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Original Article

Mechanical Behavior of Glass Fiber-Reinforced Polyphenylene Sulfide with Carbon Nanofiber Additions

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***Abstract** - This study systematically investigates the impact of Carbon Nanofiber (CNF) incorporation on the mechanical behavior of Glass Fiber-Reinforced Polyphenylene Sulfide (GF/PPS) composites. Tensile, flexural, and impact tests were conducted on composite samples with CNF loadings ranging from 0.2 wt% to 1.0 wt%, following ASTM standards to quantify the resulting changes in mechanical properties. According to tensile tests, adding 0.8 wt% CNF greatly increased stiffness, increasing tensile modulus by 11.1% and tensile strength by 4.6%. With the same CNF loading, flexural testing also showed significant gains, with a 27.2% increase in flexural modulus and a 19.5% increase in flexural strength. Scanning Electron Microscopy (SEM) sheds light on the mechanisms of failure. Furthermore, the tensile and flexural properties of GF/PPS composites are successfully improved by the selective addition of CNFs, especially at optimal concentrations, making these hybrid materials excellent choices for demanding structural engineering applications. However, the addition of CNF to GF/PPS reduced impact strength while increasing stiffness and modulus. This could have occurred because the material's ductility and toughness were diminished by the increased stiffness, which limited its capacity to absorb impact energy through deformation and might have caused fracture initiation and propagation rather than energy dissipation.*

***Keywords** - GF/PPS composite, Carbon nanofibers, Hybrid composites, Mechanical properties, Scanning Electron Microscopy.*

1. Introduction

Hybrid nanocomposites are emerging as advanced materials for structural applications due to their potential to overcome the limitations of conventional composites and monolithic materials. These hybrid systems can demonstrate synergistic benefits by carefully integrating various nanoscale reinforcements into a fiber-reinforced polymer composite, resulting in improved and frequently customized mechanical, thermal, electrical, and barrier properties. They are very appealing for demanding structural applications across a variety of industries, such as aerospace, automotive, and construction, where high performance and light weight are crucial, due to their exceptional capacity to simultaneously customize several functionalities [1, 2].

The wide range of applications for polymer based composite materials demonstrates their adaptability. Their high strength-to-weight ratio is essential in the aerospace sector for preserving structural integrity while lowering the bulk of spacecraft and airplanes. Composites also help the automotive industry produce lighter, more fuel-efficient cars without sacrificing performance or safety. Additionally, composites are essential to the renewable energy industry, especially for the creation of strong and lightweight wind turbine blades. The use of composite materials extends beyond these high-performance applications to commonplace products. Composites, for instance, are utilized in the construction sector to create strong, weather-resistant building materials that can tolerate challenging environmental circumstances. Composites are used in golf clubs, tennis rackets, and bicycles to give athletes robust, lightweight equipment that improves performance. Composite materials' versatility in meeting the unique requirements of different industries highlights their significance in both cutting-edge and commonplace technologies [3–6].

The performance of the composite is greatly influenced by the type, orientation, and distribution of its reinforcement/functional fillers inside the matrix. To maximize strength where it is most needed, fiber orientation in fiber-reinforced composites, for example, can be adjusted to match load routes inside a structure. Because it dictates the effectiveness of load transmission between the two phases, the link between the reinforcement and matrix is also crucial. [7, 8]. Functional fillers reduce shrinkage and voids, and enhance the composites' stiffness and thermal deflection temperatures [9]. A high-performance, semi-crystalline thermoplastic appreciated for its remarkable property balance, Polyphenylene Sulfide (PPS) can be used in a wide range of demanding applications. Its chemical structure, which consists of aromatic rings connected by sulfur atoms, gives it its distinctive qualities. PPS is commonly mixed with fillers and reinforcements, including glass fibers, carbon fibers, and minerals, to customize its mechanical, thermal, and electrical properties for particular applications [10]. Cho and Bahadur examined the dynamic mechanical characteristics and tribo-behaviour of PPS composites reinforced with Carbon Nanofiber (CNFs) in this study [11]. The Tg, crystallization temperature, and melting point were slightly altered by CNF reinforcement; however, the composites' steady-state wear rates when sliding against a rougher counterface were much decreased. The process of melt blending PPS and Polyarylene Sulfide Sulfone (PASS) and creating PPS/PASS/Glass Fiber Cloth (GFC) composites was examined by Zhao et al. [12]. Although the strength and modulus of the PPS/PASS blends were slightly reduced by the inclusion of PASS, these characteristics were unexpectedly improved in the PPS/PASS/GFC composites, indicating a better interaction between PPS and GFC.

Zhao et al. effectively created stiff, high-strength composites with ultra-high Glass Fiber Fabric (GFF) and PPS using a simple thermo-compression method. Their findings indicated that an 80 wt% GFF composition yielded excellent wettability and superior mechanical properties, including a flexural modulus of 78.5 GPa and a tensile strength of 850.6 MPa. The enhanced performance was attributed to increased interfacial layers and a gripping effect among GFFs, hindering crack propagation and suggesting this composite as a potential replacement for GF/epoxy composites and conventional metals [13]. Important information for selecting the appropriate types of reinforcement for demanding engineering applications in PPS composites is provided by the study carried out by Li et al. [14]. Short Glass Fiber (SGF) and Short Carbon Fiber (SCF) reinforced Polypropylene (PP) composites were produced by Rudrappa et al. [15], both separately and in hybrid form. The results showed that the best tensile and flexural qualities were obtained with hybrid reinforcement (10 wt% SGF + 20 wt% SCF). SGF reinforcement at 30 wt% showed the highest notched Izod impact strength among the investigated composites, even though SCF inclusion increased tensile and flexural strength. The effect of adding more carbon fiber layers on the mechanical, thermal, and microscopic characteristics of PPS composites made by hand lay-up and compression molding was investigated in the study by Shahzad Maqsood et al. [16].

Remarkably, adding more fiber layers improved mechanical stability, greatly improving bending modulus and transverse rupture strength without sacrificing toughness. Thermogravimetric Analysis (TGA) verified increased thermal stability with more fiber layers, while microscopic examination showed linear crack development and strong matrix-reinforcement adhesion. The impact of different compatibilizers on CF-reinforced PPS composites of polyamide size made by melts blending and injection molding was examined by Durmaz et al. [17]. While SEM and Dynamic Mechanical Analysis (DMA) showed that Joncryl offered the strongest interfacial adhesion between the CF and PPS matrix, tensile tests showed that Joncryl produced the largest gains in tensile strength and strain at break. The efficiency of Joncryl as a compatibilizer for improving these composites' mechanical characteristics and interfacial bonding is demonstrated in this work. Diez-Pascoal et al. [18] explored the impact of inorganic fullerene-like tungsten disulfide nanoparticles on the thermal and mechanical properties of CF/PPS composites. Their findings indicated that incorporating these nanoparticles enhanced fiber impregnation, compression, and flexural properties. Furthermore, the resulting hybrid laminates demonstrated a higher ignition point and a lower peak heat release rate compared to the standard CF/PPS composite.

Nevin Gamze et al.'s work shows that adding 0.5 wt% graphene nanoplatelets and 2 wt% terpolymer at the same time greatly improves the mechanical characteristics and tribo-characteristics of PPS composites reinforced with CFs. The results present a viable way to enhance the performance of composite materials in demanding applications, such as the automotive and aerospace sectors, where exceptional mechanical and wear resistance characteristics are crucial [19].

The effects of different surface coatings on the mechanical, thermal, and morphological characteristics of carbon fiber reinforced PPS composites were examined by Bedriye Ucpinar and colleagues [20]. Comparing the composites with polyurethane-coated CFs to those with unsized CFs or other coatings, the study shows that the former have greater adhesion, modulus, and tensile strength. Guimarães et al. [21] developed a method to enhance the fracture resistance and mechanical strength of polymer composites by incorporating SCFs into continuous CF/PPS laminates using hot compression molding. The study found that while the mixed composite, consisting of 50 wt% continuous and 50 wt% SCFs, exhibited lower tensile strength and shear strength compared to the purely continuous fiber composite, it showed only an 11.9% reduction in compression strength, indicating a synergic gain in this property.

Carbon Nanofibers (CNFs) have recently been explored as an additional reinforcement to further enhance the mechanical performance of Glass Fiber Reinforced Polymer Composites (GFRPCs). CNFs possess remarkable tensile strength and stiffness, along with electrical conductivity, which make them suitable for hybrid composite systems [22-24]. In the study, Müller et al. [25] investigated the creation of an electromechanical response in glass fibers with the use of electrically conductive carbon allotropes such as conductive Carbon Black (CB), Graphene Nanoplatelets (GNP), or Carbon Nanotubes (CNT) to nanostructure their interphase. Depending on the type of carbon nanoparticle and its conductive network, these modified glass fibers can subsequently be utilized in polypropylene composites for online structural-health monitoring. Their electrical signals will show qualitative variations in signal quality and sensitivity. Bidirectional CF-Reinforced Polymer Composites (CFRPCs) mechanical properties are examined by Selim Mrzljak et al. [26] in relation to the impact of oriented CNFs. The findings show that aligning the CNFs has a major effect on the CFRPCs' quasi-static and fatigue characteristics, increasing their strength and preventing damage accumulation. Al-Saleh and Sundararaj's thorough review work examined the mechanical characteristics of Vapor-Produced Carbon Nanofiber (VG-CNF)/polymer composites, starting with the VGCNFs' inherent mechanical and structural characteristics. The main determinants of these composite features are next examined, including aspect ratio, filler dispersion, and the critical function of adhesion and interface between the VGCNFs and the polymer matrix [27]. Rodriguez et al. [28] used Multiscale-Reinforcement Fabrics (MRFs) to fabricate and characterize hierarchical polymer composites, specifically CNF/fiber-reinforced polymer composites. Comparing functionalized CNFs to the basic composite, the addition of CNFs greatly increased the compressive strength and Interlaminar Shear Strength (ILSS), with amine-functionalized CNFs producing the largest gains. To enhance the thermomechanical properties of the produced nanocomposites,

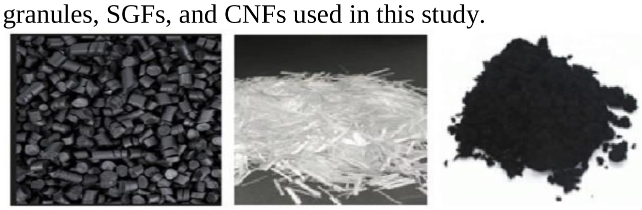
Hossain et al. [29] used sonication to scatter CNFs into a polyester matrix. An 88% increase in flexural strength and a 35% rise in storage modulus were among the notable improvements that resulted from the ideal dispersion of 0.2 wt% CNF, which was reached after 90 min of sonication at 50% amplitude. The impact of CNFs and their aggregates with micro-sized SCFs on the mechanical, thermal, and fracture properties of an epoxy (80 wt%)-Polylactic Acid (PLA) (20 wt%) composite was investigated by Nimbagal et al. [30]. Comparing composites reinforced with this integrated multi-scale filler system to those reinforced only with CNFs, the study discovered that the former had better tensile, flexural, impact, and fracture toughness properties. In particular, the hybrid nanocomposites demonstrated significant gains in these characteristics, with fracture toughness rising by 37.93–38.77% and tensile, flexural, and impact strengths increasing by 17.18–25.72%, 39.24–44.07%, and 39.87–97.05%, respectively.

Even though the mechanical, thermal, and tribological characteristics of PPS composites reinforced with different materials, namely GFs, CFs, and CNFs, are well covered in the literature currently in publication, little is known about the combined, synergistic effects of CNFs integrated specifically into PPS composites reinforced with SGFs. Prior research has examined GF cloth in PPS [12, 13], hybrid SGF and SCF in PP [15], CNF reinforcement in PPS [11], and even hybrid continuous and SCFs in PPS [21]. Nevertheless, nothing is known about the precise analysis of the interaction and improvement of properties that occur when nanoscale CNFs are added to an SGF/PPS matrix. This study is particularly interesting as it explores the addition of CNFs as a secondary reinforcement to PPS composites already reinforced with SGFs. Furthermore, this study is the first to examine the synergistic or hybrid reinforcement impact of mixing both SGFs and CNFs within the PPS matrix, even though the individual effects of CNFs [11] and different fiber reinforcements [12, 13, 15, 16, 21] in PPS are well documented. The research currently in publication has not fully investigated this particular combination, especially with regard to its effect on mechanical properties.

The goal of this work is to methodically examine how adding CNFs to SGFs reinforced PPS composites affects their mechanical properties based on existing literature. In order to find any synergistic improvements or ideal loading conditions for enhanced composite performance, this study attempts to comprehend how the presence of CNFs in combination with SGFs influences the mechanical properties, such as tensile strength, flexural strength, and impact strength. Furthermore, by analyzing tensile, flexural, and impact properties at different CNFs loading, this study seeks to contribute further to the understanding of PPS-based hybrid composite behavior as well as to develop high-performance materials for structural applications.

2. Materials and Methods

In this study, Polyphenylene Sulfide (PPS) has been chosen as a base material because of its excellent combination of mechanical properties and thermal behavior. PPS offers inherent flame retardancy, chemical resistance, and dimensional stability, making it ideal for environments where composites are exposed to heat, chemicals, or harsh operating conditions. Polyphenylene Sulfide (PPS) granules were sourced from Padmini Innovative Marketing Solutions Pvt. Ltd, Mumbai, India. Short Glass Fibers (SGFs) with a diameter of 13 µm and a length of 6 mm were procured from Fine Organics, Mumbai, India. Carbon Nanofibers (CNFs), which are derived from the thermal breakdown of hydrocarbons like methane and benzene in the presence of metal particles acting as catalysts through a fluidized bed, were provided by Aritech Chemazone Pvt Ltd, India. This material typically has a bamboo-like structure, with lengths exceeding 80 µm and diameters varying from 30 to 300 nm. Figures 1(a), (b), and (c) respectively display the PPS granules, SGFs, and CNFs used in this study.



(a) (b) (c)

Fig. 1 Photographs of (a) PPS granules, (b) SGFs, and (c) CNFs.

In order to produce high-performance composites, PPS was chosen as the matrix, and SGFs and CNFs were added as reinforcements. PPS is perfect for demanding applications because it provides a great balance of characteristics, such as strong thermal stability, chemical resistance, and outstanding processability. SGFs, an affordable and easily accessible main reinforcement, greatly improve the PPS matrix's mechanical characteristics by raising its modulus, tensile strength, and flexural strength while also enhancing dimensional stability. Nevertheless, a multi-scale reinforcement strategy is introduced with the addition of CNFs. They may act at the micro/nano-scale because of their remarkable intrinsic traits, including great tensile strength and stiffness and their nanoscale dimensions. Better load transfer, altered damage mechanisms inside the composite, and enhanced interfacial adhesion between the polymer matrix and the SGFs are all possible outcomes of this. By integrating these three elements, the study hopes to investigate possible synergistic effects and, in the end, produce composites with better mechanical performance.

2.1. Preparation of Hybrid Nanocomposites

Figure 2 illustrates the methodology for fabricating test specimens of PPS-based hybrid nanocomposites. First, different weight fractions of CNFs, glass fibers, and precisely measured PPS were made. In order to ensure homogeneous mixing and dispersion of CNFs within the PPS matrix, the composite materials used in this investigation were treated using a twin-screw extruder. Starting at 80°C in zone 1 and progressively rising to 345°C by zone 9, where the polymer achieved its molten state, the extruder ran on a carefully regulated temperature profile. The glass fibers and CNFs were effectively mixed with the PPS at this ideal temperature. Consistent material flow was guaranteed by the die, which was also kept at 345°C.

Following extrusion, the composite material was transferred into a pelletization machine, wherein it was chopped into uniformly sized pellets with a 44:1 length-to-diameter ratio that could be used for further molding. Reliable mechanical testing and analysis depend on the final composite material's consistent qualities, which were guaranteed by the careful control of these parameters.

The specimens were fabricated using a pneumatic injection molding machine, which assured exact control over material flow and shaping. Molds made to satisfy ASTM requirements for mechanical testing, viz. ASTM D638 for tensile, ASTM D790 for flexural, and ASTM D256 for impact specimens were filled with the molten composite that had been pre-mixed with specified amounts of CNF. By ensuring uniform specimen size and shape, this standardization makes it possible to evaluate mechanical properties with accuracy and dependability. Injection molding also made it easier to produce high-quality test specimens that accurately represented the PPS/CNF hybrid composites' mechanical performance at different nanofiber concentrations.

In all hybrid composites, 40 wt.% of SGFs were incorporated to prepare the final PPS/SGF/CNF hybrid composites. PPS, PPS/CNF 0.2%, PPS/CNF 0.4%, PPS/CNF 0.6%, PPS/CNF 0.8%, and PPS/CNF 1.0% were the codes assigned to the specimens according to their CNF loading.

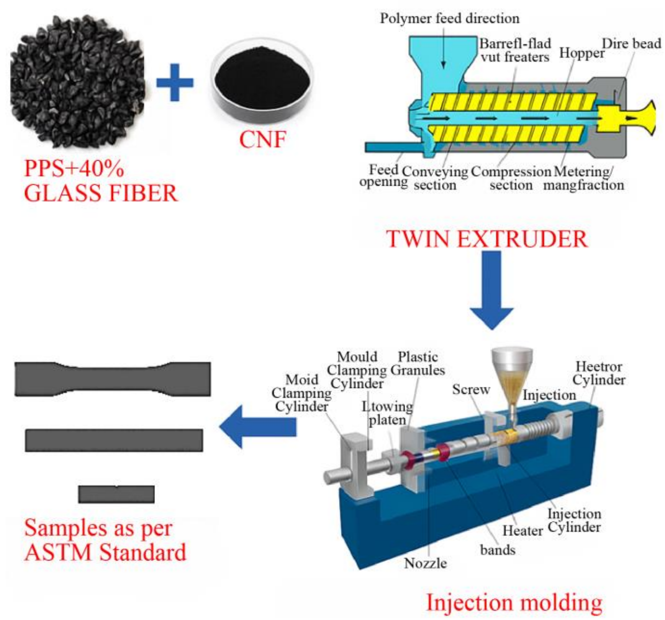


Fig. 2 Fabrication methodology for PPS-based hybrid nanocomposite test specimens

Table 1. Raw material compositions for SGF/PPS composites with varying CNFs (0-1.0 wt.%)

Composite Designation	PPS (g)	Glass Fiber (g)	Stabilizer (g)	CNF (g)	Batch Weight (g)
PPS	2990	2000	10	0	5000
PPS/CNF 0.2%	2980	2000	10	10	5000
PPS/CNF 0.4%	2970	2000	10	20	5000
PPS/CNF 0.6%	2960	2000	10	30	5000
PPS/CNF 0.8%	2950	2000	10	40	5000
PPS/CNF 1.0%	2940	2000	10	50	5000

Table 1 summarizes the detailed raw material compositions used to prepare SGF/PPS composites with 0 to 1.0 wt% CNFs.

2.2. Mechanical Testing Specimens

2.2.1. Tensile Test Specimen

As per ASTM D638, which guarantees consistent dimensions (165 mm overall length, 13 mm narrow neck, and 19 mm broad ends) for accurate tensile strength and elongation data, Type I specimens (Figure 3(a)) were used for tensile testing in this investigation. The mechanical performance of the hybrid composite may be effectively compared with that of other materials and research thanks to this standardized approach, which ensures consistent results.

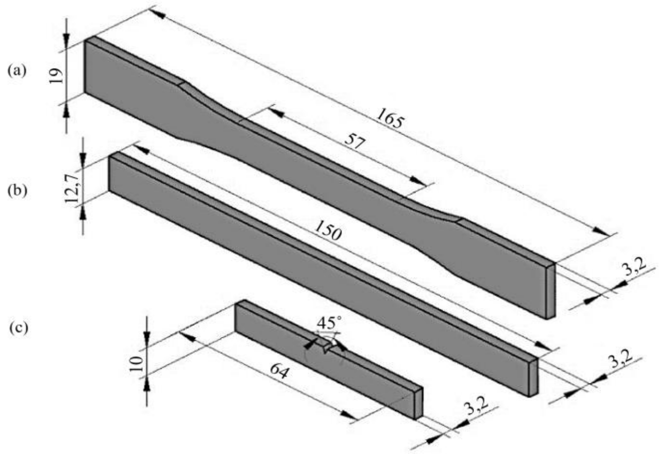


Fig. 3 Mechanical testing samples (a) Tensile test specimen ASTM D638, (b) Three-point bend test specimen ASTM D790, and (c) Impact test specimen ASTM D256.

2.2.2. Three-Point Bend Test Specimen

Two bending test methods are described in ASTM D790; specimens that fracture at less than 5% strain are subjected to the three-point bending test. The vertical load is delivered precisely at the center of standard specimens, which are normally 150 mm long, 12.7 mm wide, and 3.2 mm thick, as shown in Figure 3(b).

2.2.3. Impact Test Specimen

As per ASTM D 256, the Izod impact test specifies different specimen dimensions. The ASTM standard requires an 84 mm long, 10 mm wide, and 4 mm thick specimen, featuring a 2 mm deep V-notch precisely cut at its midpoint as depicted in Figure 3(c).

2.3. Mechanical Properties Testing

2.3.1. Tensile Testing

In accordance with ASTM D638-10 guidelines [32], tensile properties were assessed using a JJ Lloyd universal testing machine with a 20 kN capacity. Five dumbbell-shaped samples of each composite composition were tested for tensile strength, modulus, and strain at break values at a constant crosshead speed of 25 mm/min.

2.3.2. Three-Point Bending Test

A Lloyd's Universal Testing Machine with a 20 kN capacity and a 5 kN load cell was used to perform a three-point bending test in accordance with ASTM D790-03 to ascertain the flexural parameters [33]. Five samples of each material class were evaluated at room temperature. They had the following measurements: 150 mm x 12.5 mm x 3.5 mm. The load was applied at the center until maximum bending was accomplished, while maintaining a crosshead speed of 2 mm/min and a support span-to-depth ratio of 16:1. An attached computer recorded the applied load, and the average of five data points was calculated.

2.3.3. Izod Impact Test

Impact tests were conducted on an Avery Denison impact tester in accordance with the ASTM D256 standard [34]. Specimens measured 60 mm × 12 mm × 3.5 mm and were notched to achieve a remaining width of 10.16 mm. A hammer was released at a velocity of 3.46 m/s to strike each specimen. To confirm the results, five specimens were tested for each composition.

3. Results and Discussion

3.1. Effect of CNF Loading on Tensile Properties of SGF/PPS Composites

A series of tensile tests were conducted in accordance with the ASTM D638 standard using a computerized universal testing machine to evaluate the ultimate tensile strength of PPS reinforced with 40 wt% Short Glass Fibers (SGF), as well as the same composite further modified with Cellulose Nanofibers (CNFs) at varying weight fractions (0.2, 0.4, 0.6, 0.8, and 1.0 wt%) at ambient temperature. The results depicted in Figure 4 and listed in Table 2 show that the addition of CNFs to the SGF / Polyphenylene Sulfide (PPS) composites exhibits a clear trend in mechanical performance, particularly with respect to tensile strength and tensile modulus. Both strength and tensile modulus gradually improve as the CNF loading rises from 0 to 0.8 wt%. While the tensile strength increases from 210 MPa to 219.65 MPa (Table 2) over the same range, the tensile modulus increases from 11.81 MPa at 0 wt% CNF to a peak of 13.12 MPa at 0.8 wt% CNF.

Table 2. Tensile test results of SGF/PPS hybrid nanocomposites

Composites CNF (wt%)	Strength (MPa)	Modulus (MPa)	Elongation (%)
0.0	210	11813	3.79
0.2	214.71	12394	3.64
0.4	215.54	12677	3.56
0.6	217.04	12850	3.46
0.8	219.65	13120	3.35
1.0	216.42	11968	3.22

The tensile modulus increased by about 11.06% at 0.8 wt% CNF loading, from 11.81 MPa (at 0 wt% CNF) to 13.12 MPa. In the same way, the tensile strength rose from 210 MPa to 219.65 MPa, which is about 4.6% higher than the unfilled composite. The high stiffness and aspect ratio of CNFs, which are evenly distributed, facilitate efficient stress transfer and enhanced interfacial bonding within the composite matrix, and are responsible for this improvement. Nevertheless, both properties slightly decline at 1.0 weight percent CNF, with the tensile strength falling to 216.42 MPa and the tensile modulus to 11.97 MPa (Table 2). CNF agglomeration, which may result in stress concentration sites and obstruct efficient load transfer, is probably the root cause of this decrease in reinforcing efficiency. These results imply that the ideal CNF loading for mechanical enhancement in SGF/PPS composites is approximately 0.8 wt%; above this, the benefits diminish because of dispersion issues.

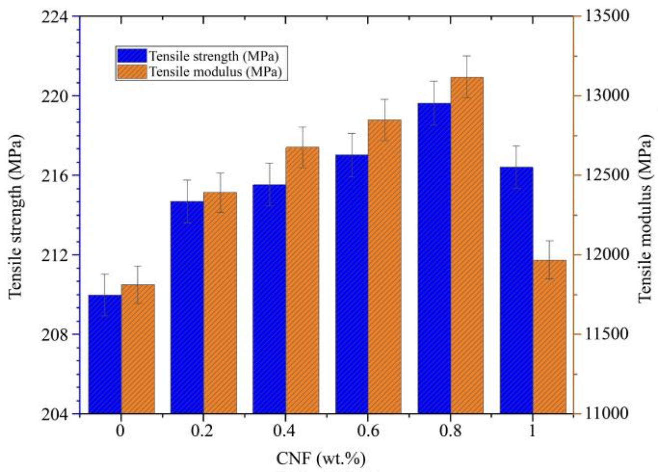


Fig. 4 Tensile strength and tensile modulus of CNF modified SGF/PPS hybrid nanocomposites

Glass fibers are excellent for increasing the load-bearing capacity of soft substrates because of their exceptionally high tensile strength and significant resistance to thermal deformation along their length. The PPS matrix in composites provides strong support for glass fibers, facilitating effective load transfer between the reinforcement and matrix. Due to the synergistic improvement in mechanical and thermal properties, a sizable portion of PPS composite materials is made of PPS reinforced with GFs [35-37]. According to Xu et al. [38], integrating Graphene Oxide (GO)-grafted glass fiber to Liquid Crystal Polymer (LCP) / PPS composites is a useful method for increasing their tensile and flexural strengths. Even in small amounts, the incorporation of TiO_2 nanoparticles into the polymer enhances an assortment of mechanical properties, which include strength, toughness, and flexibility [39]. Based on similar findings, the present work demonstrates that adding CNF up to 0.8 wt% improves the tensile strength and tensile modulus of the SGF/PPS composite.

3.1.1. Effect of CNF Loading on Percentage Elongation of SGF/PPS Composite

Table 2 summarizes the elongation percentage, and Figure 5 shows that as CNF loading increases, the elongation percentage of SGF/PPS composites gradually drops from about 3.8% to 3.2%. This pattern suggests that ductility decreases with increasing CNF loading. The decrease can be explained by the intrinsic rigidity of CNFs, which limits polymer chain mobility and makes the composite less pliable and able to undergo plastic deformation. Furthermore, CNFs have a tendency to aggregate at higher loadings, creating clusters that serve as sites of stress concentration and encourage the initiation of cracks under tensile loading. Premature failure results from these agglomerates because they obstruct efficient load transfer and uneven stress distribution. However, tensile properties are improved by lower CNF loadings (up to 0.8 wt%). Thus, it is essential to maximize the CNF content in the composite in order to preserve a balance between mechanical strength and elongation.

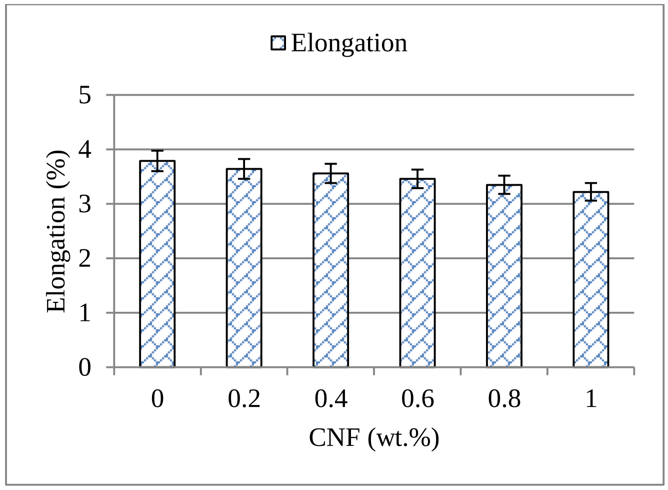
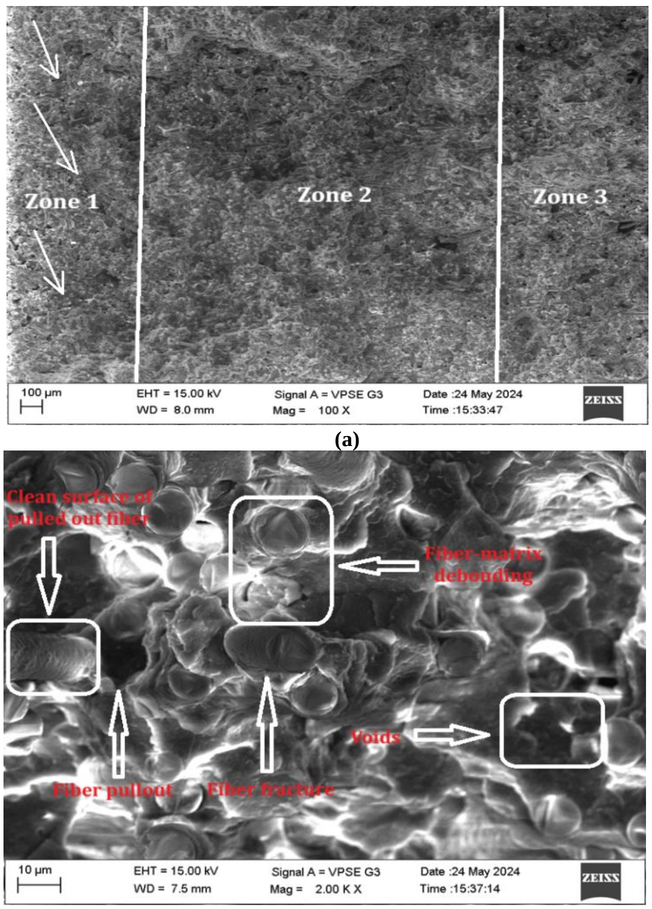


Fig. 5 Percentage of elongation of CNF modified SGF/PPS hybrid nanocomposites

3.1.2. Tensile Failure of SGF/PPS Hybrid Nanocomposites

Key failure mechanisms at different levels have been identified by the SEM fractographic analysis of tensile-failed Short Glass Fiber (SGF) reinforced Polyphenylene Sulfide (PPS) composites, as shown in Figures 6(a) and (b). Three separate zones can be seen in the low-magnification image (Figure 6(a)): Zone 1 displays oriented damage lines that indicate the beginning of a crack, most likely as a result of stress concentrations; Zone 2 depicts a stable crack propagation region with uniform morphology; and Zone 3 is a rapid fracture zone that is linked to catastrophic matrix or fiber failure.

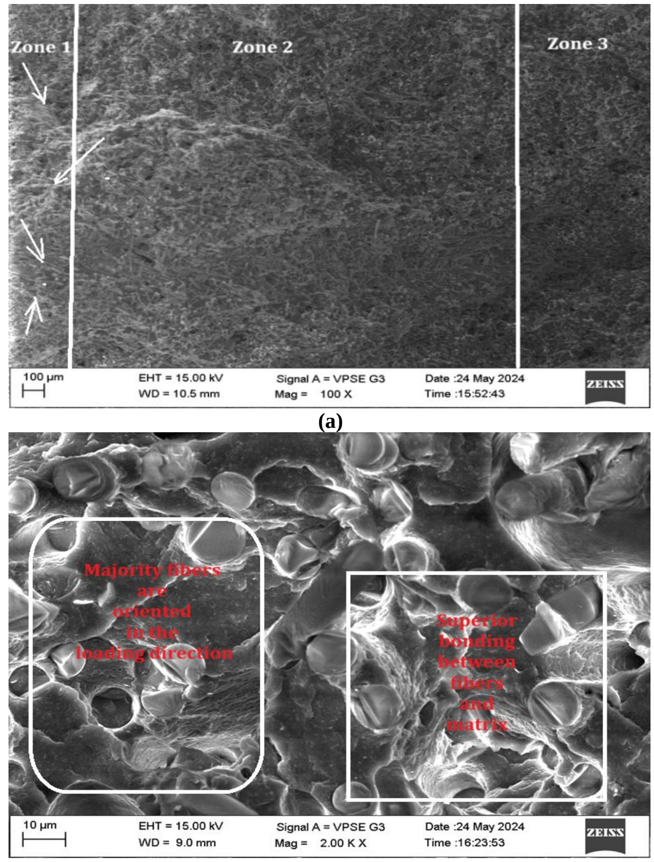
The photomicrograph depicted in Figure 6(b) indicates poor fiber-matrix adhesion, such as fiber pull-out, clean fiber surfaces, and interfacial debonding, which are highlighted in the high-magnification image. Whereas voids, which act as stress concentrators that encourage early crack initiation, indicate manufacturing flaws or insufficient matrix impregnation, fiber fractures show situations where the load exceeded fiber strength. These features together show a mixed-mode failure mechanism that includes fiber breakage, interfacial debonding, fiber pull-out, and brittle matrix cracking. This highlights the importance of interface quality and processing conditions in determining the composite's tensile performance. These observed fractographic features offer strong support for the tensile properties results obtained and provide an unambiguous explanation for the decreased modulus and tensile strength of the SGF/PPS composites discussed earlier in Figure 4.



(b)

Fig. 6. Photomicrography of SGF/PPS tensile failed sample (a) Lower magnification image (arrows indicate river marks), and (b) Lower magnification image,

The fractographic characteristics of the tensile-failed SGF/PPS composites modified with 0.8 wt% Carbon Nanofibers (CNFs) are shown in the photomicrographs in Figures 7(a) and (b). These features show different mechanisms that led to improved tensile strength and modulus in comparison to the unmodified composite (SGF/PPS). Three zones are distinguished on the fracture surface in Figure 7(a) (low magnification): The direction of crack initiation and early crack propagation under tensile loading is indicated by river marks (shown by arrows) in Zone 1. In a matrix reinforced by evenly spaced CNFs, Zone 2 exhibits a more uniform morphology with aligned textures, indicating stable crack growth. The last fracture zone, zone 3, seems more compact and refined, suggesting a more resilient and ductile failure mode.



(b)

Fig. 7 Photomicrography of 0.8 wt% CNFs modified SGF/PPS tensile failed sample (a) Lower magnification image, and (b) Lower magnification image.

Important microstructural characteristics can be seen in Figure 7(b) (high magnification): most fibers are oriented in the direction of tensile loading, which facilitates efficient load transfer and increases tensile strength. A stronger bond between the fiber and matrix is also seen, as evidenced by clean debonding surfaces and fewer indications of fiber pull-out. This strong interfacial adhesion, probably made stronger by CNF-induced interphase strengthening, shows that stress is efficiently transferred from matrix to fiber, preventing early crack initiation and debonding. These characteristics collectively show that CNF reinforcement causes a change in fracture behavior from brittle to more ductile, supporting the improved tensile characteristics previously reported for this composite system, as discussed earlier in Figure 4.

3.2. Effect of CNF Loading on Flexural Properties of SGF/PPS Composites

Flexural modulus and flexural strength are both markedly enhanced by the addition of CNF to the SGF/PPS composite up to 0.8 wt% CNF loading, according to the results shown in Figure 8. These properties are listed in Table 3. With a steady increase from 15,000 MPa at 0 wt% CNF to a maximum of 19.11 MPa at 0.8 wt% CNF, the flexural modulus shows an improvement of about 27.23%. Likewise, the flexural strength increases by 19.52%, from 300 MPa to 358.56 MPa, at 0.8 wt% CNF (Table 3). This improvement can be ascribed to the robust reinforcing effect of CNFs, which enhance the fiber-matrix interface and act as efficient load-bearing fillers to improve stress transfer and stiffness within the composite.

Table 3. Flexure and impact test results of CR-Epoxy nanocomposites

Composites CNF (wt%)	Strength (MPa)	Modulus (MPa)	Impact Strength (J/m^2)
0.0	300.01	15000	11
0.2	320.68	16916	8.89
0.4	328.96	17603	8.45
0.6	341.26	18505	7.85
0.8	358.56	19085	7.45
1.0	320.87	15985	7.19

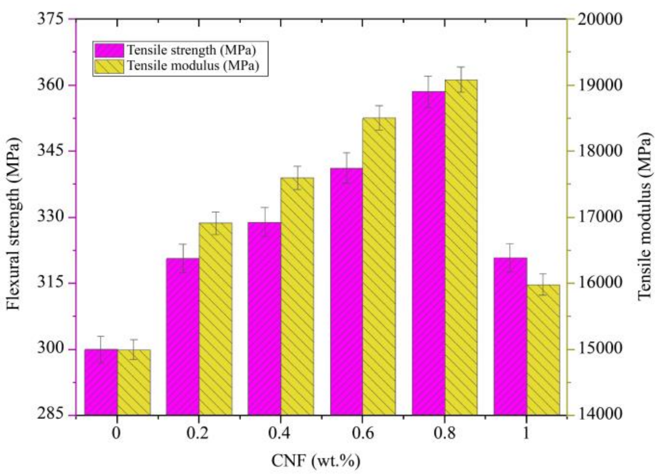


Fig. 8 Flexural strength and flexural modulus of CNF modified SGF/PPS hybrid nanocomposites

However, both strength and flexural modulus significantly decrease at 1.0 wt% CNF, indicating that excessive CNF loading causes agglomeration, poor dispersion, or stress concentration sites that weaken the composite structure. Small amounts of nanofillers, such as CNFs or TiO_2 nanoparticles, improve mechanical properties by strengthening the matrix and enhancing interfacial bonding; however, higher loadings frequently result in particle clustering and decreased performance. These trends are in line with similar findings that have been documented in the literature. For instance, Xu et al. [38] demonstrated enhanced tensile and flexural strengths in composites reinforced with functionalized fibers and TiO_2 nanoparticle-filled polymers [39] revealed improvements in strength and toughness at low filler loading. Author earlier reported that Thermoplastic Copolyester (TCE)/PTFE and Polyoxymethylene (POM) / PTFE composites, when reinforced with short glass or carbon fibers, as well as Silicon Carbide (SiC) and Alumina (Al_2O_3) fillers, exhibited enhanced flexural strength and modulus. The feasibility of a direct fiber feeding extrusion method for creating Glass Fiber (GF)-reinforced modified Polyphenylene Oxide (mPPO) composites is examined by Ahn et al. [40]. As the fiber content increased up to 50 weight percent GF, the resulting composites demonstrated improved tensile and flexural properties; however, the fiber efficiency factor for tensile strength was decreased by a larger core area seen in the cross-section of the 50 wt% GF composite. According to Liang [41], the mechanical properties of PPS/Polycarbonate (PC)/GF hybrid composites, such as Young's modulus, tensile strength, flexural strength, and elongation at break, were improved by the addition of nano-$CaCO_3$. The best results were noted at a filler content of 6 weight percent. The majority of properties decreased above this concentration, suggesting an ideal filler threshold for effective toughening and reinforcement. Thus, the optimal CNF content in this work aligns well with these established observations, confirming that balance between reinforcement and dispersion is key to maximizing composite performance.

3.3. Effect of CNF Loading on Impact Strength of SGF/PPS Composites

As the CNF loading rises from 0 to 1.0 wt%, the SGF/PPS composite's impact strength gradually declines, as shown in Figure 9, and the results are summarized in Table 3.

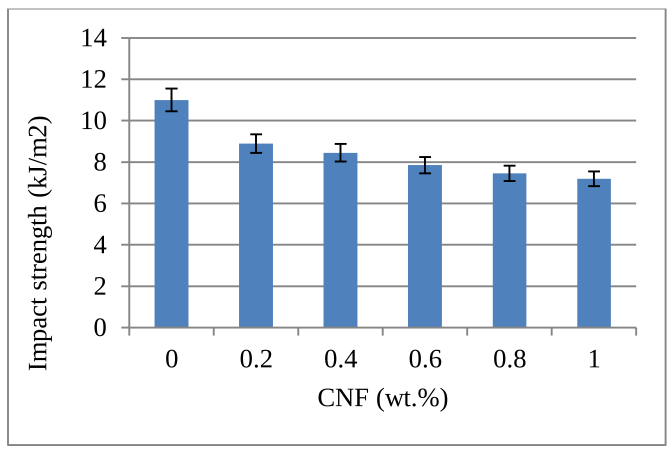


Fig. 9 Impact strength of CNF modified SGF/PPS hybrid nanocomposites

The impact strength decreases to 7.19 KJ/m² at 1.0 wt% CNF from 11 KJ/m² without CNF. This decrease is explained by the addition of rigid CNFs, which make the composite more brittle and improve its stiffness but decrease its capacity to absorb impact energy. Higher CNF loadings can also result in poor dispersion or agglomeration, which can create stress concentration points that make it easier for cracks to start and spread when struck. This type of behavior is typical of nanofiller-reinforced composites, where increased filler content frequently results in a trade-off between impact toughness and stiffness and strength.

Hossain et al.'s [42] studies of plain weave E-glass/polyester and E-glass/polyester-CNF composites under low-velocity impact loading showed that although nanophased composites, especially those containing 0.2 wt% CNF, showed higher peak loads than conventional ones, they absorbed less energy, suggesting that they were stiffer but less impact tough. In the present work, CNFs could reduce the impact strength of composites because they render the material more brittle and stiff. Although CNFs strengthen the matrix and improve tensile and flexural properties, their high modulus and rigidity limit the composite's capacity to absorb energy and deform plastically under abrupt impacts. Furthermore, at higher loadings, CNFs have a tendency to aggregate, forming stress concentration points that serve as crack initiation sites and facilitate the cracks' easier propagation under impact loading. The material's overall impact toughness decreases as a result of the localized flaws and increased brittleness.

4. Conclusion

- The results of the tensile properties demonstrate that incorporating up to 0.8 wt% CNFs to SGF/PPS composites greatly increases their tensile strength and modulus by 4.6% and 11.1%, respectively, as a result of superior interfacial bonding coupled with effective load transfer. The ideal loading level is 0.8 wt%, after which performance declines due to CNF agglomeration.
- Due to stronger fiber–matrix interfacial bonding and effective load transfer, adding CNFs up to 0.8 wt% substantially increases the flexural strength and modulus of SGF/PPS composites by about 19.52% and 27.23%, respectively. Performance decreases beyond this loading point because of CNF agglomeration and poor dispersion.
- The impact strength of SGF/PPS composites gradually decreases from 11 KJ/m² to 7.19 KJ/m² as CNF loading is increased to 1.0 wt%. This is caused by the fact that rigid CNFs have brittleness and stiffening effects, and they tend to clump together at higher loadings, building stress concentration sites that reduce the ability of the material to absorb and dissipate impact energy.
- The fractographic features clearly demonstrate that incorporating 0.8 wt% CNFs into SGF/PPS composites enhances tensile performance by promoting superior fiber alignment along the loading direction and strengthening fiber–matrix interfacial bonding. This is evidenced by river marks indicating controlled crack propagation, the uniform and cohesive fracture surface observed in Zone 2, and the absence of fiber pull-out in high-magnification images, all contributing to improved stress transfer and a tougher, more ductile failure behavior.
- SGF/PPS composites have applications for high-performance automobiles and structural elements needing high strength and stiffness due to their improved mechanical properties at ideal CNF loading. Prospective studies ought to investigate proficient dispersion methods to reduce CNF agglomeration at higher loadings and examine the impact resistance and long-term durability under real-world scenarios.

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