Comparison of mechanical and flammability properties of thermoplastic and thermoset matrix glass fibre woven fabric composites

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ABSTRACT – REZUMAT

Comparison of mechanical and flammability properties of thermoplastic and thermoset matrix glass fibre woven fabric composites

This study aims to examine the mechanical and burning properties of composites made from twill (0°/0° and 0°/90° orientations) and plain fabrics using hybrid yarns produced by combining glass and polypropylene yarns with interwoven and intermingled methods. The properties of interwoven and intermingled hybrid fabric composites were compared with thermoset composites. Each composite (56% glass fibre content) plate is produced by combining eight fabrics with the same parameters using the press moulding technique. The effects of yarn and fabric weaving types on the results were examined in detail. When the results are examined, the breakage of glass fibres in intermingled hybrid yarns negatively affects the strength results. Therefore, composites made with intermingled hybrid yarn types and plain weave types of fabric had the lowest tensile strength value (132 MPa). The composite of twill woven fabrics produced with interwoven yarns arranged in 0°/0° orientation had the highest tensile strength of 315 MPa, and these results were very close to those of thermoset composites. Although the 0°/90° oriented twill composite showed a 2.3 times lower tensile strength value than the 0°/0° oriented twill composite, it had a 7.7 times higher value when bending strength values were taken into account. The main reason for this is that glass fibres contribute to the warp and weft directions. It has been observed that the composite consisting of plain fabrics woven with commingled hybrid yarns had the highest impact resistance. Additionally, when the combustion results were examined, it was concluded that the type of yarn and fabric weaving affected the burning rate. The slower combustion of hybrid commingled yarn composites resulted from fibreglass breakage during yarn production. These findings provide valuable insights into optimizing composite materials for specific applications, considering factors such as weaving pattern, fibre orientation, and mechanical performance.

Keywords: *glass fibre, polypropylene, twill, plain, interwoven, intermingled, yarns, composites*

Comparația proprietăților mecanice și de inflamabilitate ale compozitelor din țesături din fibră de sticlă termoplastică și matrice termofixată

Scopul acestui studiu este de a examina proprietățile mecanice și de ardere ale compozitelor din ţesături cu legătură diagonal (orientări 0°/0° și 0°/90°) și țesături cu legătură pânză folosind fire hibride produse prin combinarea firelor de sticlă și polipropilenă cu metode întrețesute și amestecate. Proprietățile compozitelor de țesături hibride întrețesute și amestecate au fost comparate cu cele termofixate. Fiecare placă compozită (56% conținut de fibră de sticlă) este produsă prin combinarea a opt țesături cu aceiași parametri folosind tehnica de turnare prin presare. A fost examinată în detaliu influența tipurilor de fire și țesături asupra rezultatelor. Când rezultatele au fost examinate, ruperea fibrelor de sticlă în fire hibride amestecate afectează negativ rezultatele rezistenței. Prin urmare, compozitele realizate cu fire hibride amestecate și țesătură cu legătură pânză au avut cea mai mică valoare a rezistenței la tracțiune (132 MPa). Compozitul din țesături cu legătură disgonal produse cu fire întrețesute dispuse în orientare 0°/0° a avut cea mai mare rezistență la tracțiune, de 315 MPa, iar aceste rezultate au fost foarte apropiate de cele ale compozitelor termofixate. Deși compozitul cu legătură diagonal orientat 0°/90° a prezentat o valoare a rezistenței la tracțiune de 2,3 ori mai mică decât compozitul cu legătură diagonal orientat 0°/0°, acesta a avut o valoare de 7,7 ori mai mare când au fost luate în considerare valorile rezistenței la încovoiere. Motivul principal pentru aceasta este că fibrele de sticlă contribuie pe direcțiile de urzeală și de bătătură. S-a observat că acel compozit format din țesături cu legătură pânză ţesute din fire hibride amestecate a avut cea mai mare rezistență la impact. În plus, când au fost examinate rezultatele arderii, s-a ajuns la concluzia că tipul de fir și legătura țesăturii au afectat viteza de ardere. Arderea mai lentă a compozitelor din fire hibride amestecate a rezultat din ruperea fibrei de sticlă în timpul producției de fire. Aceste descoperiri oferă informații valoroase despre optimizarea materialelor compozite pentru aplicații specifice, luând în considerare factori precum legătura ţesăturii, orientarea fibrelor și performanța mecanică.

Cuvinte-cheie*: fibră de sticlă, polipropilenă, legătură diagonal, legătură pânză, interţesut, amestecat, fire, compozite*

INTRODUCTION

Construction, automotive, and aerospace are just a few of the industries that have undergone a revolution because of the development of sophisticated composite materials [1, 2]. Utilizing glass fibre yarns with polypropylene (PP) to produce high-performance fabrics is one promising area of composite materials research [3]. Due to their higher mechanical characteristics and increased durability, these fabrics, created using twill and plain weaving techniques, offer a wide range of applications. Composite materials, made up of two or more constituent elements with different properties, have drawn a lot of attention recently because of their outstanding features and adaptability [4]. Due to their lightweight, chemical resistance, and production simplicity, PP composites have become highly sought-after materials in several industries [5]. Scientists have investigated the integration of reinforcing elements such as glass fibres into the PP matrix to enhance its mechanical performance further [6]. Glass fibres (GF) are great choices for reinforcing polymer matrices because of their strength, stiffness, and resilience to environmental conditions [7]. Due to their special combination of properties, hybrid yarns made from PP and GF have attracted a lot of attention in the development of composite materials [8]. The synergistic application of the inherent benefits of both materials is made possible by the coupling of PP and GF in hybrid yarns, producing composites with higher mechanical performance and increased durability [9, 10].

The longer reinforcing fibres were used in the thermoplastic matrix to increase the tensile and impact strengths of the composites [11]. In comparison to frequently used short glass fibres, the length of the long glass fibres used in the Glass Mat Thermoplastic composite is around twice as long [12]. Previous studies have shown that a composite that contains long glass fibres within a thermoplastic matrix exhibits higher mechanical strength and heat resistance [13, 14]. The addition of continuous reinforcing fibres has been used in thermoplastic composites to improve their mechanical and thermal properties [15]. Three different lines of research exist:

i) The periodic stacking of textiles made of continuous reinforcing fibres and the interlacing of thermoplastic films provide composite plates. The pressing procedure involves applying heat and pressure to these stacked layers. In general, using a hot press to fabricate composite plates is a simple process. However, efficiently impregnating reinforcing fibre textiles with these thermoplastics is difficult due to the high melt viscosity of thermoplastic films. This frequently results in the development of voids or mechanical flaws in the finished composite plates [6, 16].

ii) It has also been investigated whether continuous reinforcing fibres may be evenly distributed throughout thermoplastic tape or film. Due to its higher impregnation capabilities as compared to the alternate method of stacking fibre textiles and thermoplastic layers, this specific technology is widely used in a variety of industries. Additionally, this technique is frequently used to create thin, flat, and unidirectional tapes [17, 18].

iii) Thermoplastic filaments can mix with continuous reinforcement fibres (CRF), according to their capabilities. In this method, thermoplastic filaments and continuous reinforcing fibres are mixed by air-jetting, yielding a blended yarn made of both kinds of continuous fibres. In the weaving process of thermoplastic composite fabrics and textiles, the use of mixed yarn is appropriate [19]. The impregnation of continuous reinforcing fibres demonstrates a clear benefit over competing approaches, despite the procedure's inherent complexity. Additionally, the mechanical properties displayed by the resulting textiles and composites are carefully regulated by manipulating various textile designs. High tensile strengths between 340 and 790 MPa are required in the context of vehicle frames [20, 21]. Automobile fenders and bumpers, on the other hand, favour shock-absorbing qualities over mechanical strength, necessitating low amounts of the former. Although CRF/PP-based commingled yarns and composites do not yet possess the necessary mechanical properties to effectively replace strong metal vehicle frames, they can nevertheless be used to make car fenders and bumpers [22].

Furthermore, the placement of the reinforcing threads and any potential harm that may result from the integration procedures in woven materials substantially impact the mechanical properties of these composite constructions [23]. The acquisition of particular mechanical properties, like tensile strength and flexural stiffness, can result from the optimization of loop organization and density. Additionally, using tuck stitches, which involve keeping yarns in place when weaving, can potentially improve the localized thickness and stiffness of the fabric in specific areas [24]. This can therefore result in improved mechanical performance and characteristics in those particular locations. Weft and warp inlays include incorporating reinforcing strands into the woven fabric either continuously or sporadically, depending on which way the weft or warp is running [25]. Using this method permits careful manipulation and organization of the reinforcing yarns, which influences the anisotropic properties displayed by the composites. By changing the fibre orientation and distribution, the mechanical properties in various dimensions can be tailored to meet the requirements of a particular application [26]. Nevertheless, it is crucial to bear in mind that the integration procedures during the weaving process may potentially compromise the integrity of the reinforcing threads, thereby impacting the overall mechanical properties of the composites. Localized fibre breakage or damage to the interface between the fibres and the matrix material are two examples of possible effects that could arise from the inclusion of reinforcement yarns. It is essential for maintaining the integrity and effectiveness of the woven composites to comprehend and control these potential drawbacks. It is crucial to engage in careful consideration and optimization of these aspects to get the appropriate mechanical performance in woven composites [27].

Methods such as twisting or air texturing are used during intermingled yarn production, and these composites damage the reinforcement yarn and may lead to a decrease in mechanical properties [18]. This may lead to a decrease in composite performance [10, 28]. Our suggested method is to incorporate reinforcement and thermoplastic yarn into the fabric structure through separate loops and openings, thus minimizing the damage to the reinforcement yarn. In this way, a slight increase in composite performance is achieved. This process will also reduce the surplus production costs. The main goal of this research is to investigate the mechanical and combustion properties of plain weave and twill (0°/0° and 0°/90° directions) glass fibre-reinforced polypropylene matrix composites and to compare their performance with the glass fibre-reinforced thermoset composites. It is carefully researched how the type of yarn, weave, and fibre orientation affect several mechanical parameters, such as tensile strength, bending strength, impact damping, and combustion performance.

MATERIALS AND METHODS

In this study, textiles made of glass fibres (GF) and polypropylene (PP) yarns were combined to create thermoplastic-based composite materials. As reinforcement and matrix components, PP, GF and polyester resin were used, respectively. Table 1 provides the technical details of the materials used in the investigation.

The composite samples were created by interwoven and intermingled glass and polypropylene yarns, resulting in twill fabrics with orientations at 0°/0° and 0°/90°, as well as plain fabrics. Figure 1 displays the yarns used in the study. Y2-coded yarn is monofilament, while Y1, Y3, and Y4 are multifilament.

Interwoven yarns consist of Y1 (GF) and Y2 (PP), PP is used in the warp direction and GF is used in the weft direction (table 2). In the hybrid intermingled yarn specified with the code Y3. The glass fibres of thermoset composites produced to compare the mechanical properties of GF-reinforced PP matrix composites are Y4-coded yarn.

Table 3 provides detailed descriptions of the properties of the fabrics that make up composites. Figure 2 displays the fabrics made from Y1, Y2, Y3, and Y4 yarns. F1 refers to a fabric composed of PP that has been reinforced with GF. The fabric referred to as F1 is manufactured by employing PP fibre in the warp direction and GF in the weft direction. In contrast, F2 refers to the fabric type characterized by the utilization of hybrid intermingled yarn in the weaving process. F3 refers to the GF fabric that is used to create thermoset composites. The total number of fabric ply in all composite samples used is 8. All composite examples employed a total fabric ply number of 8. Table 4 provides information on the composite specimens' density, volumetric percentages, and fibre orientation.

Table 1

GF AND PP PROPERTIES EMPLOYED IN COMPOSITE STRUCTURES

Materials	Yarn diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Density (g/cm^3)	Melting point (°C)
PP	8	65	8.25	10	0.9	170
GF (E-glass)	14.5	3445	76	4.8	2.6	846
Polyester Resin	-	55	3.4	2.1	1.17	490

Table 2

TECHNICAL CHARACTERISTICS OF THE YARNS USED TO CREATE TEXTILES

Yarn codes	Yarn type	Tex (g/10,000 m)	Composition by weight (%)	Production method
Y1	GF	311	100% GF	Multi filament
Y2	PP	67	100% PP	Mono filament
Y3	GF-PP	444	60% GF – 40% PP	Multi filament
Y4	GF	135	100% GF	Multi Filament

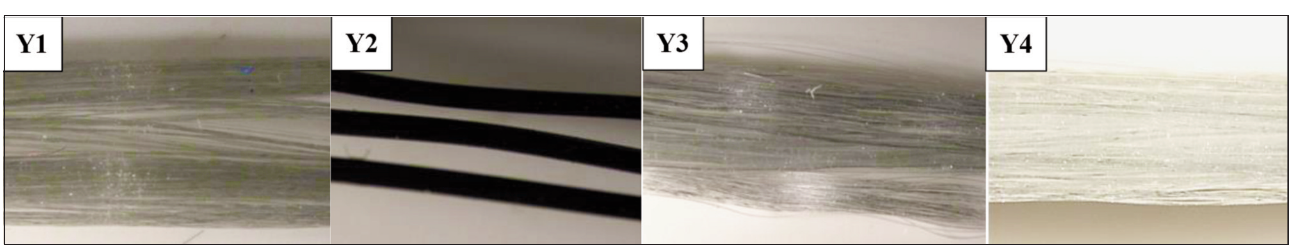


Fig. 1. The yarns applied in the study (X5)

Table 3

TECHNICAL CHARACTERISTICS OF THE YARNS USED TO CREATE TEXTILES					
Fabric codes	**Yarns used (weft/warp)**	**Density (number/cm)**		**Density (g/m^2)**	**Weave type**
		weft	**warp**		
F1	Y1/Y2	21 ± 3%	7 ± 3%	362	Twill
F2	Y3/Y3	5 ± 3%	5 ± 3%	360	Plain
F3	Y4/Y4	7 ± 3%	7 ± 3%	200	Plain

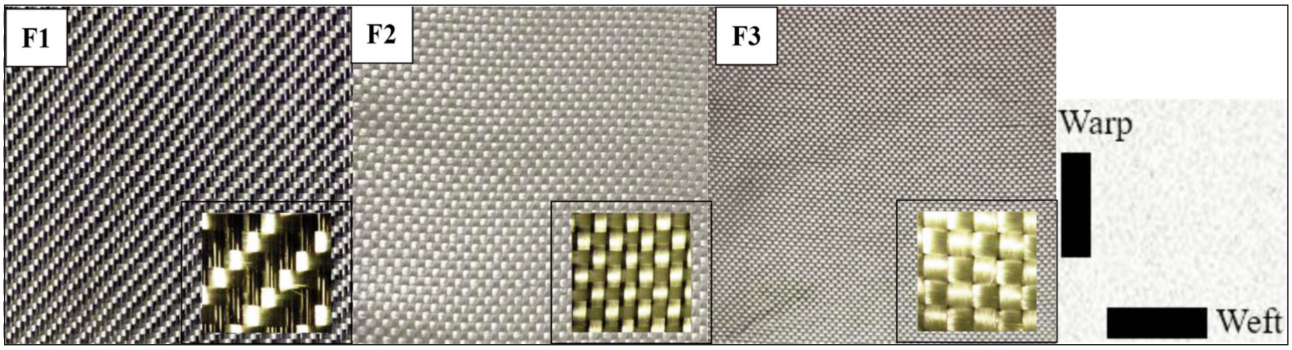


Fig. 2. Fabrics produced from the yarns

Bursa Technology Coordination and R&D Center (BUTEKOM) handled every stage of the production and testing of composite samples (hybrid yarn-fabric-composite).

A calliper was used to measure the thickness of the composite plates after they had been produced. Equation 1 was used to calculate the fibre volumetric fraction (V_f) based on the fabric weight and plate thickness:

$$V_f = \frac{n \cdot m}{\rho \cdot h} \times 100 \qquad (1)$$

where n (the fabric ply is eight), m (the nominal weight shown in table 4), ρ (fibre density), and h (plate thickness) are all given. For GF, the density is 2.6 g/cm^3. In table 4, C1 shows the unidirectional glass fibre array, while C2 and C3 show the bidirectional glass fibre array. In C2, composite plates were produced by stacking one ply in the 0-degree direction and the other in the 90-degree direction, while the unidirectional fabric was stacked on top of each other. Since C3 is an intermingled hybrid yarn, the fibre directions are bidirectional. C4 is a 56% GF-reinforced epoxy matrix composite.

The following equations were used to calculate the fibre volume fraction in the warp and fill directions separately:

$$m_{warp} = \frac{\delta_{warp} \cdot m}{10000} \times \frac{100 + \varphi_{warp}}{10000} \times T_{warp} \qquad (2)$$

$$m_{weft} = \frac{\delta_{weft} \cdot m}{10000} \times \frac{100 + \varphi_{weft}}{10000} \times T_{weft} \qquad (3)$$

where m_{warp} and m_{weft} are the areal weight of warp and weft yarns, respectively, δ is the yarn density per meter, φ is the yarn crimp percentage and T is the linear density in units of tex. The warp and fill subscripts indicate the yarns in the warp and fill directions. The fibre volume fractions in the warp and fill directions ($V_{f\text{-}warp}$ and $V_{f\text{-}weft}$) were separately identified as follows:

$$V_{f\text{-}warp} = \frac{n \cdot m_{warp}}{\rho_{warp} \cdot h} \times 100 \qquad (4)$$

$$V_{f\text{-}weft} = \frac{n \cdot m_{weft}}{\rho_{weft} \cdot h} \times 100 \qquad (5)$$

where ρ_{warp} and ρ_{weft} are the densities of the warp and weft fibres, respectively. The fibre volume fractions calculated for each composite sample are presented in table 4 for the warp and fill directions.

Equation 6 was used to calculate the densities of the composite samples that were produced:

$$\rho_c = \rho_f V_f + \rho_m V_m \qquad (6)$$

where ρ_c, ρ_f, and ρ_m are the densities of composite material, reinforcement fibre, and matrix, respectively. V_f and V_m represent the reinforcing fibre and matrix volumetric ratios. The density of PP is 0.92 g/cm^3.

To create composite plates, all fabrics are cut into 30*30 cm squares using a CNC fabric cutter device (figure 3), and then they are stacked on top of one another with the same weft-warp directions.

Fabrics were made into composites (C1, C2, and C3) using the hot-pressing machine in the lab. There are three steps to moulding. The hot press machine's temperature was set to 170°C before the manufacturing of composite plates began, and the machine waited until it reached that temperature. After the first compression stage was finished, the second compression stage was performed under 100 bar pressure for

Table 4

FIBRE ORIENTATION, VOLUMETRIC FRACTIONS AND DENSITY OF THE COMPOSITES							
Composites codes	**Fabric code used**	**Fibre orientation in the fabric**	**Plate thickness (mm)**	V_f (%)	$V_{f\text{-weft}}$ (%)	$V_{f\text{-warp}}$ (%)	ρ_c (g/cm^3)
C1	F1	0°/0°	2.05 ± 0.5	56	56	0	1.86
C2	F1	0°/90°	2.05 ± 0.5	56	28	28	1.86
C3	F2	0°/0°	2.05 ± 0.5	56	28	28	1.86
C4	F3	0°/0°	1.54 ± 0.5	56	28	28	1.97

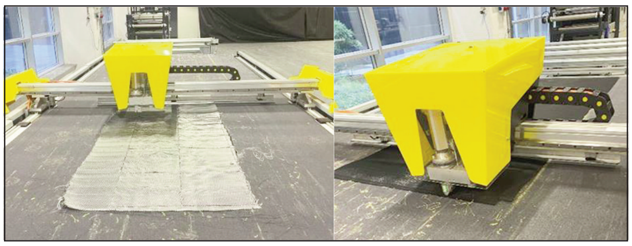


Fig. 3. CNC fabric cutter device

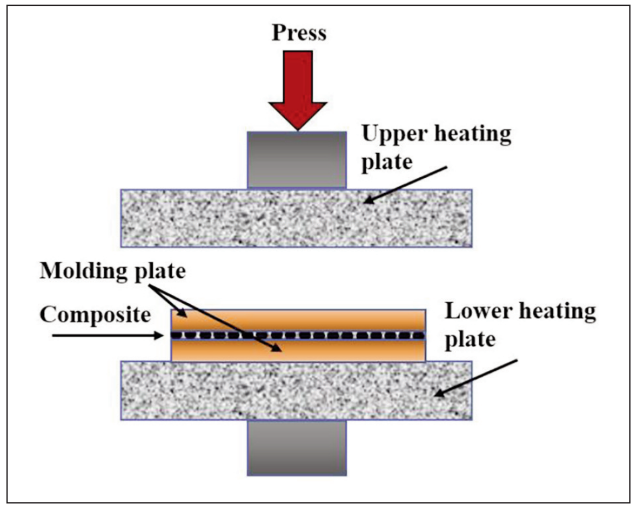


Fig. 4. A schematic of a 2D thermoplastic moulding

300 seconds, and the final stage, the third compression, was performed under 120 bar pressure for 300 seconds. Each stage of the compression process lasted for 300 seconds. The manufacturing of composite plates in a three-step hot pressing machine was finished immediately after cooling for 300 seconds under 5 bars of pressure. Figure 4 presents a schematic illustration of the system.

GF-reinforced thermoset composite was produced to make a full performance comparison of the produced samples. F3-numbered plain weave glass fibre fabrics, whose properties are given in table 2, are stacked on top of each other. The vacuum infusion technique (figure 5) was utilized to prepare eight-plied composite samples at room temperature (20±2°C). Throughout the procedure, a functioning fan placed on the table assisted in the process. Initially, the matrix material was formed by combining a specific amount of accelerator and hardener with Duratek DTS1200 epoxy resin. Composite fabrication took place on a tempered glass surface. Before commencing production, a release agent was applied to the tempered glass to facilitate easy separation of the composite plate. Next, a ply of resin was applied to the tempered glass, followed by a ply of fabric. This sequence was repeated until the desired number of fabric ply was achieved. Peel-ply and perforated film were then placed over the fabric ply. Finally, vacuum sealing tape was used to seal the sample, and a vacuum bag was attached. A small opening was created in the vacuum bag to allow the manifold tube to pass through. The vacuum pump was activated to remove excess resin from the sample, operating at approximately 1 bar of pressure for about 2 hours. After the designated time elapsed, the vacuum tube was cut and sealed with tape to prevent air from entering. The sample was left in this position for 24 hours to harden. Following that, post-curing took

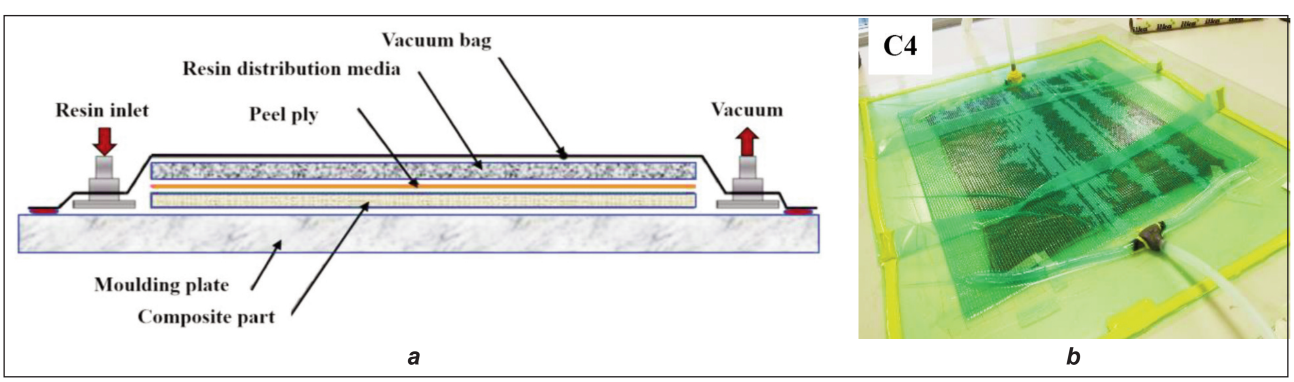


Fig. 5. Photos of: *a* – schematic diagram of vacuum infusion technique; *b* – production of C4 sample with vacuum infusion technique

place for 2 hours at 120 degrees, then for an additional 2 hours at 90 degrees.
The moulded thermoplastic composite plates were prepared in the dimensions defined by the relevant standards using CNC and aligned cutting devices to analyse their mechanical properties. The test specimens were cut in the warp direction. After the chin support apparatus was prepared and adhered to the test samples, they were left to be conditioned.

Mechanical testing

Figure 6 illustrates the setup for the tests conducted on the samples. Tests for tensile, bending, and impact were performed. Five samples of each type of composite were made for testing. The 0 direction was used to cut all test specimens. The tensile testing (100 kN) was done using a Besmak-BMT 100E universal tensile tester. The ISO 527-4 guidelines were followed in the creation of the tensile test samples. To maintain the test specimens' condition, they were kept in clean water at 50°C for 25 days. The ambient temperature for the test was 23°C and 50% RH. The tensile speed was set to 2 mm/min, and the prestress value was 50 N. The length measured by the video extensometer was 50 mm (figure 6, *a*). Flexural strength is the highest stress that a material can bear before losing its ability to bend effectively. On a three-point bending tester of the SHIMADZU brand, the bending test was conducted. The TS EN ISO 178 three-point bending standards were followed in the preparation of the bend test specimens. The test speed is 2 mm/min, the test ambient temperature is 23.2°C, and the test humidity is 50.10% (figure 6, *b*). The distance between the supports is 64 mm. The Charpy impact test, which is applied to evaluate the fracture behaviour of materials and to obtain information about ductility, was carried out in accordance with the ISO 179 standard. The test ambient conditions were 23±2°C and 50±10%RH (figure 6, *c*).

Combustion analyser

The samples created within the parameters of the study were subjected to UL94 combustion tests used for polymer materials for combustion classification. To experiment, five samples were prepared (figures 6, *c* and *d*).

RESULTS AND DISCUSSION

Each experiment used a minimum of five samples to determine whether the results were repeatable. Reports were made on average values. When a difference reached $p \leq 0.05$, it was deemed statistically significant.

Mechanical properties of the composites

The mechanical properties of composite materials are significantly influenced by the reinforcing material's structural features. The mechanical properties of the yarn were affected by its crimp values, yarn densities (measured in yarn/cm), and usage directions. When yarn densities are increased in overly dense fabric composites, the fibre volume fraction also increases. Due to the contemporaneous rise in yarn crimp, this phenomenon could, however, negatively affect the mechanical properties. The density and weaving structure both significantly influenced how tightly the yarn crimps. Due to its extensive yarn interlacing, the plain-weave fabric exhibited the highest crimp ratings. As the yarn density was increased, the plain-weave fabric, namely sample C3, showed a noticeable rise in yarn crimp values. In comparison to plain-woven fabric, samples C1 and C2, which were made of twill-weave fabric, showed better pliability and drape ability. This specific weaving method keeps an even distribution of fibres in both the warp and fill orientations, demonstrating a favourable balance between deformability and stability.
The tensile strengths of 8-ply fabrics created using fabrics of different weaving types and different orientations were analysed. Figure 7, *a* shows the outcomes of the tensile tests for several composites. The regression coefficient for C1, C2, C3 and C4 was found to be 0.99. This shows that the tensile test result is reliable. Compared to C2 and C3 composites, C1 appears to have a greater tensile strength of approximately 2.2 times. However, the following point needs to be taken into consideration here: the 0° (weft) direction was used to prepare each tensile test specimen. Weaving glass fibres in the weft direction produces F1 fabric, which creates C1 and C2 composites. The glass fibre carries the load in all ply of C1 samples (0°/0° orientations). Sample C2 is 0°/90° orientation, and in these 0° plies, PP supports the load. However, in the C2 and C3 samples, since the

a *b* *c* *d* *e*

Fig. 6. Tests of: *a* – tensile; *b* – three-point bending; *c* – charpy impact; *d* and *e* – combustion

glass fibre is shared in half in the warp and weft directions, half of the total glass fibre density in the composite carries the load. Therefore, it would be more accurate to make a comparison by taking half the strength values of the C1 sample specified in table 5. In this case, C1 tensile strength is taken into account as 157.07 MPa. This way, a more accurate comparison will be made between C1, C2, and C3. In this case, C1 showed an average 17% higher value than the C2 and C3 samples. In this case, the composite production parameters of C1 show that it is slightly better than C2 and C3. The glass fibre weft and warp density are the same in the C3 sample since it has a plain fabric weave type. Although the fabric types of C2 and C3 are different, there is an equal density of GF and PP in total in the warp and weft directions (table 4). According to the data obtained from the tensile test, C2 showed slightly higher tensile strength than C3. In conclusion, the mechanical properties were significantly influenced by the orientation. The tensile strength behaviours of thermoset composites C4 (56% GF content) were found to be very close to the values obtained from C1. Furthermore, figure 8 displays the scanning electron microscope (SEM) image of the fractured surface obtained from the tensile test conducted on the C4 composite. It is evident that the bonding between the matrix and the glass fibre is highly good, with no observed occurrence of the pull-out phenomenon. A stress-modulus plot is given in figure 7, *b*. The highest stress/modulus value among thermoplastic samples was obtained from C1. However, as stated above, since C1 is in the 0/0 orientation, the glass fibres bear the entire load, and in C2 and C3, the glass fibre density was distributed equally in the warp and weft directions. Hence, a more accurate approach would involve comparing C1 and C2 by halving the modulus value of C1. As indicated in table 5, the modulus value of C1 was 16.81 MPa. Therefore, half of this value was considered, which amounts to 8.41 MPa. When viewed in this manner, the tensile modulus of both C1 and C2 composites demonstrated nearly identical values, indicating the correctness of the production process. Since C1 and C2 are constructed using fabrics of the same yarn and weave type, the sole difference lies in C2's 0°/90° orientation. In addition, when compared with C3 fabric, C2 showed 25% higher performance than C3. This phenomenon can be attributed to two factors:

1) Comparatively fewer yarn crimps can be found in twill-woven composites than in plain-weave materials. Since the C2 sample is a twill weave, when the two samples are compared, there is less yarn crimp than the C3 sample (plain fabric), which negatively affects the tensile strength.

2) The yarns of C3 fabric are hybrid- intermingled. As seen in figure 9, the breakage of glass fibres during the formation of hybrid-intermingled yarns negatively affected the mechanical strength [29]. When the C1 sample was compared to the thermoset C4 sample produced as the reference sample, an increase of only 0.6% was observed in the thermoset C4 sample. Based on these results, it is concluded that the C1 sample was successful.

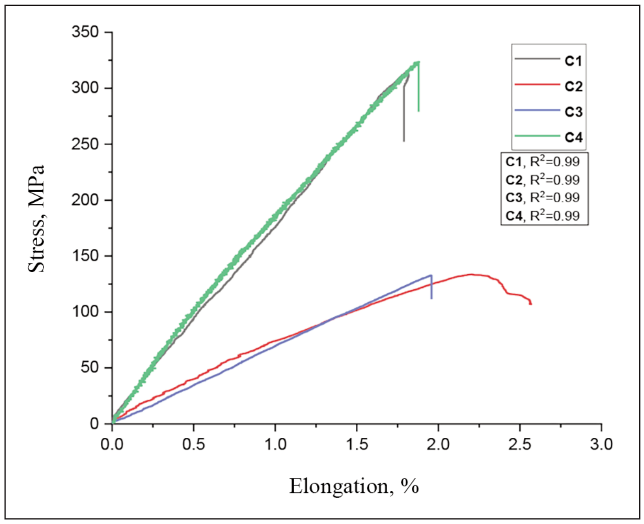
Table 5

EXPERIMENTALLY DETERMINED TENSILE PROPERTIES OF THE COMPOSITE SAMPLES

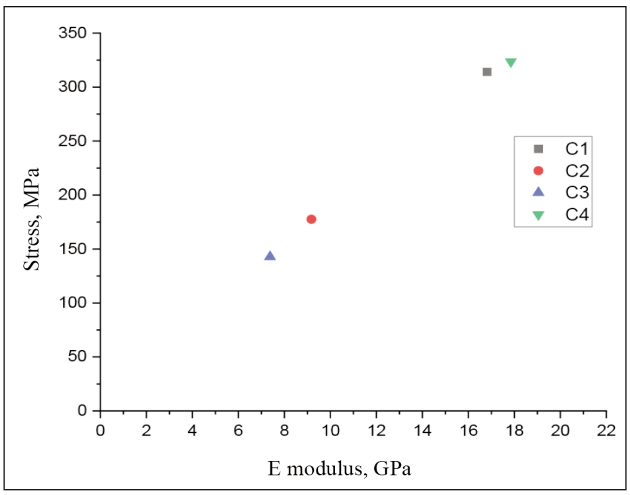
Composites codes	**C1**	**C2**	**C3**	**C4**
Tensile modulus (MPa)	16.81	9.18	7.38	17.85
Tensile strength (MPa)	314.13	133.67	132.75	323.62
Max elongation (%)	1.82	2.57	1.96	1.88
Specific tensile modulus (MPa)	9.85	4.94	3.97	10.20
Specific tensile strengths (MPa)	178.89	95.43	76.74	184.93

In figure 7, *c*, the specific tensile modulus and the specific strengths (stiffnesses) of composites are presented. Specific mechanical properties can be obtained by dividing by density [30]. Knowing the density of composites (table 4), the specific tensile strength and specific tensile modulus can be calculated. This characteristic accounts for the good fatigue behaviour of composites [31]. The specific strength values of C4, a thermoset composite, showed almost the same values as those of C1, a thermoplastic composite. Hence, a twill thermoplastic composite consisting of 56% glass fibres and 44% polypropylene, manufactured using interwoven yarns in a 0°/0° orientation (C1) intended for enhanced stiffness, possessed an equivalent safety factor as a 56% glass fibre-reinforced thermoset composite (C4). In addition, the sample was formed from GF-reinforced PP-matrix composites (between C1, C2, and C3), with the highest specific tensile properties being C1 composite, which consists of twill-woven fabrics made of PP-woven warp and GF-weft yarns. In addition, it showed almost the same performance as the reference 56% GF-reinforced epoxy matrix C4 composite. This result showed that the C1 composite is successful. The primary reason why the C3 composite formed by the hybrid intermingled yarn technique (Y2 yarn composed of GF-PP) and plain weave type had relatively lower specific tensile properties was the breaking of GF during the hybridization process, as shown in figure 9.

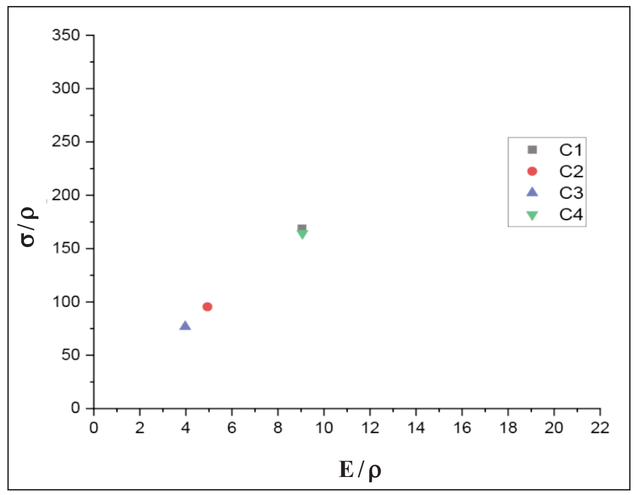
ANOVA results were examined, and it was seen that the tensile test results were within the 95% confidence interval. Table 6 shows the detailed analysis of variance results for the responses, respectively, where DF, SS, MS, F, and p represent the degree of freedom, the sum of squares, the mean of squares, F statistics, which is a ratio between-group variation and within-group variation, and the p-value that determines the significance of the test, respectively. The F values of the four models implied the models were significant. The p values of less than 0.01% indicated the model term was significant.



a



b



c

Fig. 7. Tensile test results: *a* – stress vs. elongation; *b* – stress vs. modulus of elasticity; *c* – specific tensile characteristics

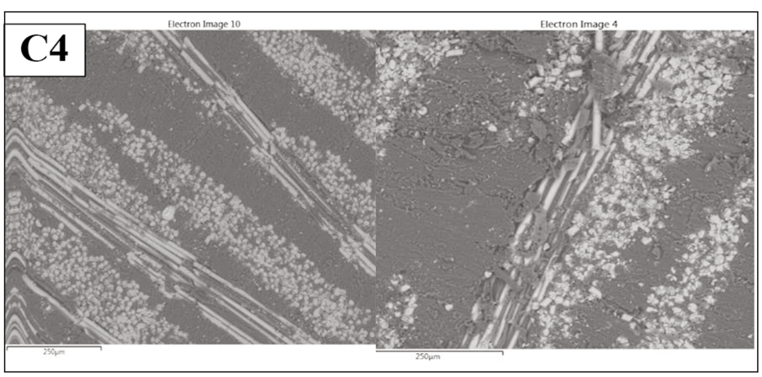


Fig. 8. SEM images of the fractured surfaces as a result of the tensile test of 56% GF-reinforced (C4) epoxy matrix samples

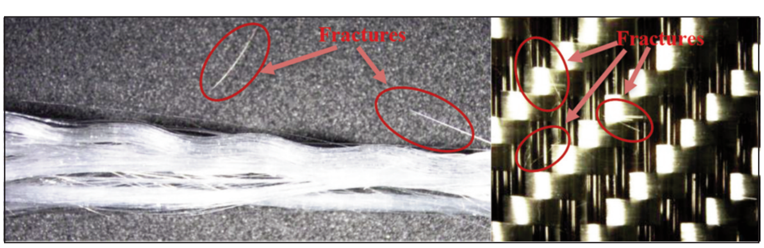


Fig. 9. Appearance of GF fractures on intermingled fabric

The Charpy impact strengths of composite materials are shown in figure 10. In comparison to the impact strengths of C1 (1.2 times higher) and C2 composites (2.2 times higher), composites intermingled hybrid fibres, particularly C3, demonstrated markedly higher impact strength values. The significant degree of interlacing between the different yarns improved the crimp qualities of plain-woven fabric. The impact strength of the C3 specimen significantly increased as a result of the experimental findings. As opposed to the C2 composite material aligned at an angle of 0°/90°, the composite material aligned along the C1 direction at a 0°/0° angle showed much better impact resistance performance (approximately 1.8 times greater) [32].

The outcomes of the three-point bending test are shown in figure 11 to help identify the mechanical properties of materials against bending. Comparing the plain-woven fabric in C3 to the twill-woven

Table 6

RESULTS OF ANOVA FOR TENSILE TEST RESULTS						
Composites	**Variable**	**DF**	**SS**	**MS**	**F-value**	**p-value**
C1	Model	1	1.48×10^9	1.48728×10^9	1.69264×10^8	0.000
	Error	162865	1.43×10^6	8.78676		
	Total	162866	1.48×10^9			
C2	Model	1	2.11×10^8	2.11842×10^8	2.092171×10^6	0.000
	Error	142103	1.43×10^7	101.25		
	Total	142104	2.26×10^8			
C3	Model	1	1.68×10^8	1.68277×10^8	4.52366×10^8	0.000
	Error	114599	4.26×10^4	0.37199		
	Total	114600	1.6832×10^8			
C4	Model	1	1.48557×10^9	1.48557×10^9	8.59508×10^7	0.000
	Error	205847	3.56×10^6	17.28		
	Total	205848	1.48×10^5			

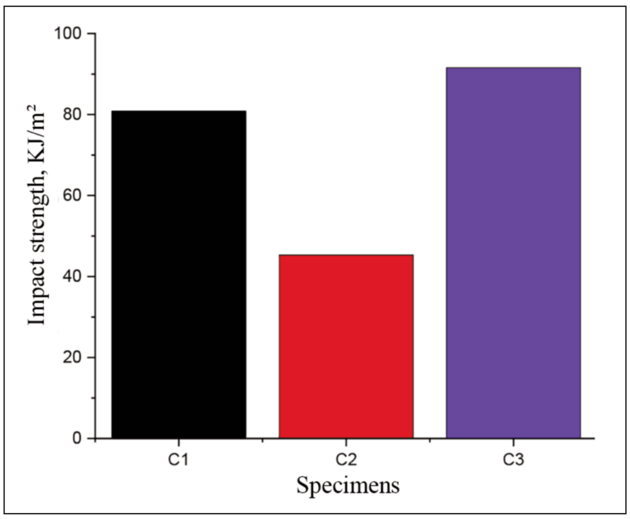


Fig. 10. Impact strength of the specimens

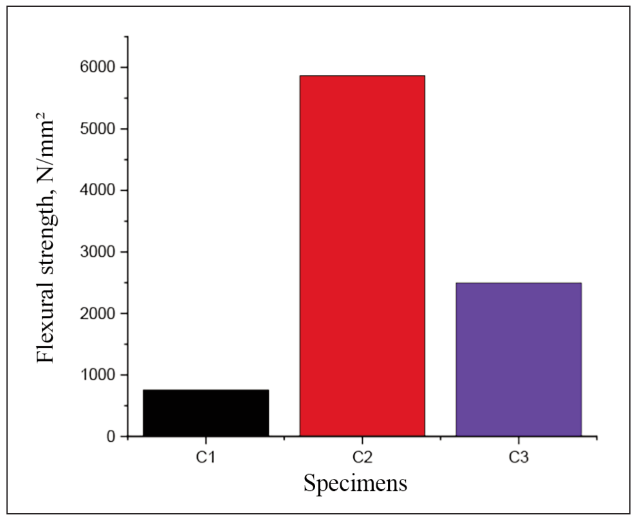


Fig. 11. Flexural strength of the specimens

fabric in C2, more flexibility and drape could be seen (figure 11). The weaving method under discussion successfully maintained a consistent dispersion of fibres in both the warp and weft orientations, exhibiting a suitable equilibrium between deformability and stability. The C2 composite woven in the 0°/90° direction was found to have the highest flexural strength upon evaluation. When hybrid fibres were used, the flexural strength of C2 showed a significantly higher value, around 2.4 times greater than the composite sample C3. The flexural strength of C1 was found to be almost 7.7 times lower than that of C2, woven with the same fibres but in different orientations when compared to C2. The mechanical behaviour of composite laminates made from commingled fabrics with glass and polypropylene fibres was investigated in a study by Formisano et al. [32] and similar to our findings, the results showed that samples with a 0°/90° orientation performed the best in terms of flexural strength [33].

UL94 combustion tests were performed on the specimens created as part of this study to categorize the combustion behaviour of polymer materials. In all of the materials whose results are shown in figure 12, combustion was seen. The results of the combustion test were noteworthy; they showed that the C1 and C2 composites burned for about the same amount of time and underwent severe combustion. However, when compared to that seen in other composites, the combustion event seen in the C3 composite revealed unique properties. According to figure 12, the C3 composite's combustion process took 281 seconds to complete. The combustion was also shown to have a sluggish burning feature. GF breaking during the production of intermingled hybrid yarn is what caused this phenomenon. Additionally, it was thought that the materials' weaving patterns were what accounted for the variance in combustion times. The more porous structure of twill-woven composite textiles, in particular those with C1 and C2 weaves, allowed for improved air permeability. This property consequently caused

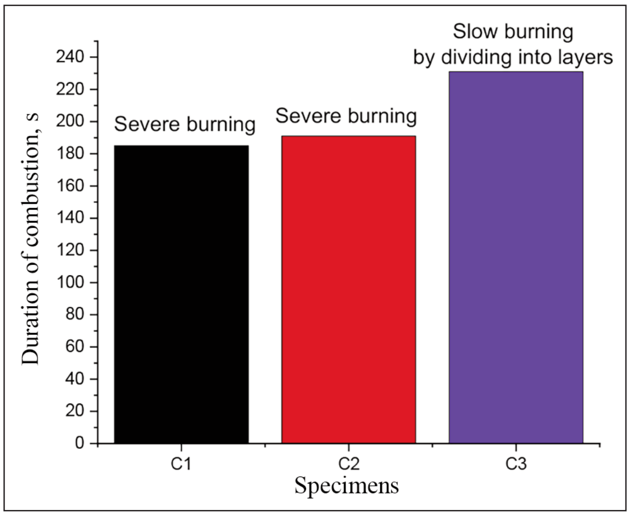


Fig. 12. Composites combustion behaviour

combustion dynamics and flame propagation to accelerate. When a material burns, it undergoes a process of pyrolysis, where it decomposes due to the application of heat. The decomposition products are then available for combustion when they mix with oxygen. The more porous a material, the easier it is for oxygen to penetrate the material and react with the decomposed products. In the case of textiles with twill weaves, especially C1 and C2 weaves, the increased porosity facilitates the ingress of oxygen, thereby promoting faster decomposition and combustion of the material. Due to their more compact structure and ability to provide improved protection against flame movement, plain-woven (C3) composite materials are effective at reducing the spread of flames.

CONCLUSION

The impact of weaving type and fibre orientation on the mechanical and combustion parameters of the composite samples was thoroughly examined in this study.

The unidirectional (0°/0°) twill fabric was found to have the best performance according to the results of the tensile test, obtaining a maximum value of 314.81 MPa. The twill-woven composite had a tensile strength of 177.5 MPa when oriented in the 0°/90° direction. The plain-woven composite, on the other hand, had a tensile strength of 142.8 MPa. The strength of the composite created utilizing unidirectional twill woven-type materials was almost two times higher than that of other composites. In addition, it was determined that the reason for the decrease in strength and modulus of fabrics produced with intermingled hybrid yarn was due to the breakage of glass fibre during hybridization. When thermoplastic composite samples and thermoset composite samples were compared, the composite (56% GF – 44% PP) consisting of 0°/0° orientations of twill fabrics woven with interwoven yarns showed almost the same tensile strength values as thermoset (56% GF) composites.

Although the fibre densities of the C2 sample produced with the interwoven method and the C3 sample produced with the intermingled method are equal in the warp and weft directions, the Specific modulus of fabric composites produced by the interwoven method was 1.3 times higher than that of intermingled fabric composites. This difference is due to damage to the glass fibre during intermingled yarn production. During the air texturing process, the glass fibre yarn breaks and this leads to a decrease in the composite mechanical properties. The Specific Tensile modulus value of the C1 sample, produced by the interwoven method and aligned with 0°/0° orientation, was almost the same as the thermoset matrix C4 sample, produced as a reference and with the same fibre density. This ultimately shows that our proposed method is successful.

According to the results of the bending test, the 0°/90° directional twill fabric demonstrated the best performance, producing a value of 5864.15 MPa. It was determined that the glass fibres' orientation in the warp direction was the main factor.

Based on the results of the Charpy impact test, it was determined that the composite material had the best impact energy performance among plain fabrics, with a value of 91.56 KJ/m^2. According to research, plain weaving varieties exhibited a two-fold improvement in impact-damping performance when compared to twill weaving kinds.

It was found that plain fabric composites had a progressive burning process characterized by ply-by-ply division based on their combustion characteristics. Twill fabric composites, on the other hand, showed a more ferocious burning behaviour. The combustion test revealed that burning in the specimens of C1 and C2 was severe and relatively fast compared to C3. The slow combustion in the C3 sample, woven from hybrid intermingled yarn, caused by the breakage of fibreglass during yarn production, leading to interruptions in combustion. Moreover, combustion occurred in ply.

It is clear that the interwoven method has a higher advantage than the intermingled method, both in terms of mechanical properties and production cost and speed, and it is thought that this will be a good alternative method for thermoplastic composites.

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