



Impact toughness of CPP- and PET-Based hybrid thermoplastic laminates under edgewise charpy testing

Edgewise charpy testi altında CPP ve PET bazlı hibrit termoplastik laminatların darbe dayanıklılığı

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Abstract

This study examines the Charpy impact characteristics of laminated thermoplastic composites made from cast polypropylene (CPP) and polyethylene terephthalate (PET) matrices, reinforced with glass, carbon, and hybrid fiber stacking sequences. Laminates for composite materials were produced using the process of stacking films and hot-pressing them, followed by cutting, and then tested according to ISO 179-1 directives. The Charpy impact test was performed on five specimens for each configuration to measure both impact energy and toughness. The data show that both the matrix's plasticity and the stacking sequence significantly influence the impact response. CPP composites displayed the best toughness against plain configurations of 7.2 J for carbon and 5.4 J for glass, while the hybrids reached up to 7.26 J for glass-carbon-glass and 6.65 J for carbon-glass-carbon. PET composites carried less toughness in standard configurations of 4.5 J for both carbon and glass, while the hybrid carbon-glass-carbon configuration improved toughness to 7.45 J. The CPP_GCG laminate absorbed about 86% more energy than the PET_G, while CPP composites absorbed 30–35% more than PET composites for all the studied stacking structures. The fractography of specimens confirmed the occurrence of ductile fracture for the CPP composites and brittle failure for the PET composites. The data demonstrate the effectiveness of combining a ductile matrix with hybrid stacking structures to elevate the toughness against impacts, as well as the tolerance to damages for laminated composites.

Keywords: Charpy impact test, Fiber-reinforced thermoplastics, Impact toughness, Hybrid composites, Absorbed energy

Öz

Bu çalışmada, cam, karbon ve hibrit elyaf istifleme dizileriyle güçlendirilmiş döküm polipropilen (CPP) ve polietilen tereftalat (PET) matrislerden yapılmış lamine termoplastik kompozitlerin Charpy darbe karakteristikleri incelenmektedir. Kompozit malzemeler için laminatlar, filmlerin istiflenmesi ve sıcak preslenmesi, ardından kesilmesi ve ardından ISO 179-1 direktiflerine göre test edilmesi işlemi kullanılarak üretilmiştir. Charpy darbesi, hem darbe enerjisi hem de tokluk ölçümleri için her konfigürasyondaki beş numune üzerinde gerçekleştirildi. Veriler, hem matris plastisitesinin hem de istifleme dizisinin darbe tepkisini büyük ölçüde etkilediğini göstermektedir. CPP kompozitleri, karbon için 7.2 J ve cam için 5.4 J'lik düz konfigürasyonlara karşı en iyi tokluğu gösterirken, hibritler cam-karbon-cam için 7.26 J ve karbon-cam-karbon için 6.65 J'ye ulaşmıştır. PET kompozitler, hem karbon hem de cam için 4.5 J'lik standart konfigürasyonlarda daha az tokluk taşıırken, hibrit karbon-cam-karbon konfigürasyonu tokluğu 7.45 J'ye çıkardı. CPP_GCG laminatı, PET_G'den yaklaşık %86 daha fazla enerji emerken, CPP kompozitleri incelenen tüm istifleme yapıları için PET kompozitlerinden %30-35 daha fazla enerji emdi. Numunelerin fraktografisi, CPP kompozitleri için sünek kırılmanın ve PET kompozitleri için gevrek kırılmanın meydana geldiğini doğruladı. Veriler, darbelere karşı tokluğu ve lamine kompozitler için hasar toleransını artırmak için sünek bir matrisi hibrit istifleme yapılarıyla birleştirmenin etkinliğini göstermektedir.

Anahtar kelimeler: Charpy darbe testi, Elyaf takviyeli termoplastikler, Darbe tokluğu, Hibrit kompozitler, Emilen enerji

1 Introduction

Thermoplastic matrix composites, comprising a matrix of polymer reinforced with glass or carbon fibers, have drawn much attention in the past few years based on their high impact properties, light weight, recyclability, and processability. Thermoplastic matrix composites are being increasingly utilized in the automobile, aerospace, and defense industries where good high-performance properties along with design flexibility are desired [1]. Thermoplastic composites have some added benefits over conventional thermoset composites due to their features like infinite shelf life, resistance to repeated impacts, high-volume producibility, and reprocessing characteristics.

In recent research, the strategies of processing parameters and development have focused on improving the formability, mechanical strength and enhancement of optimized fiber-reinforced thermoplastics. For example, Zhao et al. [2] studied

the hot stamping formability of continuous glass fiber reinforced polypropylene (PP) composites and determined the optimum processing structure. Ragupathi and Balle [3] demonstrated that ultrasonic reconsolidation preserved up to 96% of the flexural strength and 95% of the interlayer tensile strength in reconsolidated PP-glass fiber composites, confirming the reusability of the method.

Bakkal et al. [4] examined the fatigue performance of thermoplastic composites with various fiber orientations and reported superior results for 0°/90° orientations compared to ±45° arrangements. Shoşig et al. [5] investigated the mechanical response of glass fiber-reinforced thermoplastics at high strain rates, offering valuable insight into their failure mechanisms under dynamic loading.

The effect of structural parameters such as reinforcement type and layer sequence on composite performance has led to the development of hybrid composite designs. Jamshaid et al. [6] compared the mechanical and thermal properties of PA6 matrix

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hybrid composites reinforced with basalt and Kevlar fabrics and showed that the layering sequence was decisive on the final performance. Dönmez Çavdar et al. [7] investigate the advancement of hybrid thermoplastic composites fortified with natural fibers and inorganic fillers. The research assesses the mechanical, thermal, and morphological characteristics of these composites, emphasizing their applicability in sustainable materials.

Kaya [8] contrasted intralayer hybrid carbon/cam thermoplastic composites with their non-hybrid counterparts in low-velocity impact and post-impact compression testing, concluding that hybridization can substantially enhance the damage tolerance of the coatings, even under high-energy conditions.

In addition to material selection and stacking configuration, the manufacturing process plays a critical role in determining the mechanical performance of thermoplastic composites. Ozbay et al. [9] investigated the filament winding technique to produce hybrid yarn thermoplastic composites and highlighted how processing parameters affect structural integrity. Kaplan [10] similarly reviewed various manufacturing methods for hybrid yarns used in thermoplastic composites and highlighted their effects on mechanical and thermal properties, especially in high-performance applications.

Furthermore, Erkendirici [1] examined the Charpy impact characteristics of high-density polyethylene (HDPE) matrix composites reinforced with plain-woven S-2 glass fibers, revealing that both impact energy and toughness improved with an increase in the number of layers and fiber volume fraction. His findings emphasized the incorporation of failure modes including matrix fracture, fiber rupture, and interfacial debonding, all influenced by the stacking sequence and thickness of the laminate.

The Charpy impact test is a widely used method for evaluating a material's toughness by measuring the energy absorbed during fracture when a notched specimen is struck with a pendulum hammer. Historical and methodological evaluations of the Charpy test highlight its cost-effectiveness and importance in material characterization, though its results are best interpreted when comparing similar materials [11], [12]. Moreover, investigations into thermoplastic composites using the Charpy test have shown that impact toughness and energy absorption depend on factors such as layer count, volume percentage, and processing techniques with further studies extending these assessments to various materials and testing conditions [13], [14].

Miron et al. [15] performed instrumented Charpy tests on thermoplastics manufactured via the melt deposition (FFF) technique, including PLA, PC, PP, and PA12, and discovered that the printing orientation substantially influenced the impact performance. A study in the Journal of Thermoplastic Composite Materials analyzed PEEK-based fiber-reinforced thermoplastic composites, emphasizing the influence of fabric texture and fiber type on Charpy impact energy absorption [16]. A separate investigation revealed that acrylic-based glass fiber-reinforced thermoplastic composites (GFRTCP) shown superior impact strength relative to traditional composite systems [17]. Tarpani et al. [18] examined the translaminar Charpy toughness characteristics of carbon-epoxy and fiber-metal (TiGr) laminates throughout a broad temperature spectrum, yielding significant insights into the influence of temperature on impact work variation. Grellmann et al. [19] devised an instrumented Charpy impact energy testing method capable of differentiating between elastic and plastic materials, hence enabling the evaluation of thermoplastics' fracture resistance

irrespective of their geometry. These studies unequivocally illustrate the adaptability of the Charpy test in assessing the impact performance of thermoplastic systems across diverse manufacturing settings and variables.

Thermoplastic composites are generally produced by extrusion, and the literature primarily focuses on their production parameters and reinforcement materials. However, studies on thermoplastic composites as films are rarely encountered in the literature.

Despite the wealth of studies on thermoplastic composites, there continues to be a lack of comparative analysis on the Charpy impact performance of both plain and hybrid stacking arrays in thermoplastic systems using two different matrix types (cast polypropylene (CPP) and polyethylene terephthalate (PET)). This study aims to address this gap by evaluating the impact behavior of flat and hybrid stacking arrays of laminated thermoplastic composites reinforced with glass and carbon fibers using CPP and PET as matrix materials. The findings aim to clarify how hybrid configurations affect energy absorption and toughness, and how the selected matrix type contributes to the overall impact performance.

2 Material and method

2.1 Materials

In this study, two different thermoplastic matrices—cast polypropylene (CPP) and polyethylene terephthalate (PET)—were used for the fabrication of laminated composite plates. CPP films were provided by Superfilm, PET films were provided by Eres Sentetik (Gaziantep, Turkey).

These matrices exhibit distinct physical and mechanical characteristics that influence the impact behavior of fiber-reinforced thermoplastics.

Cast polypropylene (CPP) and polyethylene terephthalate (PET) possess unique material characteristics that affect the efficacy of fiber-reinforced composites. CPP is distinguished by its low density, high ductility, and superior impact resistance, rendering it exceptionally appropriate for applications necessitating energy absorption and flexibility. Conversely, PET demonstrates greater tensile strength and stiffness, as well as enhanced thermal stability, yet it shows reduced elongation at break and a propensity for brittleness under impact loading. Consequently, composites produced with CPP matrix typically exhibit superior impact toughness, as evidenced by the experimental findings, owing to CPP's capacity for plastic deformation and excellent energy dissipation. PET composites have enhanced structural stiffness and superior tensile characteristics but are more susceptible to brittle failure under abrupt loads. Furthermore, CPP provides enhanced processability at reduced temperatures and superior chemical resistance, but PET's increased density results in somewhat heavier composite structures. Consequently, when impact resistance and ductility are emphasized, CPP is the superior matrix material. In contrast, PET is favored in applications where enhanced stiffness, strength, and thermal performance are essential, notwithstanding a compromise in impact toughness.

For reinforcement, unidirectional E-glass fiber fabric (areal density: 200 g/m²) and plain-weave carbon fiber fabric (areal density: 200 g/m²) were used. Both fiber types were cut into uniform plies and utilized in plain and hybrid stacking

sequences. The reinforcements were provided by Dost Kimya (Istanbul, Turkey).

The thermoplastic matrix films were supplied in roll form: CPP films with a nominal thickness of 60 µm, and PET films with 100 µm thickness. The thickness variation between the matrices was intentionally selected to match processing compatibility and to ensure sufficient resin flow and fiber wet-out during compression molding.

Composite laminates were produced using the film stacking method followed by hot compression molding, a technique commonly adopted for thermoplastic composites. In this method, each fiber ply was sandwiched between two thermoplastic matrix films. The lay-up was then consolidated in a steel mold under a heated hydraulic press. For CPP-based laminates, the pressing temperature was 170 °C, while 180 °C was used for PET-based systems. In both cases, a heating and holding duration of 60 minutes was applied under an approximate pressure of 3 MPa. Cooling was conducted under pressure to avoid delamination or void formation.

Eight different composite plate configurations were fabricated in total, including:

- 12 layers of glass fiber (CPP_G, PET_G),
- 12 layers of carbon fiber (CPP_C, PET_C),
- Hybrid configurations:
3 glass / 6 carbon / 3 glass (CPP_GCG, PET_GCG),
3 carbon / 6 glass / 3 carbon (CPP_CGC, PET_CGC).

Each composite consisted of 12 reinforcement layers and interleaved matrix films, resulting in plate thicknesses ranging from approximately 2.4 mm to 4.1 mm, depending on the stacking sequence and matrix type. A summary of the produced laminate configurations and thicknesses is presented in Table 1. A schematic representation of the stacking sequences used in the four composite configurations (i.e., glass, carbon, GCG, and CGC types) is provided in Figure 1, demonstrating the layer arrangements and fiber orientations for both CPP and PET matrix systems.

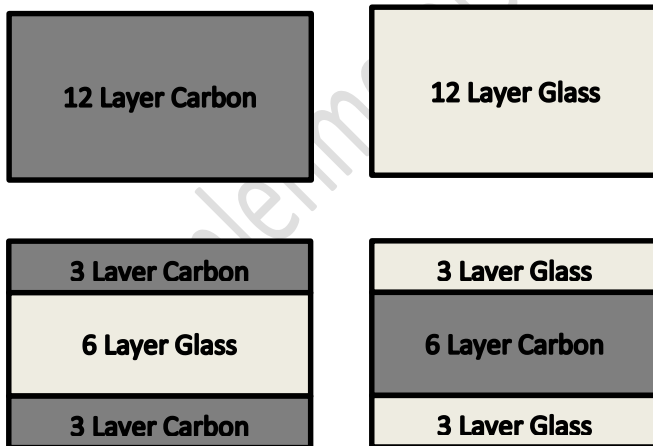


Figure 1. Arrangements of Plain Carbon, Plain Glass, CGC and GCG plates.

2.2 Specimen Preparation

The composite laminates produced in size of 240x275 mm using CPP and PET matrices with different reinforcement

stacking sequences were cut into standardized specimens for mechanical testing. All samples were prepared in accordance with the ISO 179-1 standard for Charpy impact testing. Laminated plates were first trimmed using a diamond blade cutter to remove edge irregularities and ensure uniform panel boundaries. Specimens were then cut into rectangular bars with dimensions of 55 mm × 10 mm, as specified by the ISO standard.

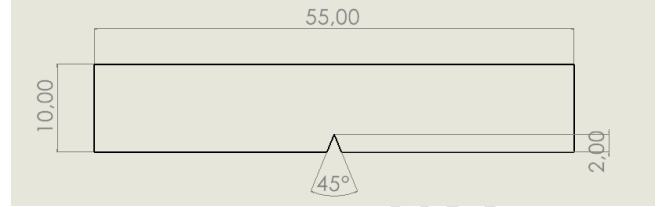


Figure 2. Charpy Impact Test Specimens.

Table 1. Structural characteristics of laminated composite plates.

Specimen Name	Stacking Type	Matrix	Thickness (mm)
CPP_G	12 Glass	CPP	2.4
CPP_C	12 Carbon	CPP	2.9
CPP_GCG	3G/6C/3G	CPP	2.7
CPP_CGC	3C/6G/3C	CPP	2.8
PET_G	12 Glass	PET	3.3
PET_C	12 Carbon	PET	3.7
PET_GCG	3G/6C/3G	PET	3.6
PET_CGC	3C/6G/3C	PET	4.1

3 Charpy Impact Test

The impact resistance of the composite laminates was evaluated using Charpy impact tests conducted in accordance with the ISO 179-1 standard, which is widely applied for characterizing the toughness of fiber-reinforced thermoplastics under dynamic loading conditions. Tests were performed using a pendulum-type Charpy impact tester (Kögel 3/70) equipped with a 15 J hammer and a calibrated analog energy scale. Each specimen was placed horizontally on the support anvils such that the notched side faced the striker.

A calculation method is required to determine the impact toughness after testing. One way to quantify the impact toughness of a plastic or composite is by using the following formula:

$$a_c U = (E/bh) f x \quad (1)$$

Where $a_c U$ is represents the impact toughness, E denotes the energy recorded during the test, and b and h signify the breadth and thickness of the test specimen, respectively. For each composite configuration, a minimum of five replicate tests were conducted. The average absorbed energy and impact toughness values were calculated, and standard deviations were reported to assess data variability.

4 Results and Discussion

A total of 20 Charpy impact tests were performed in edgewise configuration, with five replicate specimens tested for each of the four laminate types (carbon, glass, GCG, and CGC) within both CPP and PET matrix systems. The results were analyzed in terms of absorbed impact energy and impact toughness to

evaluate the effects of matrix type and stacking configuration on the dynamic performance of the composites.

As shown in Figure 3, all CPP-based composites exhibited relatively high impact energy values, attributable to the matrix's flexibility. The highest energy absorption was measured as 7.27 J in the hybrid structure CPP_CGC sample, which was slightly above the pure carbon reinforced CPP_C laminate (7.20 J). The lowest impact energy was found in the glass reinforced CPP_G laminate (5.40 J), as expected.

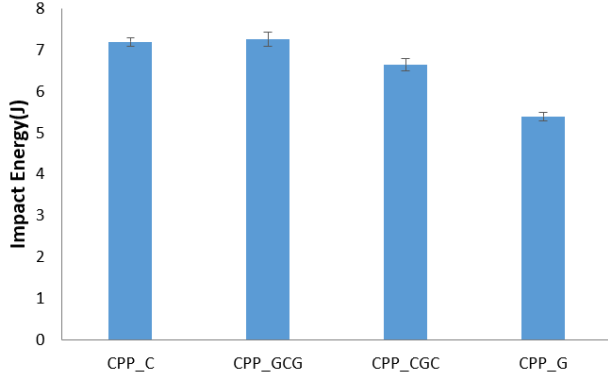


Figure 3. Impact energy results for CPP matrix.

Figure 4 shows the impact energy values for PET-based composites. The carbon-glass-carbon hybrid configuration (PET_CGC) achieved 7.45 J, which is better than all other PET-based laminates, including pure carbon (PET_C) and glass (PET_G) configurations, which absorbed only 4.53 J and 4.55 J, respectively. The other hybrid configuration, PET_GCG laminate, achieved 6.65 J of energy absorption.

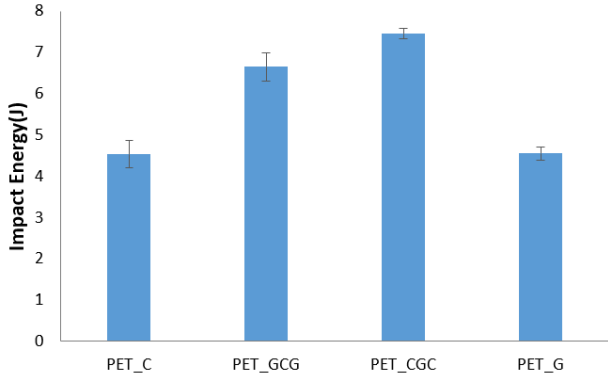


Figure 4. Impact energy results for PET matrix.

Table 2. Impact Energy results

Specimen Name	Impact Energy (J)	Standard Deviation
CPP_G	5.40	0.1
CPP_C	7.20	0.1
CPP_GCG	7.27	0.17
CPP_CGC	6.65	0.15
PET_G	4.55	0.15
PET_C	4.53	0.33

Specimen Name	Impact Energy (J)	Standard Deviation
PET_GCG	6.65	0.35
PET_CGC	7.45	0.12

Figures 5 and 6 depict the hardness influence of the CPP and PET matrices. Figure 5 demonstrates that the CPP_GCG laminate had the highest impact toughness value of 0.269 J/mm², consistent with the energy absorption trend, succeeded by CPP_CGC at 0.2375 J/mm² and CPP_G at 0.234 J/mm². The pure carbon configuration (CPP_C) attained a minimum toughness value of 0.227 J/mm². This suggests that carbon reinforcement in hybrid topologies improves energy absorption and enables enhanced energy distribution over the cross-section. Additionally, Table 2 presents the average impact energy values obtained from Charpy tests, corroborating the observed toughness trends across the different laminate designs. Table 2 and Table 3 give the average impact energy and average impact toughness values, respectively.

According to Figure 6, it is seen that the highest impact toughness value of 0.179 J/mm² was obtained from the PET_CGC hybrid configuration, while PET_GCG obtained a very close value of 0.171 J/mm². Due to the brittle nature of the PET matrix, lower toughness values (0.157 and 0.122 J/mm²) were obtained in the pure glass and carbon configurations (PET_G and PET_C, respectively). When CPP and PET matrices were compared, CPP-based laminates had higher ductility and energy dissipation capacities, thus outperforming PET-based laminates in terms of both energy absorption and impact toughness.

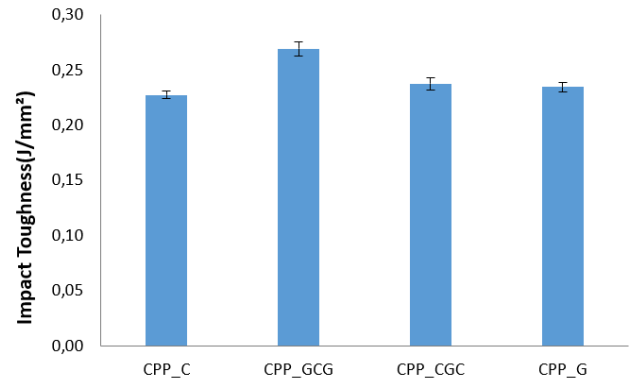


Figure 5. Impact toughness results for CPP matrix.

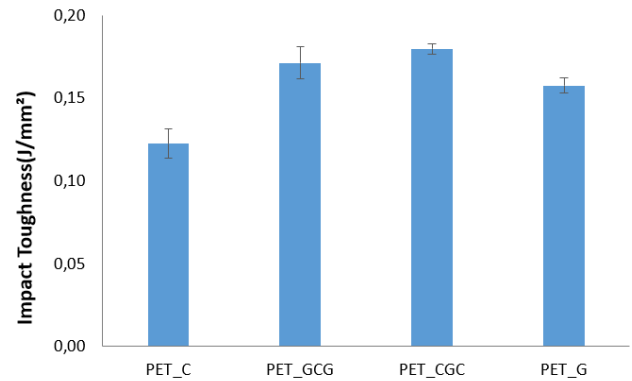


Figure 6. Impact toughness results for PET matrix.

Table 3. Impact Toughness results

Specimen Name	Impact Toughness (J/mm ²)	Standard Deviation
CPP_G	0.235	0.004
CPP_C	0.223	0.003
CPP_GCG	0.269	0.006
PET_G	0.237	0.005
PET_C	0.122	0.008
PET_GCG	0.171	0.009
PET_CGC	0.237	0.003

The Edgewise Charpy impact test results revealed that the impact energies of plain glass and plain carbon configurations were enhanced when using CPP as the matrix material. And for hybrid arrangements impact energy increased by PET matrix. The findings indicate that whereas CPP composites generally offer improved impact toughness in conventional configurations, the hybrid stacking sequence markedly enhances the performance of PET composites, particularly in the carbon-glass-carbon configuration.

The results of this research were conducted to determine the Charpy impact behavior of matrix ductility and fiber stacking architecture in laminated thermoplastic composites. It can be said that the better energy absorption and impact toughness of CPP matrix compared to PET and the better formability of polypropylene material directly affect the energy dissipation properties. The experimental results also confirm the work of Kaya [8], who showed that hybrid stacking arrangements significantly contribute to the impact energy and impact resistance through damage tolerance in polypropylene matrix composites.

The better impact energy results obtained from hybrid configurations in the present study seem to be beneficial in reducing crack propagation and optimizing energy. Similarly, it is also in agreement with the study conducted by Jamshaid et al. [6], who stated that fiber stacking is effective in controlling both mechanical and thermomechanical responses of hybrid thermoplastic composites. The improvement achieved in the PET_GCG hybrid configuration suggests that the layer stacking reduces structural failure under dynamic loading conditions such as impact, thus ignoring the brittleness of the PET matrix.

Furthermore, the general trend observed in this work — namely, that increased fiber volume and distributed reinforcement enhance impact toughness — finds support in the study by Erkendirci [1]. Although their work focused on HDPE-based systems and involved different test standards, the positive correlation between layer count and energy absorption offers a complementary perspective on the role of laminate architecture in dynamic loading scenarios.

The fracture surfaces depicted in the Figure 7-8 indicate that CPP (cast polypropylene) matrix composites demonstrated a more ductile fracture behavior than PET (polyethylene terephthalate) matrix composites. Fiber shrinkage, matrix deformation, and interlayer separations are prominently observed in CPP-based samples, signifying that the impact energy is absorbed more efficiently. Notably in the CPP_GCG and CPP_G samples, significant fibril formations were identified on the fracture surfaces, indicating that the fibers were extracted from the matrix prior to fracture, dissipating energy,

and demonstrating predominant ductile behavior. Conversely, a more brittle fracture behavior was seen in PET matrix samples, characterized by smooth, short, and fractured fiber ends, which exemplified typical brittle fiber fractures. This suggests that the PET matrix, owing to its more rigid structure, was unable to absorb energy, leading to abrupt breakage. Moreover, hybrid constructions (CGC and GCG) demonstrated enhanced impact resistance relative to flat glass or carbon-reinforced structures in both matrix types. This indicated that the energy distribution was more uniform and the fiber-matrix interaction was enhanced due to the synergistic effect of several fibers. The CPP matrix demonstrated superior impact resistance, which was further enhanced by hybrid reinforcement configurations.

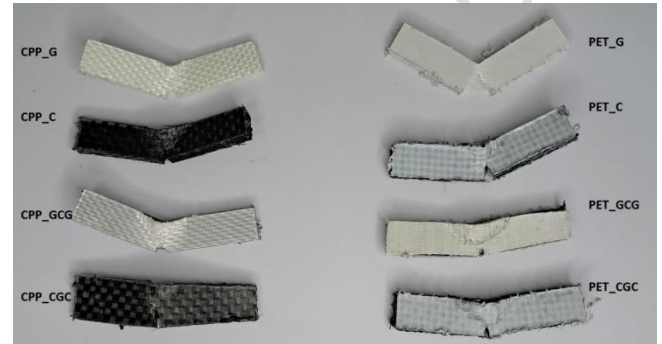


Figure 7. Macroscopic view of Charpy-tested composite specimens.

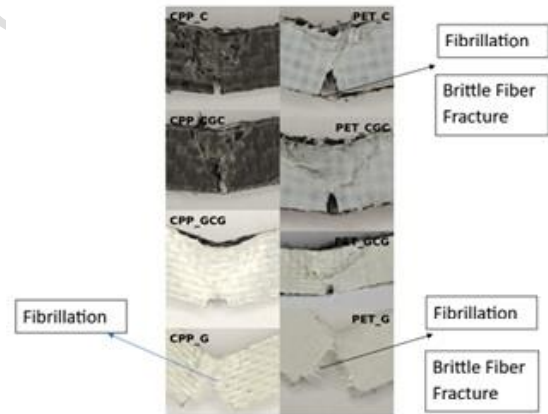


Figure 8. Close-up views of fracture surfaces after Charpy impact test.

5 Conclusions

This work examined the Charpy impact performance of laminated thermoplastic composites utilizing CPP and PET matrices, reinforced with glass, carbon, and hybrid fiber arrays; the influence of matrix type and layer configuration on energy absorption capacity and impact toughness was assessed.

The notable enhancement in impact toughness seen in hybrid stacking sequences, especially the GCG configuration, aligns with prior research highlighting the synergistic benefits of integrating carbon and glass fibers in thermoplastic composites. Swolfs et al. [20] emphasized that the hybridization of high-stiffness carbon fibers with more ductile glass fibers improves energy absorption by optimizing the balance between stiffness and toughness. Gopinath et al. [21] similarly indicated that G/C/G-type stacking sequences

markedly enhance edgewise impact resistance through improved stress distribution and progressive damage processes. The enhanced performance of CPP-based laminates relative to PET-based ones can be attributed to the better ductility of CPP, which enables more efficient energy dissipation during dynamic loading, as observed by Kim and Mai [22]. Moreover, Oksman et al. [23] shown that ductile thermoplastic matrices enhance the fiber-matrix interfacial adhesion upon impact, hence significantly augmenting toughness. The findings together confirm that both matrix ductility and hybrid fiber architecture are essential in enhancing the impact performance of thermoplastic composites under edgewise loading.

In the Edgewise Charpy impact tests, hybrid reinforcement designs, particularly the GCG sequence, markedly improved the impact toughness of both CPP and PET-based thermoplastic composites. The CPP_GCG arrangement demonstrated the greatest energy absorption, surpassing PET_G by around 86% and CPP_G by 27%, underscoring the efficacy of integrating carbon and glass fibers in layered stacking. PET_GCG demonstrated a 52% enhancement compared to PET_G, while its performance was still inferior to that of its CPP-based equivalents. The results affirm that, although CPP offers a more ductile matrix with intrinsically greater toughness, implementing hybrid fiber configurations can notably improve the impact resistance of stiffer PET composites under edgewise loading.

6 Author contribution statement

In the study carried out, Author 2 contributed to the formation of the idea, design, procurement of the materials used and examination of the results; Author 1 contributed to the production of the samples used, evaluation of the results obtained, proofreading and reviewing the article's content

7 Ethics committee approval and conflict of interest declaration

There is no need for ethics committee approval for the prepared article.

There is no conflict of interest with any person/institution in the prepared article.

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