass hybrid laminates, and Sapuan et al. (2020) explored the mechanical properties of basalt/glass sandwich structures [2,16]. Kufel et al. (2021) investigated the mechanical properties of basalt/glass hybrid composites at various temperatures [9].

Although the use of basalt fibers in hybrid composites has gained attention in recent years, most studies focus on interlayer or fiber-mixed hybridization rather than woven fabric structures. The novelty of this study lies in the use of woven hybrid fabrics, where basalt yarn is integrated as the warp material and hybridized with carbon and glass fibers as weft yarns. This approach has rarely been explored in the literature and provides a unique perspective on the mechanical performance of hybrid textile composites.

Table 1. The mechanical properties of carbon fibers obtained from various precursors [6]

Precursors	Tensile Strength (MPa)	Modulus (GPa)	Elongation at break (%)
PAN	2500-7000	250-400	0.6-2.5
Mesophase pitch	1500-3500	200-800	0.3-0.9
Rayon	≈1000	≈50	≈2.5

This study aims to investigate the tensile and flexural properties of hybrid fabric composites produced by weaving basalt yarn as warp and hybridizing it with 3K carbon, 12K carbon, E-glass (300 tex), and basalt (1200 tex) yarns as weft. The fabric structures were reinforced with epoxy resin using the hand lay-up method, and mechanical tests were conducted to evaluate their performance. The findings of this study contribute to the development of sustainable and high-performance textile-based hybrid composites.

2. MATERIALS AND METHOD

2.1. Yarns Used in Reinforcing Woven Fabric Structures

In this study, hybrid and non-hybrid woven fabrics were produced using 3K carbon/basalt, 12K carbon/basalt, glass/basalt, and basalt/basalt fiber combinations. The notation "K" in carbon fibers (e.g., 3K and 12K) refers to the number of carbon filaments in the yarn, with 3K containing 3,000 fibers and 12K containing 12,000 fibers. As a result, 12K carbon yarn has a thicker structure compared to 3K carbon yarn. The main properties of the carbon reinforcement yarns used in this study, as provided by the manufacturers, are summarized in Table 2.

Table 2. Characteristics of 3K and 12K carbon yarn

Property	3K Carbon	12K Carbon
Tensile Modulus (GPa)	245	254
Tensile Strength (MPa)	4227	5015
Yarn Number (g/1000m)	201	805
Density (g/cm^3)	1.79	1.8
Elongation (%)	1.7	2

The glass yarns used in the production of reinforcement fabrics are E-glass yarns with a linear density of 300 tex. E-glass is preferred over other types of glass in composite manufacturing due to its superior tensile strength and Young’s modulus. The technical specifications of the glass yarns, as provided by the manufacturer, are presented in the table below.

Table 3. Characteristics of glass yarn

Property	E-Glass
Monofilament diameter (µm)	13
Linear density (tex)	300
Tensile Strength (MPa)	2673
Tensile Modulus (GPa)	81
Shear Strength (MPa) with epoxy	70

The basalt yarns used in the reinforcement of woven fabric structures have a filament diameter of 17 µm and a linear density of 1200 tex. The technical properties of the basalt yarns, as provided by the manufacturer, are presented in the table below. The reinforcement fibers were supplied by [Spinteks, Turkey].

Table 4. Characteristics of basalt yarn

Property	Basalt Yarn
Monofilament diameter (µm)	17
Linear density (tex)	1200
Tensile Strength (MPa)	2900-3100
Tensile Modulus (GPa)	86

2.2. Production of Woven Fabric Structures

A modified Dornier rigid rapier weaving machine was used to produce woven fabric structures. The warp yarns were fed from a creel, while the weft insertion was carried out using a rapier system. The machine operated at 88 rpm with a weaving width of 150 cm and a reed number of 5. The produced fabrics had a width of 100 cm and a length of 2.5 m. The fabric constructions followed a plain weave pattern. Basalt yarn (1200 tex, 17 µm) was used as the warp in all fabric samples, while 3K carbon, 12K carbon, E-glass (300 tex), and basalt (1200 tex) were used as the weft. In Figure 1, the weaving, weft, drawing-in and carding plans of the woven fabrics obtained as samples are given. The physical properties of the woven fabrics are given in Table 5. The images of the woven fabrics produced in this study are shown in Figure2 for reference.

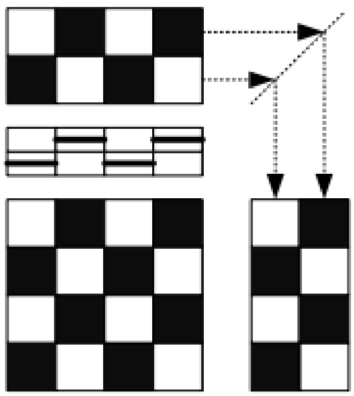

Figure 1. Plain weave construction
(weaving, weft, drawing-in and carding plans)

Table 5. Fabric Weight and Density

Weft Yarn	Warp Yarn	Fabric Weight (g/m²)	Weft Density (weft/cm)	Warp Density (warp/cm)
3K Carbon	Basalt	563	3	5
12K Carbon	Basalt	753	3	6
Glass	Basalt	542	3	6
Basalt	Basalt	856	3	6

Figure 2. 3K carbon/basalt, 12K carbon/basalt, basalt/basalt, glass/basalt fabrics respectively

2.3. Fabrication of Composite Structures

The composite structures were produced using the manual lay-up method with a single layer of reinforcing fabric. Epoxy resin was preferred as the matrix material. Epoxy resins have many excellent properties, including good chemical and solvent resistance, high mechanical strengths and industrially competitive material cost, and high degradation temperatures [17]. Huntsman MY-740 was used as the resin, and Huntsman HY-918 hardener was added to the resin as an auxiliary material.

The resin and hardener were mixed at a ratio of 100:85 and applied onto a 50 cm × 50 cm heat-resistant release film. A hand roller was used to ensure even distribution. The impregnated fabric was placed on the mold, covered with a release film, and deaerated using a roller to remove trapped air. Afterward, the composite plates were enpressed at 100°C for 3 hours and left to cure at room temperature for 24 hours (Figure 3). The thickness variations of the composites, influenced by the manual lay-up process, are presented in Table 8.

Table 6. Thickness of the Obtained Composites with Standard Deviation

Composite Type	Thickness (mm)
3K Carbon/Basalt	0.504 ± 0.011
12K Carbon/Basalt	0.654 ± 0.021
Basalt/Basalt	0.702 ± 0.015
Glass/Basalt	0.404 ± 0.011

Values represent the mean thickness and standard deviation (n = 5) of the composite specimens measured after fabrication. Then, it was cut on the CNC machine in suitable sample sizes.

2.4. Mechanical Testing of Composites

All mechanical tests were conducted under standard conditions, and five specimens per composite type were tested in accordance with ASTM standards.

2.4.1. Tensile Test

Tensile tests were performed according to ASTM D3039-76 using a universal testing machine (Figure 4). The test parameters were: Sample dimensions: 25 mm × 250 mm, grip distance: 150 mm, test speed: 2 mm/min (millimeters per minute), load cell: 100 kN (kilonewtons), environmental conditions: 23 ± 2 °C (degrees Celsius), 50 ± 10% RH (relative humidity)

2.4.2. Three Point Bending Test

Three-point bending tests were performed according to ASTM D790 to evaluate the flexural properties of the composites (Figure-5). The test setup included: Sample dimensions: 12.7 mm × 50.8 mm, support span: 25.4 mm, test speed: 1.2 mm/min, load cell: 5 kN, environmental conditions: 20 ± 2°C, 65 ± 4% RH.

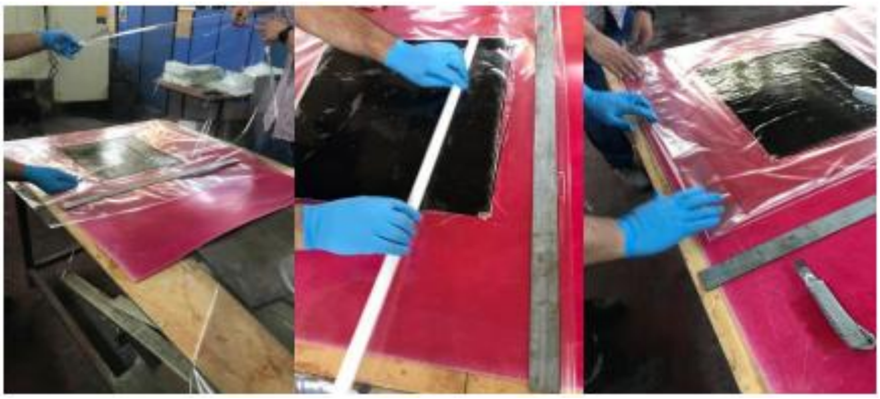

Figure 3. The process of applying the release film and removing the air within it using a roller.

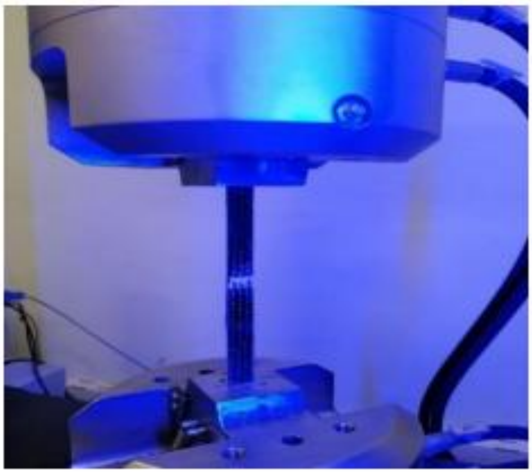

Figure 4. Tensile specimen at the point of failure during testing

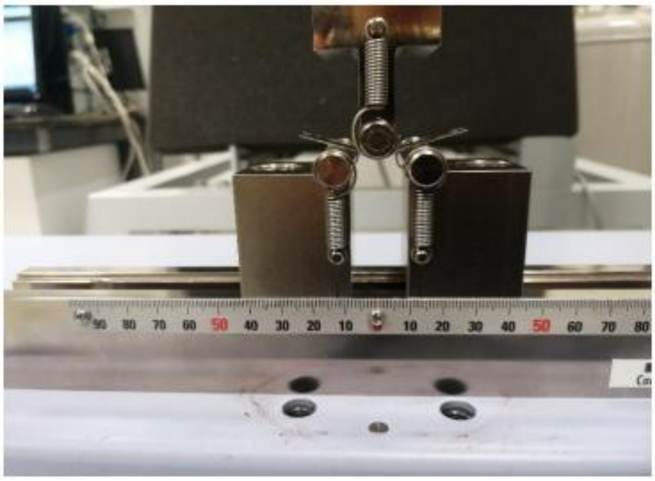

Figure 5. Test setup for the three-point bending test

2.5. Statistical Evaluation of Test Results

The test results were statistically evaluated using the Minitab Statistical Software package. A one-way analysis of variance (ANOVA) was conducted at a 95% confidence level. The resulting p-values were used to assess the statistical significance of the variations due to differences in raw material types. A p-value greater than or equal to 0.05 ($p \geq 0.05$) was interpreted as statistically insignificant, indicating that the observed differences could be considered negligible.

3. RESULTS

3.1. Tensile Strength Test Results

Tensile tests were performed in both the warp and weft directions of the hybrid and non-hybrid textile-reinforced composites. The key mechanical properties measured include maximum force (kN), stress at maximum force (MPa), elongation at maximum force (%), and modulus of elasticity (MPa). The results, along with their coefficient of variation (CV%), are summarized in Tables 7–10.

Table 7. 3K Carbon/Basalt Tensile Strength Result

TENSILE STRENGTH	3K Carbon/Basalt			
	Warp Direction		Weft Direction	
	Value	CV%	Value	CV%
Maximum Force (kN)	3.9±0.44	9.59	1.1±0.06	4.03
Stress at Maximum Force (MPa)	445±46.34	8.49	120±5.88	4.28
Elongation at Maximum Force (%)	1.6±0.25	12.6	2.2±0.06	2.4
Modulus of Elasticity (MPa)	29414±1165	1.71	7415±1777	20.76

Table 8. 12K Carbon/Basalt Tensile Strength Results

TENSILE STRENGTH	12K Carbon/Basalt			
	Warp Direction		Weft Direction	
	Value	CV%	Value	CV%
Maximum Force (kN)	4.1±0.31	6.47	3.5±0.05	1.41
Stress at Maximum Force (MPa)	289±20.40	6.9	252±7.89	2.80
Elongation at Maximum Force (%)	1.9±0.20	9.4	2.6±0.07	2.29
Modulus of Elasticity (MPa)	18393±740	3.18	15688±889	3.65

Table 9. Glass/Basalt Tensile Strength Results

TENSILE STRENGTH	Glass/Basalt			
	Warp Direction		Weft Direction	
	Value	CV%	Value	CV%
Maximum Force (kN)	4.2±0.58	11.57	0.20±00.1	4.19
Stress at Maximum Force (MPa)	550±73.10	11.85	28±1.40	4.35
Elongation at Maximum Force (%)	1.59±0.20	11.80	1.15±0.29	22.04
Modulus of Elasticity (MPa)	37502±1869	5.29	7835±1047	11.57

Table 10. Basalt/Basalt Tensile Strength Results

TENSILE STRENGTH	Basalt/Basalt			
	Warp Direction		Weft Direction	
	Value	CV%	Value	CV%
Maximum Force (kN)	3.9±0.13	3.42	3.3±0.10	3.59
Stress at Maximum Force (MPa)	298±9.68	2.84	237±7.68	3.06
Elongation at Maximum Force (%)	1.9±0.09	3.3	2.65±0.04	1.33
Modulus of Elasticity (MPa)	18771±546	2.30	15117±213	1.47

Table 7-10 Summary:

The maximum force values in the warp direction were consistently higher than in the weft direction for all composite types.

The highest stress at maximum force in the warp direction was obtained in glass/basalt hybrid composites (550 MPa), while in the weft direction, 12K carbon/basalt composite showed the highest stress value (252 MPa).

The elongation at maximum force was generally higher in the weft direction, except for glass/basalt composites, where the warp direction exhibited a greater elongation percentage.

The modulus of elasticity was always greater in the warp direction, with glass/basalt composites displaying the highest modulus (37.5 GPa).

Discussion on Weft-Warp Differences:

The warp direction demonstrated superior mechanical performance due to the higher tension in warp yarns during weaving, reducing crimp and increasing load-bearing capacity.

The differences in stress at maximum force across composites can be attributed to fiber fineness, the folding effect, sizing, and shear strength of the weft yarns. Glass fibers had lower resistance to shear forces, which contributed to their reduced tensile strength in the weft direction.

The modulus of elasticity followed a similar trend, with the highest values observed in the warp direction.

The results in the tables are analyzed in graphics (Figure 6-9).

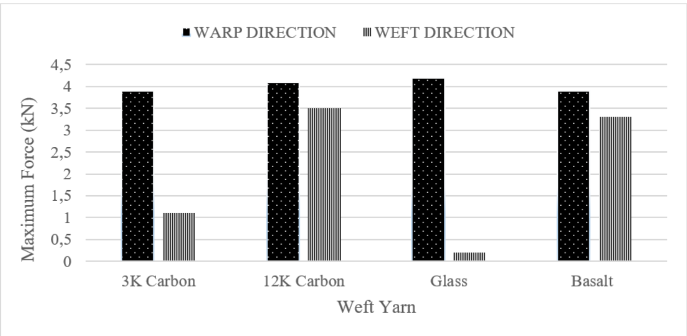

Figure 6. Comparison of maximum force (kN) in warp and weft directions

As shown in Figure 6, the maximum force was consistently observed in the warp direction across all samples, with warp-direction values demonstrating relatively low variability. In contrast, in the weft direction, the maximum force values for the 12K carbon and basalt composites were both similar to each other and relatively close to their corresponding warp values. The largest discrepancy between warp and weft directions was recorded in the glass fiber-reinforced composite. This variation is attributed to the inherently higher tensile strength of carbon and basalt fibers compared to E-glass. Furthermore, the lower maximum force observed in the 3K carbon composite compared to the 12K carbon is likely due to the smaller filament count and finer yarn structure in the 3K configuration.

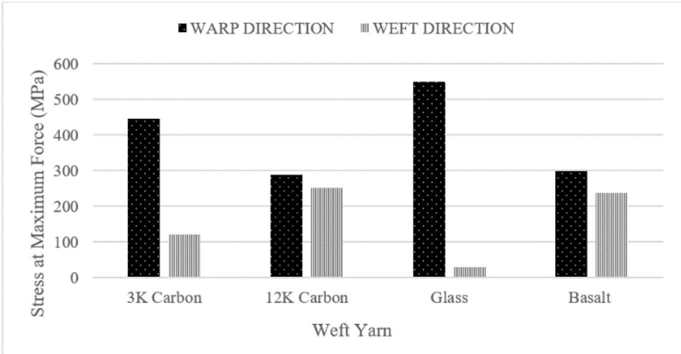

Figure 7. Comparison of stress at maximum force (MPa) in the warp and weft directions

As illustrated in Figure 7, the stress at maximum force was consistently higher in the warp direction for all composite types. In the weft direction, the 12K carbon and basalt composites showed stress values close to their warp counterparts and to each other. The most significant discrepancy between warp and weft directions was observed in the glass fiber-reinforced composite. Interestingly, the warp-direction stress values of the glass and 3K carbon composites were higher than those of the 12K carbon and basalt composites.

Although the same yarn was used in the warp direction across all samples, the differences in warp-direction stress values can be attributed to the influence of the weft yarn on the overall composite structure. Factors such as yarn fineness, folding effect, sizing (surface coating), and shear resistance of the weft yarn play a role in this interaction. Finer yarns tend to have less structural influence due to their lower volume. Conversely, a higher number of folds in the weft yarn can significantly affect the strength contribution of the warp yarn. Variations in sizing determined by the manufacturer—can also influence interfacial adhesion and ultimately tensile performance.

The lower tensile performance of glass weft yarns is likely due to their finer diameter and inherently lower resistance to shear forces. Consequently, the stress at maximum force in the warp direction of the glass/basalt hybrid composite was higher than that of the other configurations.

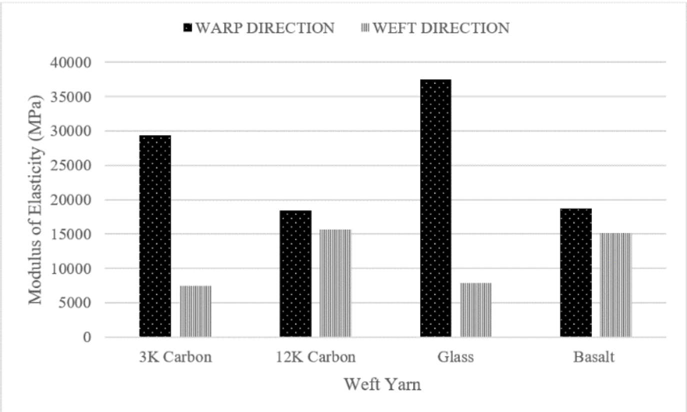

Figure 8. Comparison of elastic modulus (MPa) in the warp and weft directions

As shown in Figure 8, the highest elastic modulus was consistently observed in the warp direction, with the glass fiber composite exhibiting the greatest value. The modulus of elasticity, which represents a material's resistance to elastic deformation, is typically higher in the warp direction due to the higher pre-tension and alignment of yarns compared to the weft direction.

The reason why the glass/basalt hybrid composite exhibits the highest modulus in the warp direction is consistent with its behavior under maximum stress. The relatively low influence of glass yarns in the weft direction on the mechanical behavior of basalt yarns in the warp direction contributes to this result. In contrast, other weft yarn types have a more pronounced effect on the warp yarn performance.

In the weft direction, 12K carbon and basalt composites showed modulus values close to both each other and to their respective warp values. The most significant difference between warp and weft modulus values was observed in the glass fiber composite. Additionally, in the weft direction, 12K carbon exhibited the highest modulus, followed by basalt, 3K carbon, and lastly, glass fiber.

As presented in Figure 9, the highest percentage elongation at maximum force was observed in the weft direction for the 3K carbon, 12K carbon, and basalt composites. This is attributed to the structural characteristics of woven fabrics, where the warp yarns are held under tension and the weft yarns are more crimped, allowing for greater extension under load. In contrast, the glass fiber composite exhibited a higher elongation value in the warp direction. Among all tested composites, glass fiber showed the lowest elongation at maximum force, which is likely due to its lower crimp and limited flexibility compared to other yarn types.

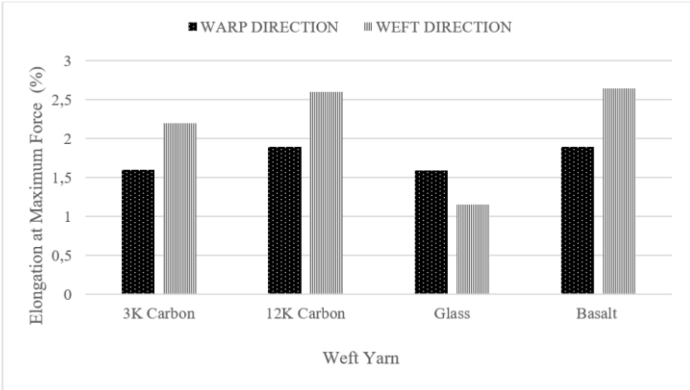

Figure 9. Comparison of elongation at maximum force (%) in the warp and weft directions

The tensile strength results demonstrated a consistent trend in which the warp direction provided superior performance compared to the weft direction across all hybrid composites. This behavior is mainly attributed to the pre-tensioned nature of warp yarns during fabric production, which aligns with findings from Guo et al. (2022) [14]. Their study revealed that interlayer hybrid composites, particularly those combining carbon and glass fibers, displayed higher tensile strength in the warp direction due to better load-bearing alignment and reduced interfacial debonding between fiber layers. Furthermore, they noted that hybridization enhanced the pseudo-ductility effect, where brittle carbon fibers fail first, allowing ductile fibers like glass or basalt to continue absorbing the tensile load, thereby increasing structural safety. These mechanisms provide an explanation for the observed behavior in this study, particularly the superior warp-direction tensile performance of the Glass/Basalt and 12K Carbon/Basalt hybrids. The interaction between warp and weft yarns, including yarn fineness, folding effects, and interfacial bonding quality, further influences the overall tensile response of the laminate. Poyyathappan et al. (2014) also reported that the inclusion of carbon fibers in glass-based laminates significantly improved tensile strength under cyclic loading conditions, supporting our observation that carbon/basalt hybrids showed enhanced performance over glass/basalt and basalt/basalt combinations [18].

The values presented in Table 11 were obtained by relating the specific strength to the fabric weight of each composite.

Table 11. Specific Strength Values of Composites Based on Density

Composite Type	Density (g/cm^3)	Warp Strength (MPa)	Weft Strength (MPa	SPECIFIC STRENGTH (WARP) (MPA.cm^3/g)	SPECIFIC STRENGTH (WEFT) (MPA.cm^3/g)
3K CARBON/BASALT	1.78	445±46.34	120±5.88	250.00 ± 25.84	67.42 ± 3.30
12K CARBON/BASALT	1.76	289±20.40	252±7.89	163.74 ± 11.56	142.78 ± 4.47
GLASS/BASALT	2.02	550±73.10	28±1.40	272.28 ± 36.19	13.86 ± 0.69
BASALT/BASALT	2.05	298±9.68	237±7.68	145.37 ± 4.72	115.61 ± 3.75

As demonstrated in Table 11, the specific strength values of the composites, calculated based on density, demonstrate significant variations depending on the material content and structure direction. In general, the specific strength values obtained in the warp direction are higher than the weft direction in all composites. This phenomenon can be attributed to the fact that yarns in the warp direction are placed tauter during the manufacturing process and are in straight alignment, thereby enhancing their load-bearing capacity.

The glass/basalt composite demonstrated the highest specific strength value (272.28 ± 36.19 MPa.cm³/g) in the warp direction. The superior performance of the Glass/Basalt composite can be attributed to the high mechanical properties of the basalt fibers utilized in the warp direction, along with the reduced effect of the glass fibers in the weft direction. Conversely, the composite exhibited the lowest specific strength value (13.86±0.69 MPa.cm³/g) in the weft direction. This is attributable to the fact that glass fibers exhibit reduced capacity to bear loads in the weft direction, a phenomenon attributable to their comparatively lower crimp ratio and reduced resistance to shear forces.

The 3K Carbon/Basalt composite exhibited the second highest performance in the warp direction with a specific strength of 250.00 MPa·cm³/g. However, the corresponding value in the weft direction was considerably lower (67.42±3.30 MPa·cm³/g), which can be attributed to the finer structure and lower volume of the 3K carbon yarn. As a result, its contribution to the mechanical behavior of the warp-direction basalt yarns was limited.

In contrast, the 12K Carbon/Basalt composite demonstrated a more balanced performance in both directions. The specific strength in the weft direction (142.78±4.47 MPa·cm³/g) was notably high, suggesting that the coarser 12K carbon yarns provided structural reinforcement to the warp-direction basalt fibers. The higher tex value of these yarns likely enhanced load transfer across the composite.

The Basalt/Basalt composite presented consistent and stable results in both directions, owing to its homogeneous reinforcement structure. With specific strength values of 145.37±4.72 MPa·cm³/g in the warp and 115.61±3.75 MPa·cm³/g in the weft direction, this configuration reflects reduced directional dependence and a uniform stress distribution throughout the composite.

3.2. Three Point Flexural Strength Test Results

Flexural tests were conducted to evaluate the bending behavior of the composites. Tables 12 summarize the maximum force, stress at maximum force, elongation at maximum force, and modulus of elasticity for the tested samples.

The three-point bending test results reveal significant differences in flexural performance among the hybrid composites. The highest flexural stress was observed in the Glass/Basalt composite in the warp direction (740.4 ± 62.6 MPa), attributed to the inherent rigidity of the glass fibers and their interaction with basalt fibers. Additionally, this composite exhibited the highest modulus of elasticity (23607 ± 3295 MPa), indicating superior flexural stiffness.

Table 12. Flexural Strength Test Results of Hybrid Composites (Mean ± SD)

Composite Type	Direction	Max Force (kN)	Flexural Stress (MPa)	Elongation (%)	Modulus of Elasticity (MPa)
3K Carbon/Basalt	Warp	44.4 ± 1.44	461 ± 37	3.6 ± 0.22	14032 ± 1538
	Weft	7.0 ± 0.25	68.9 ± 2.89	2.8 ± 1.29	8167 ± 672
12K Carbon/Basalt	Warp	81.0 ± 3.11	321.8 ± 9.6	5.0 ± 0.18	8934 ± 805
	Weft	36.5 ± 3.43	142.6 ± 11	5.2 ± 0.34	5906 ± 451.6
Glass/Basalt	Warp	51.6 ± 1.54	740.4 ± 62.6	3.21 ± 0.29	23607 ± 3295
	Weft	4.2 ± 0.56	54.2 ± 6.97	1.36 ± 0.32	4896 ± 958
Basalt/Basalt	Warp	75.4 ± 7.1	290.5 ± 38.6	5.51 ± 0.3	7620 ± 562
	Weft	41.5 ± 2.25	144.0 ± 14.7	5.76 ± 0.50	5361 ± 795

The Basalt/Basalt composite demonstrated the highest elongation in both directions (5.51 ± 0.3% warp, 5.76 ± 0.50% weft), reflecting its capacity to deform under load and its balanced structure due to the homogeneous fiber content.

The 12K Carbon/Basalt composite achieved the highest maximum force in the warp direction (81.0 ± 3.11 kN), though its flexural strength was lower than the Glass/Basalt composite. In the weft direction, it showed balanced performance with considerable elongation and stress values.

The 3K Carbon/Basalt composite presented relatively lower performance in the weft direction (68.9 ± 2.89 MPa), while showing moderate stiffness and strength in the warp direction. This suggests the influence of finer carbon fibers, which may contribute less structural support compared to their 12K counterparts.

In summary, glass-reinforced composites exhibited superior flexural strength and stiffness, basalt-reinforced composites excelled in flexibility, and carbon-reinforced composites offered a balance between the two.

The results in the tables are analyzed in graphics (Figure 10-13).

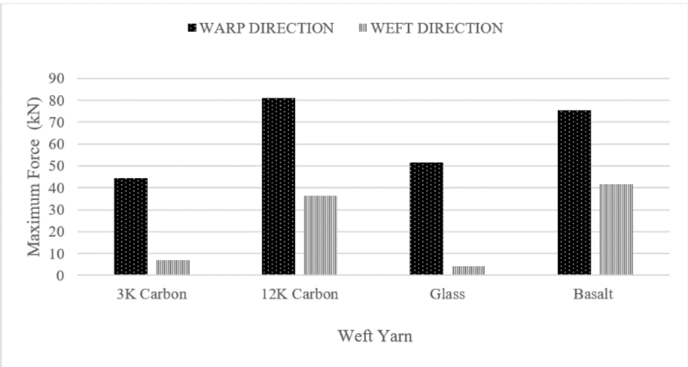

Figure 10. Maximum force (kN) graph in the weft and warp directions

In Figure 10, a significant discrepancy is observed between the maximum force values obtained in the warp and weft directions across all composite types. This difference primarily arises from the structural characteristics of the woven fabric: the warp yarns are more tensioned and aligned, thereby exhibiting greater resistance under flexural loading, while the weft yarns are crimped and less capable of bearing high loads.

Among the weft-direction results, 12K carbon and basalt-based composites yielded comparable maximum force values, which can be attributed to the inherently high tensile strengths of both fibers. In contrast, the E-glass yarn exhibited the lowest maximum force, reflecting its relatively lower mechanical strength. Additionally, the lower performance of 3K carbon in comparison to 12K carbon is explained by its finer yarn structure and reduced filament count, which limit its contribution to the overall load-bearing capacity.

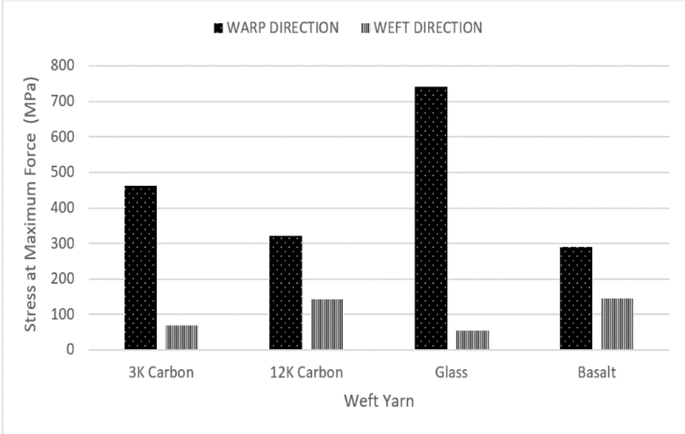

Figure 11. Stress at maximum force (MPa) graph in weft and warp directions

In Figure 11, the Glass/Basalt composite exhibits the highest stress at maximum force in the warp direction. The stress values of the other composites are relatively close to one another and notably lower than that of the glass-reinforced configuration. In the weft direction, the Glass/Basalt composite displays the lowest stress value, while the Basalt/Basalt composite demonstrates the highest. Overall, stress values in the weft direction are closer in magnitude compared to those in the warp direction.

Across all tested composites, the highest stress values were consistently recorded in the warp direction, emphasizing the structural advantage of warp yarns, which are generally more aligned and tensioned. The most pronounced difference between warp and weft values is observed in the Glass/Basalt composite. Although the same basalt yarn was used in the warp direction across all samples, the variation in warp-direction stress can be attributed to the influence of the weft yarns.

Specifically, the mechanical and structural properties of the weft yarn—such as fineness, crimp level, sizing (coating), and shear strength—play a critical role in the overall stress transfer and composite behavior. Finer weft yarns tend to exert less mechanical influence on warp yarns due to their lower volume and load-transfer capability. Conversely, increased crimp in the weft can amplify the stress imposed on the warp yarns during loading. Additionally, differences in yarn sizing, which vary by manufacturer, can significantly alter fiber–matrix adhesion and consequently impact stress distribution.

Given these factors, the E-glass yarn used in the weft direction is comparatively finer and possesses lower shear strength than the other fibers studied. This combination likely leads to reduced interaction with the warp yarn, thereby enabling the basalt yarn in the warp to sustain higher levels of stress. As a result, the hybrid composite with glass in the weft and basalt in the warp direction exhibited the highest stress at maximum force among the configurations.

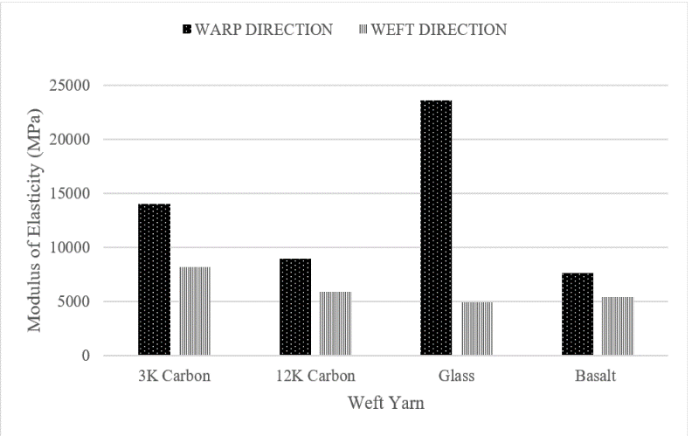

Figure 12. Modulus of elasticity (MPa) graph in weft and warp directions

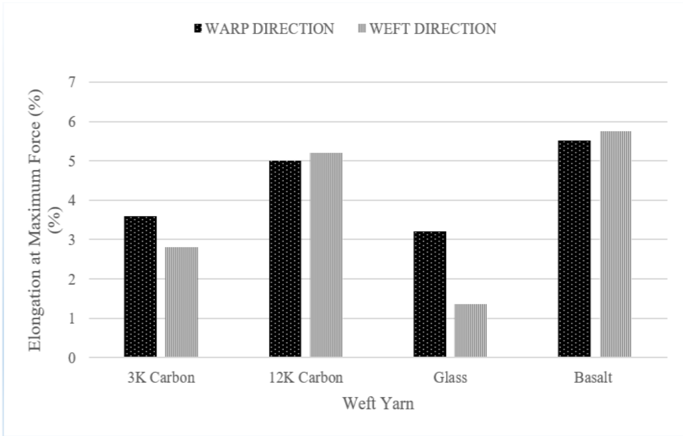

Figure 13. Elongation at maximum force (%) graph in weft and warp directions

In Figure 12, the Glass/Basalt composite exhibits the highest modulus of elasticity in the warp direction, indicating superior stiffness compared to the other configurations. This is followed by the 3K Carbon/Basalt composite, which also demonstrates relatively high stiffness. The 12K Carbon/Basalt and Basalt/Basalt composites show similar modulus values in the warp direction, both significantly lower than that of the glass-reinforced sample.

In the weft direction, the lowest modulus of elasticity was recorded for the Glass/Basalt composite, while the highest value was observed in the 3K Carbon/Basalt composite. The modulus values in the weft direction were generally close across all composites.

As expected, the modulus of elasticity was consistently higher in the warp direction for all composites. This is attributed to the higher tension, alignment, and structural contribution of warp yarns, which provide increased resistance to deformation during bending. The modulus of elasticity, defined as a material's resistance to elastic deformation, is inherently affected by yarn properties and orientation.

The notably high modulus in the warp direction for the Glass/Basalt composite corresponds with its peak stress at maximum force, reaffirming the role of glass fibers in enhancing rigidity when positioned in the load-bearing direction. Conversely, the influence of glass fibers in the weft direction is limited, due to their lower crimp and interaction with the warp basalt yarns.

In the weft direction, the 12K Carbon/Basalt and Basalt/Basalt composites produced similar modulus values, both higher than that of the glass composite but lower than the 3K Carbon/Basalt composite. The most significant difference in modulus between the warp and weft directions was observed in the Glass/Basalt system, highlighting the anisotropic behavior introduced by fiber type and orientation.

In Figure 13, the percentage elongation at maximum force is generally consistent between the warp and weft directions for most composites, except for the Glass/Basalt configuration, which exhibits a noticeable discrepancy. The Basalt/Basalt composite displays the highest elongation values in both directions, followed by the 12K Carbon/Basalt composite. The next in the ranking are the 3K Carbon/Basalt and Glass/Basalt composites, with the latter demonstrating the lowest elongation percentages among all configurations.

The lower elongation observed in the Glass/Basalt composite can be attributed to the reduced crimp and limited flexibility of glass fibers within the woven structure. The minimal folding (crimp) effect of glass fibers restricts their ability to deform under tensile loading, leading to reduced strain values compared to other fiber types.

The three-point bending test results revealed that all hybrid composites exhibited significantly higher flexural strength in the warp direction compared to the weft direction. This behavior is largely attributed to the inherent structural tension in warp yarns and their alignment during weaving. According to Guo et al. (2022), the improved mechanical performance in the warp direction of interlayer hybrid composites is due to enhanced fiber alignment, load transfer efficiency, and reduced interfacial delamination [14]. Similarly, Chen et al. (2019) emphasized that in hybrid configurations with stiff fibers such as carbon and glass placed near the outer layers (surface plies), these fibers bear the majority of the flexural load, especially in the warp direction [16]. This arrangement leads to higher stiffness and bending resistance, aligning with the observed superiority of Glass/Basalt and 12K Carbon/Basalt laminates in warp-oriented flexural tests. Dong (2024) further confirmed that hybridizing high-stiffness fibers like carbon and glass and positioning them at the outer plies significantly enhances the flexural strength of composite laminates. This supports our finding that Glass/Basalt laminates yielded the highest flexural strength [19]. Kadiyala et al. (2022) observed that introducing glass fibers into carbon composites increased strain-to-failure by 58% while improving overall flexural behavior, which is consistent with the ductile behavior observed in Basalt/Basalt and Carbon/Basalt systems in our results [20]. Altaee and Mostafa (2023) also demonstrated that the arrangement and distribution of reinforcing fibers significantly influence flexural properties, providing further validation for the effect of yarn positioning in hybrid composite performance [21].

3.3. Influence of Hybridization on Mechanical Properties

The results clearly demonstrate that hybridization has a substantial effect on the mechanical behavior of the composite structures. Notably:

The Glass/Basalt hybrid composite exhibited superior tensile and flexural rigidity, especially in the warp direction, attributed to the high stiffness of the glass fibers combined with the axial strength of basalt.

The 12K Carbon/Basalt composites provided a well-balanced strength distribution between the warp and weft directions, reflecting the structural reinforcement capacity of the thicker carbon yarns and their contribution to load transfer in both axes. The Basalt/Basalt composites displayed the highest elongation values, indicating enhanced ductility and potential for better energy absorption under mechanical stress.

These findings agree with El-Baky et al. (2022), who emphasized that hybridization enables tailoring of mechanical properties based on fiber type, volume fraction, and stacking configuration [15]. The strategic selection and arrangement of reinforcement fibers play a critical role in optimizing the composite's performance depending on the intended application.

3.4. Statistical Analysis of Results

Statistical evaluations were performed using one-way analysis of variance (ANOVA) at a 95% confidence level to determine the significance of differences in tensile and flexural properties among the composite groups. The analysis was applied separately for warp and weft directions across different fiber combinations.

In this context:

A p-value less than 0.05 ($p < 0.05$) indicates a statistically significant difference between groups.

A p-value greater than or equal to 0.05 ($p \geq 0.05$) suggests that the observed variations are not statistically significant.

The ANOVA results showed that the differences in mechanical performance particularly in tensile strength and modulus of elasticity were statistically significant between certain hybrid configurations (e.g., Glass/Basalt vs. Carbon/Basalt). These findings statistically reinforce the mechanical trends observed in the experimental data and support the influence of fiber type and orientation on overall composite behavior.

4. CONCLUSION

This study examined the tensile and flexural behaviors of hybrid composites reinforced with 3K carbon, 12K carbon, glass, and basalt fibers. Composite laminates were produced using basalt yarns in the warp direction and different fiber types in the weft direction, followed by mechanical testing through uniaxial tensile and three-point bending methods.

Based on the experimental findings:

- In carbon-based hybrid composites, increasing the yarn count (from 3K to 12K) improved tensile and flexural strength, but reduced elongation at maximum force.
- The Glass/Basalt hybrid composite exhibited the highest tensile and flexural strength in the warp direction, owing to the stiffness of the glass fiber and its synergistic effect with basalt.
- The 12K Carbon/Basalt composite demonstrated the highest tensile strength in the weft direction, while Basalt/Basalt showed the highest flexural strength in the same direction.
- The highest modulus of elasticity in the warp direction was recorded in the Glass/Basalt composite for both tests. In the weft direction, 12K Carbon/Basalt yielded the highest modulus in the tensile test, while 3K Carbon/Basalt led in the bending test.
- The Basalt/Basalt composite exhibited the highest elongation values in both warp and weft directions, indicating superior ductility.

These results highlight the potential of basalt fibers to substitute partially or entirely for carbon fibers in structural composites, particularly when balanced mechanical performance, cost-efficiency, and environmental considerations are priorities.

The hybridization of basalt with glass or carbon allows for tailoring mechanical behavior based on application needs. Given the natural abundance of basalt, especially in countries like Türkiye, integrating basalt fibers into textile-based composites presents an opportunity for sustainable and economically viable material development, particularly in fields such as defense, automotive, and health technologies.

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