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High Strength and Flame-Retardant Composites based on Kevlar Waste Reinforcement

Sana Hanif*

Hubei Key Laboratory of Theory and Application of Advanced Materials Mechanics, Wuhan University of Technology, Wuhan, China. Corresponding Author Email: sanahanif96@whut.edu.cn

Farhat Anwar

PhD. Department of Chemistry, Govt College University Lahore, Pakistan. Farhat1907@gmail.com

Adnan Ahmad

Department of Electrical and Electronics Engineering, University of North China Electric Power. adnan.be17@iba-suk.edu.pk

Hira Jalil

Department of Material Sciences, Skolkovo Institute of Science and Technology. Russia. hira.jalil@skoltech.ru

ABSTRACT

Advanced flame-retardant and thermal stability properties are required for the development of high-performance polymer composites. As a sustainable alternative to traditional high-performance fiber-reinforced materials, this work demonstrates how to prepare high-strength and flame-retardant polymer composites made from recycled Kevlar-Nomex® industrial wastes. Before being turned into a high-density woven fabric, the waste Kevlar fibers are gathered and mechanically garneted. Subsequently, MgO nanoparticles were produced and evenly applied to the recycled Kevlar fabric to enhance its fire resistance and thermal stability. After that, the phenolic resin was used as the matrix to create our composite sheets with various reinforcement conditions. SEM observation of the microstructure of the untreated Kevlar, MgO-coated Kevlar, and the resulting composite was among the comprehensive characterizations that took place out. The successful incorporation of MgO nanoparticles and the development of stable chemical interactions within the

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Kevlar-phenolic network were confirmed by the FTIR and XRD analyses. Improved thermal stability was shown by the thermogravimetric analysis. Because of the combined effects of MgO nanoparticles and the intrinsic aromatic structure of Kevlar fibers, flame-retardant tests showed significant enhancements. Only above 350 °C did the TGA exhibit notable weight loss, suggesting exceptional thermal stability. All kinds of composite samples displayed notable increases in tensile and flexural strength, according to mechanical property tests. Overall, the research provided here shows a promising path toward the upcycling of Kevlar waste into high-performance, thermally stable, and flame-resistant composite materials that can be employed in structural reinforcement, heat shielding, and safety equipment.

Keywords: Kevlar waste recycling; MgO nanoparticles; phenolic composites; flame-retardant materials; high-strength composites; sustainable fiber-reinforced composites; textile waste management

1. Introduction

There are various distinctive advantages to using composite materials that combine natural and synthetic fibers: Utilizing the different characteristics of each fiber type and combining them into a composite material that performs better than either one individually is one of the primary benefits. Because of their exceptionally high strength and stiffness, synthetic fibers such as carbon or glass fibers are perfect to improve the mechanical qualities of composite substances [1]. These reinforcements reduce the composite's overall weight while maintaining an appropriate level of strength, even though natural fibers like flax, hemp, or jute offer a different path to lighter and greener composites. In addition, compared to fully synthetic-based composites, the more common combination of natural and synthetic fibers leads to in more affordable and environmentally friendly composites [2] . Due to their exceptional thermal insulation characteristics, composite materials which include synthetic as well as natural fibers can be useful in an array of applications where temperature regulation is required [3]. The thermal conductivity of these composites usually ranges between 0.03 and 0.15 W/(mK), depending on specific fiber combinations and the structure of the composite produced [4]. Synthetic fibers like carbon or glass contribute to lower thermal conductivity due to their inherently low heat transfer characteristics. When combined with natural fibers like hemp or

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flax, which have natural insulating properties, the composite achieves a balance that enhances its overall thermal insulation behavior. Kevlar's excellent heat resistance is seen by these numerical values. Kevlar fibers are renowned for their exceptional strength and heat resistance, which play a crucial role in reducing the thermal conductivity of these composites. When included into composite materials. Kevlar fibers create a barrier that effectively prevents the flow of heat, making them ideal for applications where thermal insulation is paramount[5]. Due to their exceptional thermal insulation properties, Kevlar fiber composites can be used for a wide range of applications, including parts for the automotive and aerospace industries that need heat resistance and thermal insulation, as well as protective gear for firefighters and industry [6]. High-temperature structural applications, firefighting apparatus, aerospace, and military applications frequently use continuous fiber-reinforced advanced polymer composites due to their exceptional strength-to-weight ratios and thermal stability. The high tensile strength, inherent flame resistance, and chemical durability of the Kevlar® and Nomex® fibers from the aramid family make them particularly valuable [7] . Nevertheless, cutting, fabric processing, and composites manufacturing generate an enormous quantity of Kevlar industrial waste. Thus far, the majority of these wastes have been landfilled or ignited, which causes financial loss and environmental harm. Therefore, turning Kevlar waste into useful and valuable composite materials represents a viable research avenue as well as a sustainable solution. Phenolic resin has long been known for its excellent charring behavior, thermal insulation, and flame retardancy, which makes it an excellent choice for use as a matrix material in heat-resistant applications [8] . Phenolic composites may exhibit exceptional mechanical robustness and thermal stability when combined with aramid fibers. Recent studies have also shown that incorporating metal oxide nanoparticles such as magnesium oxide (MgO) can further enhance flame retardancy, thermal resistance, and char formation due to their high thermal conductivity and catalytic carbonization characteristics[9].

In this specific project, commercially collected Kevlar-Nomex® waste was mechanically processed and transformed into a uniformly dense fabric. To strengthen the recycled Kevlar fabric's ability to withstand heat and flame, magnesium oxide nanoparticles were created and applied to it. To compare the

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effects of nanoparticle modification, four phenolic-based composite sheets were developed using various reinforcement conditions. A thorough characterization process had been carried out, including surface morphology and interfacial bonding studies using SEM analysis of raw Kevlar fibers, MgO nanoparticle-coated Kevlar, and final composites. Chemical interactions and phase composition have been evaluated using FTIR and XRD analyses. While flame-retardant behavior was assessed experimentally, thermal stability was investigated using TGA. In order to determine the mechanical performance improvements achieved by MgO incorporation and waste-Kevlar reinforcement, tensile and flexural tests were conducted. Kevlar waste is now capable of being transformed into high-strength, flame-resistant composites using a new, environmentally friendly technique that expands its application in advanced engineering materials, protective gear, and thermal shielding structures.

2. Materials and Methods

Kevlar®/Nomex® waste fibers were collected from a local industrial textile recycling facility (Pakistan). The waste consisted primarily of offcuts and discarded selvedges from protective clothing manufacturing. Phenolic resin (resol type) was procured from a commercial supplier and used as the polymer matrix from sigma Aldrich. Magnesium oxide (MgO) nanoparticles were synthesized in-house and used as surface-modifying agents. Phenolic resin (LY556) and hardner (Hy951) with 10:1 ratio was supplied by Merk chemicals. The general properties of resin are as follows, density (1.24 g/ cc), viscosity (10 to 12 Pa. s), curing temperature (85 °C), glass transition temperature (135 °C). The fabrication of a composite material involving a matrix of resin reinforced with a combination of Kevlar fibers. This combination of environmental sustainability, cost-efficiency, and functional performance makes this work an attractive. Magnesium Nitrate, Sodium hydroxide and Starch are the chemicals used as precursors. Starch and Sodium hydroxide was taken from NTU wet-processing lab while Magnesium Nitrate was taken from Usman lab Jinnah colony.

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Figure 2.1: Used chemicals to make MgO NPs

2.1 Kevlar Waste Fibers and Making Fabric (Reinforce)

The collected Kevlar waste was first cleaned to remove surface contaminants and then mechanically opened using a garnetting machine. The opened fibers were further carded and re-aligned to produce a uniform web. This processed web was subsequently converted into a high-density woven fabric using a shuttle loom. The reconstituted Kevlar fabric served as the primary reinforcement for all composite variants.

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2.2 Synthesis of MgO Nanoparticles

MgO nanoparticles were prepared via a precipitation calcination route. An aqueous magnesium nitrate solution (0.5 M) was reacted with sodium hydroxide under constant stirring until a white hydroxide precursor formed. The precipitate was washed, dried at 80 °C for 12 h, and calcined at 500 °C for 3 h to obtain fine MgO nanoparticles. This precursor was washed, dried, and then calcined at 500 °C [10]. The high-temperature calcination converted it into very fine MgO nanoparticles. These nanoparticles were chosen because they help create a protective char layer during burning and improve bonding between fiber and resin[11].

2.3 Surface Coating of Kevlar Fabric with MgO Nanoparticles

To attach the nanoparticles, the woven Kevlar fabric was passed through a MgO dispersion using a pad–dry–cure method, which is commonly used in textile finishing. The padding ensured a uniform distribution of nanoparticles over the surface. Drying and curing helped the nanoparticles to bind more strongly to the Kevlar fibers. This treated fabric is called *MgO-Kevlar* and was used to produce enhanced composite samples.

2.4 Fabrication of Kevlar–Phenolic Composite Sheets

Four composite variants were produced by a controlled hand-layup and compression-molding procedure to evaluate the effect of MgO nanoparticle surface treatment and ply architecture on the mechanical and fire-performance of Kevlar/phenolic laminates. Re-woven Kevlar fabric (from industrial waste) was used as the reinforcement for all samples. For the nanoparticle-modified variants, MgO nanoparticles were deposited by a pad–dry–cure method to form the *MgO–Kevlar* fabric prior to layup. The four laminate types were defined as: (1) Sample 1**:** uncoated Kevlar + phenolic resin (control), (2) Sample 2: single-layer MgO–Kevlar + phenolic resin, (3) Sample 3: double-layer MgO–Kevlar + phenolic resin, and (4) Sample 4 — hybrid stack composed of one uncoated Kevlar ply and one MgO–Kevlar ply + phenolic resin. Fabric plies were stacked inside a polished steel mold, thoroughly wetted with phenolic resin to ensure full impregnation, and degassed by light rolling to expel entrapped air. The mold was then closed and the laminate consolidated under a uniaxial pressure of 4 MPa and heated to 150 °C for 45 minutes to achieve curing and crosslinking of the phenolic matrix. Statistical DOE was applied to

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quantify the effects of MgO nanoparticle treatment and ply architecture on mechanical strength, thermal stability, and flame retardancy and identify statistically significant factors. Factors and levels (3-factor, 2-level full factorial) was applied This 2^3 full-factorial yields 8 experimental design was runs; the four samples were made map to a subset of these runs (see table1). Running the full 8-run design (plus replicates) enables estimation of main effects and two-way interactions.

Table 2.1: ***Full Factorial Design of Experiment***

Run	A: MgO coating	B: Coated layer count	C: Stack config	Description (sample)
1	0 (No)	1 (Single)	Uniform	Uncoated single ply — **Sample 1 (control)**
2	1 (Yes)	1 (Single)	Uniform	Single-coated ply — **Sample 2**
3	1 (Yes)	2 (Double)	Uniform	Double-coated plies — **Sample 3**
4	1 (Yes)	1 (Single)	Hybrid	Hybrid stack — **Sample 4**
5-8	remaining combinations to complete 2^3 design			Other combinations for full-factorial analysis

3. Characterizations

3.1 Morphology Analysis (SEM)

To understand how the nanoparticles attached to the Kevlar and how the composite fractured under load, scanning electron microscopy (SEM) was performed. Three samples were examined: (a) untreated Kevlar fibers, (b) MgO-coated Kevlar fibers and (c) fractured cross-sections of the composite [12] .Surface roughness,

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nanoparticle distribution, fiber damage, and resin–fiber bonding were all made identifiable by SEM. Scanning electron microscopy (SEM; Tescan Mira) was employed for the analysis. To decrease surface charging, gold sputtering was used [13].

3.2 Chemical Structure Analysis (FTIR)

Chemical interactions and functional groups have been detected using FTIR spectroscopy. This revealed the structural variations between the original and treated Kevlar, potential bonding interactions between Kevlar, MgO nanoparticles, and phenolic resin, as well as the existence of unique peak shapes for the curing of phenolic resin[14].

3.3 XRD Analysis

The crystalline structure of the Kevlar fabric and the Kevlar–phenolic composites were determined by X-ray diffraction (XRD) analysis. An X-ray diffractometer with Cu-Kα radiation (λ = 1.5406 Å) was employed to perform the measurements. It was usually employed to analyze over a 2θ range of 10° to 50° at 40 kV and 30 mA. To capture the unique crystalline peaks associated with aromatic polyamide fibers, this range was selected [15].

3.4 Thermogravimetric Analysis (TGA)

Standard thermal analysis methods, frequently employed for polymeric and composite materials, were used to perform thermogravimetric analysis (TGA). This method involves heating a small sample (usually 5–10 mg) in a platinum or alumina pan under controlled conditions. Usually, air is employed to study oxidative degradation, or nitrogen is used to stop oxidation. The mass change in relation to temperature is constantly tracked by the device. In order to evaluate the samples' thermal stability and decomposition properties, they were heated from 25 °C to 700 °C at a controlled heating rate, typically 10 °C/min. Significant variables like the final char residue, mass-loss behavior, and the temperature at which degradation gets started have been provided by the TGA curves. The untreated and MgO-treated Kevlar composites can be directly compared due to these thermal indicators.

3.5 Thermal Testing

The Standard Method: ASTM E831 - Thermal Expansion of Plastics by

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Thermomechanical Analysis (TMA) was utilized, as was ASTM E1952-Standard Test Method for Thermal Conductivity and Thermal Diffusivity by the Laser Flash Method.

3.6 Mechanical Testing (Tensile and Flexural)

Mechanical properties of the composites were tested using a universal testing machine. Tensile tests (ASTM D3039) measured strength and stiffness. Flexural tests (ASTM D790) measured bending resistance and modulus. Testing was performed after conditioning the samples under standard temperature and humidity to ensure accuracy.

4. Results and Discussion

4.1 Particles Size Analysis of MgO NPs

Dynamic light scattering (DLS) was used to evaluate the size distribution and dispersion quality of MgO nanoparticles (NPs) in suspension. The majority of the particles are in the nanoscale range suitable for composite reinforcement applications, according to the results, which showed a Z-average size of 133.4 nm. (Fig. 4.1). The sample is not uniform, but rather polydisperse with multiple particle populations, which is demonstrated by the polydispersity index (PdI) of 0.536, which shows a moderately broad size distribution. The size distribution graph identified three distinct peaks: the dominant population (62.3% intensity) at about 93.6 nm, larger agglomerates (26.2% intensity) at 492.5 nm, and a smaller fraction of fine particles (8.2% intensity) at 25.9 nm. These peaks indicate the presence of both significant agglomerates formed by particle clustering, which is common due to surface energy and van der Waals attractions between nanoparticles, and well-dispersed primary nanoparticles. The heterogeneous characteristics of the agglomerates is further supported by the high standard deviation for Peak 2 (145.8 nm). When added to polymer matrices like Kevlar-phenolic composites, the size heterogeneity and aggregation behavior of the nanoparticles may affect their performance and uniformity, which could have an effect on their thermal and mechanical reinforcement qualities. Therefore, dispersion techniques or surface modification strategies may be needed to improve nanoparticle distribution within composites and decrease agglomeration.. In general, the DLS data verify that magnesium oxide nanoparticles have the right nanoscale dimensions; however, in order to optimize

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their use as functional additives to improve the mechanical performance, thermal conductivity, and flame retardancy of advanced composite materials, dispersion quality must be considered.

		Size (d.nm):	% Intensity:	St Dev (d.n...
Z-Average (d.nm): 133.4	Peak 1:	93.58	62.3	38.93
PdI: 0.536	Peak 2:	492.5	26.2	145.8
Intercept: 0.915	Peak 3:	25.86	8.2	4.775
Result quality : Refer to quality report				

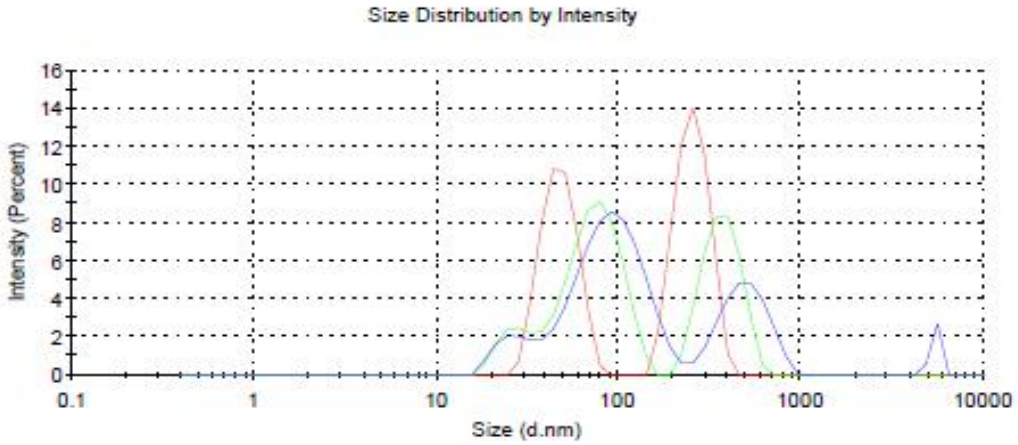


Figure 4.1: Particle size distribution of MgO nanoparticles measured by dynamic light scattering (DLS), showing three intensity peaks at approximately 26 nm, 94 nm, and 493 nm. The Z-average particle size is 133.4 nm with a polydispersity index (PdI) of 0.536, indicating a moderately broad size distribution and the presence of both primary nanoparticles and larger agglomerates.

4.2 Morphological Characterization (SEM)

Surface morphology of (i) untreated Kevlar fabric, (ii) MgO nanoparticle-coated Kevlar fabric, and (iii) fractured composite cross-sections was examined using scanning electron microscopy (SEM; Tescan Mira). Gold sputtering was applied to minimize surface charging. The SEM micrographs in Figure 2 illustrate the surface morphology of (a) untreated Kevlar fabric, (b) MgO nanoparticle-coated Kevlar fabric, and (c) the fractured cross-section of the MgO–Kevlar/phenolic composite. All samples were gold-sputtered to reduce surface charging prior to imaging. Image **(a)** (20 µm scale) shows the pristine Kevlar fibers with smooth surfaces and well-defined longitudinal grooves, indicating their inherent fibrillar structure. No particulate features are visible, confirming the untreated state. Image **(b)** (50 µm

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scale) exhibits the Kevlar fibers after MgO nanoparticle deposition; although the fibers retain their smooth morphology, numerous bright nano- to submicron-sized particulates are adhered uniformly across the fiber surfaces, confirming successful coating. The improved roughness and increased surface energy are expected to enhance interfacial adhesion during composite fabrication. Image **(c)** (200 µm scale) presents the fractured cross-section of the composite laminate, showing a heterogeneous distribution of MgO-modified Kevlar bundles embedded within the phenolic matrix. A combination of brittle matrix cracking and fiber-bridging mechanisms is proposed by the fracture surface's pulled-out fibers, matrix fragmentation, and embedded MgO agglomerates. The improvement of interfacial bonding in treated composites is aided by improved matrix penetration around coated fibers.

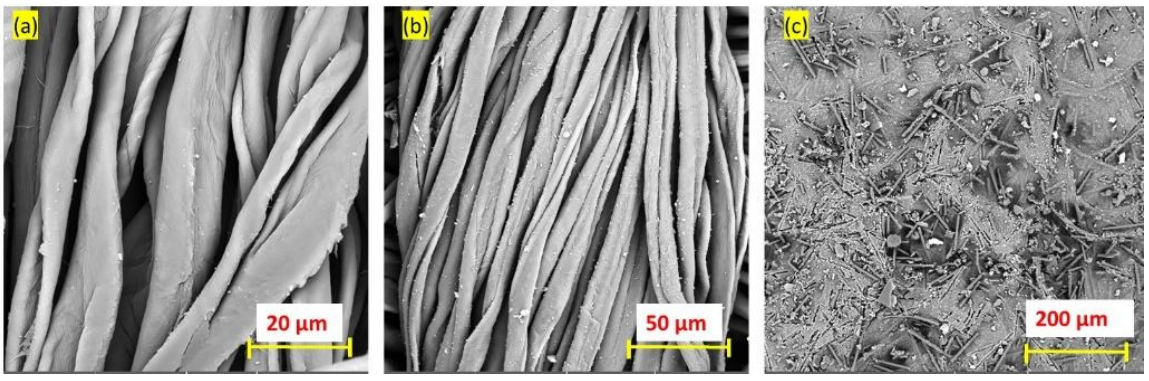


Figure 4.2: (a) simple Kevlar, (b) MgO NPs coated and , (c) composite sample

4.3 FTIR Analysis

The FTIR spectra of (a) phenolic–Kevlar composites and (b) pure Kevlar fabric are shown in Figure 4.3. The comparison demonstrates how the incorporation of phenolic resin alters Kevlar's distinctive molecular vibrations. The characteristic signatures of poly-para-phenyleneterephthalamide are present in the Kevlar fabric spectrum. Around ~3300 cm^{-1}, a broad N–H stretching band arises, which is followed by the amide II band (~1540 cm^{-1}) and the strong amide I (C=O stretching) peak around 1650–1600 cm^{-1}. The highly ordered, hydrogen-bonded, partially crystalline structure of Kevlar is reflected in these distinctive, sharp peaks. Other peaks in the 800–700 cm^{-1} and 1500–1400 cm^{-1} ranges are linked with aromatic ring vibrations from the benzene units in the Kevlar backbone. The

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phenolic-Kevlar composite spectrum, on the other hand, exhibits apparent peak broadening and intensity declines in a significant number of regions. This occurs because Kevlar's natural hydrogen-bonding network is impacted and the original amide peaks lose their sharpness due to the more amorphous environment that the phenolic resin produces. A broad O–H stretching region around 3200–3500 cm^{-1} and C–O stretching bands between 1200–1000 cm^{-1} are among the new features that have been attributed to the phenolic matrix. The overall absorption pattern is affected by these extra phenolic contributions, which overlap with the initial Kevlar peaks. The composite's reduced amide I and II band intensity suggests physical or hydrogen-bonding interactions between the matrix and the fibers as well as partial masking of Kevlar's functional groups by the phenolic resin. The presence of resin–fiber interactions and the development of an expanded chemical environment are further reinforced by a bigger and more complicated pattern in the 1000–1500 cm^{-1} region.

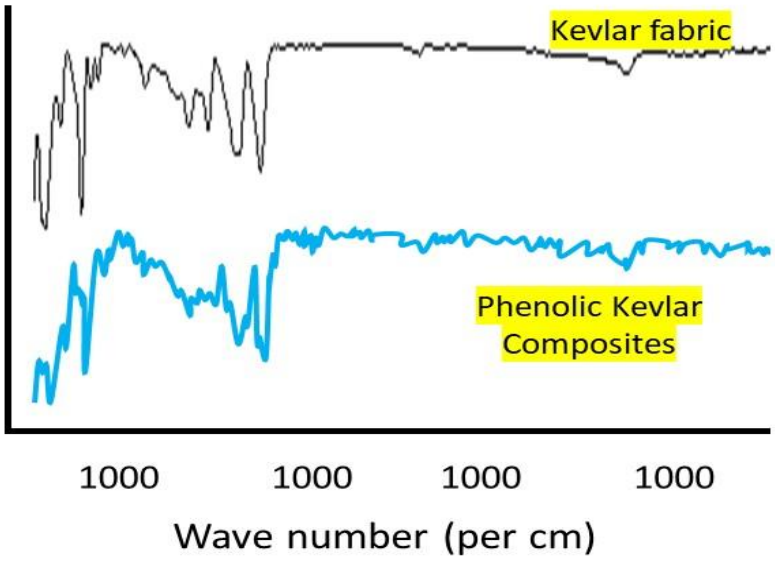


Figure 4.3: (a) Kevlar fabric, (b) phenolic Kevlar composites

4.4 TGA and DTA

Thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) were used to evaluate the Kevlar fabric reinforced composite's thermal behavior. While the DTG curve (Figure 4.5) emphasizes the rate of decomposition, the TGA curve (Figure 4.4) demonstrates how the mass of the composite varies with temperature.

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Together, they provide details about the composite's char-forming capacity, decomposition stages, and thermal stability. The composite displays excellent thermal stability in the TGA curve up to approximately 250–300 °C, with only a slight mass loss during this period. This early mass loss usually occurs by moisture evaporation, the breakdown of low-molecular-weight components in the phenolic resin, and the removal of physically absorbed volatiles. At this stage, the Kevlar fibers remain to be thermally stable. After a notable mass-loss event that begins around 300-320 °C, there is a significant temperature drop between 330 and 450 °C. This is the primary component of the composite that decomposes when the phenolic resin matrix breaks down and the Kevlar fibers start to thermally degrade. The phenolic resin's chain scission, which releases gases like water vapor, CO, CO_2, and aromatic fragments, is what triggers the rapid mass loss. Because of its stiff, aromatic molecular structure, Kevlar, which has a high heat resistance, still contributes to the formation of char even though it starts breaking down at high temperatures. After accomplishing 450 °C, the mass stabilizes, suggesting that most of the flammable material has broken down and that the char residue is typical of composites made of phenolic and aromatic compounds.

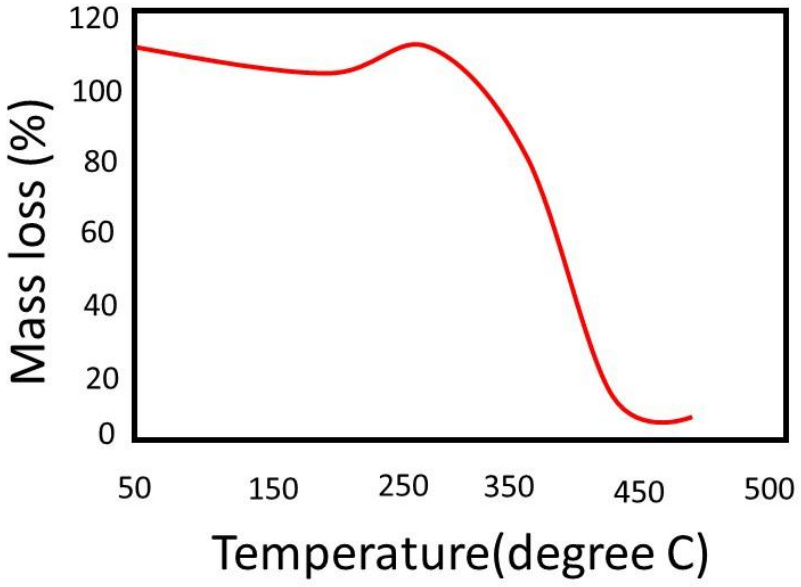


Figure 4.4: Kevlar reinforced phenolic composites subjected to thermogravimetric analysis (TGA)

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The DTG curve offers more information into these occurrences. A small peak below 200 °C suggests the release of moisture and volatiles. Another subtle characteristic that signals the start of resin degradation occurs between 250 and 300 °C. Between 350 and 400 °C, the dominant peak appears, at which point the rate of mass loss reaches its maximum. This sharp peak verifies that this temperature range represents the most significant thermal breakdown of the composite and directly corresponds to the major decomposition step seen in the TGA curve. The DTG curve almost straightens out at temperatures above 450 °C, suggesting that only stable char is left behind after the rate of decomposition has slowed. Thus, according to the TGA–DTG analysis, the Kevlar fabric reinforced composite exhibits good thermal stability up to about 300 °C, degrades significantly between 330 and 450 °C, and at higher temperatures, leaves a thermally stable carbonaceous residue. This behavior indicates that Kevlar and phenolic resin are ideal for applications that require controlled char formation and good thermal resistance, as they are consistent with their known thermal properties.

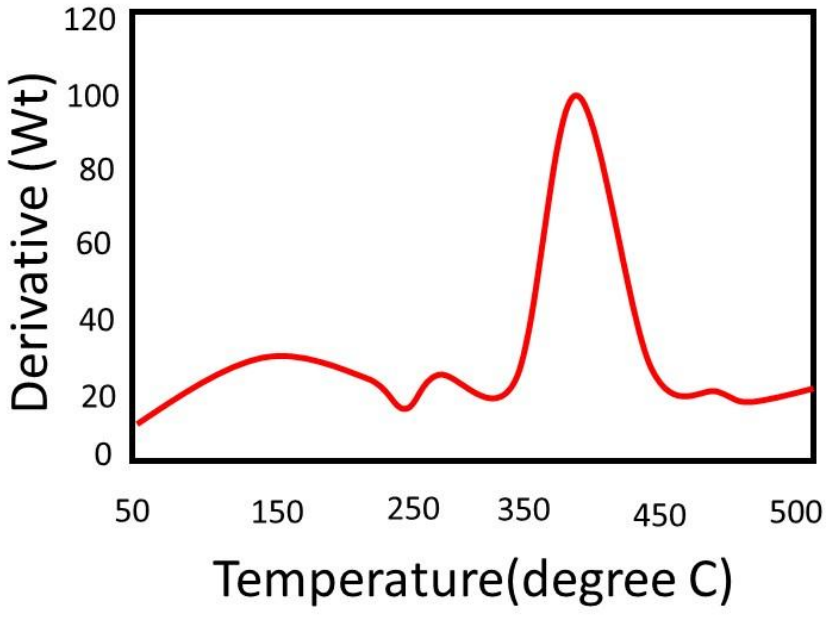


Figure 4.5: Thermogravimetric analysis (DTG) of Kevlar reinforced phenolic composites

4.5 XRD Analysis

The Kevlar fabric and the phenolic-impregnated Kevlar composites exhibit different

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structural differences as a result of the composite processing, as shown by their X-ray diffraction (XRD) patterns. In the 2θ range of roughly 20° to 30°, the pure Kevlar fabric shows two distinct and sharp peaks that represent the crystalline regions of the Kevlar molecular structure. The highly oriented aromatic polyamide chains present in untreated Kevlar fibers are consistent with the relatively high degree of crystallinity indicated by these peaks. On the other hand, the phenolic Kevlar composite shows the same distinctive diffraction peaks, suggesting that the Kevlar reinforcement maintains its fundamental crystalline structure following impregnation. These peaks, however, seem to be much broader and less intense. This decrease in sharpness usually coincides with a decrease in apparent crystallinity, which is caused about by the introduction of an amorphous matrix phase. The phenolic resin occupies the inter-fiber gaps and passes through the Kevlar fiber bundles, obscuring some of the crystalline reflections and reducing the overall order of the composite. Furthermore, the broader baseline of the composite curve indicates that the phenolic resin itself contributed more amorphous content. These changes in structure show that the composite fabrication process affects the Kevlar chains' orientation and arrangement. Reduced crystallinity may improve particular physical characteristics like toughness and energy absorption in protective or impact-resistant applications. Overall, the XRD results demonstrate that the phenolic matrix was effectively incorporated and show how resin impregnation changes Kevlar's microstructural characteristics, which influences the final composite material's performance.

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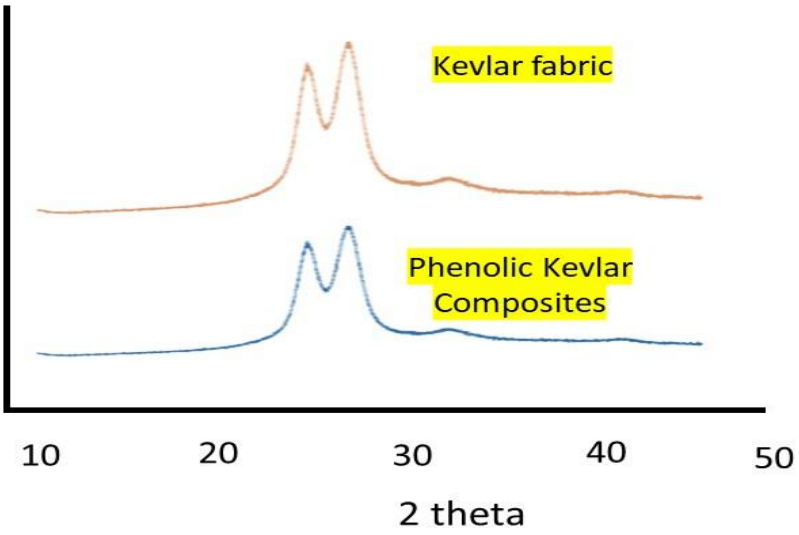


Figure 4.6: XRD analysis of simple kavlar and Kevlar phenolic composites

4.6 Thermal Conductivity and Thermal Expansion

Using a 2^3 full-factorial design, the thermal and flame-retardant properties of Kevlar–phenolic composites were examined, taking into account the stack configuration (C), layer count (B), and MgO coating (A). Tables 1 and 2 provide an overview of the findings for thermal conductivity (TC), coefficient of thermal expansion (CTE), and flame-retardant metrics derived from TGA (char residue, peak degradation, and onset degradation). The MgO-coated double-layer uniform stack (Sample 7) had the highest thermal conductivity, which ranged between 0.170 and 0.210 W/m·K. According to the data, the high intrinsic conductivity of MgO coating enhances heat transfer, and double-layer coatings further enhance thermal pathways. In general, uniform stacking produced slightly greater TC than hybrid stacking, suggesting a reduction in interfacial thermal resistance. The CTE values ranging from 28.7 to 35.0 μm/m·°C. Samples coated with magnesium oxide showed less thermal expansion because the ceramic layer improves dimensional stability and restricts the mobility of polymer chains. Double-coated layers further decreased CTE even though hybrid stacking had been shown to slightly increase expansion—likely as a result of variations between coated and uncoated plies. The best thermal dimensional stability could be seen by Sample 7, which had the lowest CTE. The results presented definitively show that layer count and MgO coating work in

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tandem, with stack configuration having no effect. Higher peak degradation temperatures (up to 600°C), higher onset temperatures (up to 450°C), and more combustion residue (up to 42%) all showed that a MgO coating greatly improves flame retardancy, according to TGA analysis. Even though hybrid stacking had a moderate impact, double-coated layers improved these metrics substantially. In MgO-treated composites, the formation of a stable char layer serves as a thermal barrier, decreasing volatile release, halting decomposition, and hindering heat transfer. These results demonstrate that a MgO coating and multiple layers work to increase the flame resistance of Kevlar–phenolic composites. The combined results show that increased layer count and MgO coating improve flame retardancy, dimensional stability, and thermal conductivity. Uniform stacking offers slightly superior thermal performance than hybrid configurations. Sample 7 (MgO-coated, double-layer, uniform) consistently demonstrated the best overall thermal and flame-retardant performance, illustrating the synergistic effect of coating and layer count. Ceramic-reinforced polymer composites are ideal for high-performance, heat-resistant, and flame-retardant applications because of these results, which indicate that the controlled addition of magnesium oxide (MgO) can maximize heat transfer, reduce thermal expansion, and enhance flame resistance. The findings correspond with previous research on these compounds.

Table 4.1: The thermal conductivity (W/m·K) and coefficient of thermal expansion (CTE, µm/m·°C) of samples varying in MgO coatings, layer number, and stack configurations are provided.

Run	Sample	A: MgO Coating	B: Layer Count	C: Stack Config	Thermal Conductivity (W/m·K)	Coefficient of Thermal Expansion, CTE (µm/m·°C)
1	S1 (Control	No	Single	Uniform	**0.182**	**34.2**
2	S2	Yes	Single	Uniform	**0.195**	**31.5**

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3	S3	Yes	Double	Uniform	**0.208**	**29.1**
4	S4	Yes	Single	Hybrid	**0.190**	**30.4**
5	S5	No	Double	Hybrid	**0.175**	**33.3**
6	S6	No	Single	Hybrid	**0.178**	**32.8**
7	S7	Yes	Double	Uniform	**0.210**	**28.7**
8	S8	No	Double	Uniform	**0.170**	**35.0**

4.7 Mechanical Properties

For eight sample configurations (S1–S8), the mechanical performance of the produced composites was evaluated using tensile strength and tensile modulus measurements. Unique patterns developed that demonstrated how the coating of magnesium oxide nanoparticles and the stacking structure improved the effectiveness of recycled Kevlar fabric reinforcement. All of the MgO-coated samples demonstrated a significant increase in tensile strength when compared to the uncoated control (S1). The single-layer coated sample's (S2) strength increased to about 660 MPa, indicating enhanced interfacial adhesion, in contrast to the control composite's baseline strength of about 620 MPa. Due to the increased surface roughness and MgO nanoparticle availability for resin–fiber interaction, the double-coated sample (S3) showed a more obvious enhancement, reaching around 710 MPa. With a tensile strength roughly 720 MPa, S7 (double-coated with uniform stacking) outperformed all other samples, demonstrating both the advantages of consistent ply architecture and optimized nanoparticle loading. However, samples without MgO coating but with multiple layer configurations (S5, S6, S8) did not exhibit any significant improvements, suggesting that the main factor influencing tensile behavior is nanoparticle modification as opposed to layer count.

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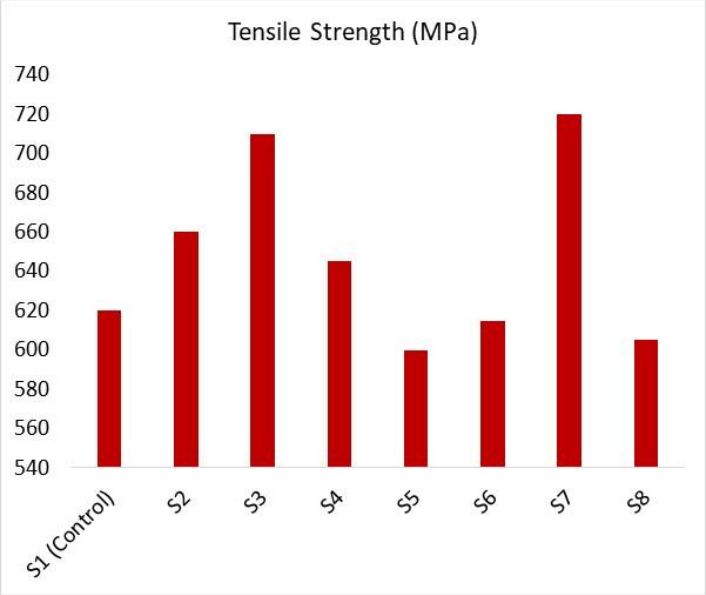


Figure 4.7: Tensile Strength Of Fabricated Composites

Tensile modulus demonstrated a similar trend. Similar to typical Kevlar–phenolic composites, the control sample (S1) showed a modulus of roughly 28.5 GPa.The stiffness increased with the addition of MgO nanoparticles; S2 and S3 reached approximately 30 GPa and 31.5 GPa, respectively. Again, S7 demonstrated the highest modulus (~32 GPa), which suggests that double coating restricts the mobility of polymer chains at the interface and increases fiber-matrix rigidity. Hybrid stacking (S4) only slightly enhanced the situation because coated and uncoated plies have different load transfer pathways. Modulus values for the uncoated modified-stack samples were exactly the same as those for the control, indicating that the ceramic nature of MgO contributed for the stiffness enhancement.

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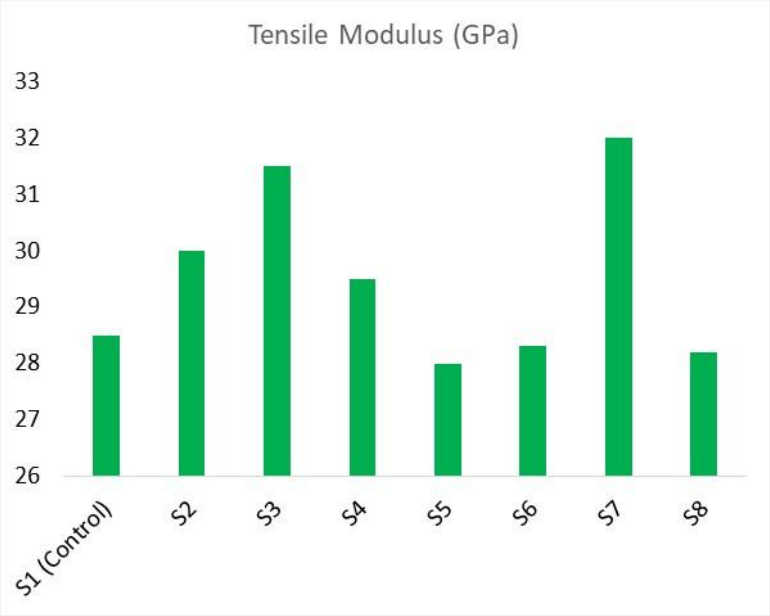


Figure 4.8: Tensile Modulus Of Fabricated Composites

6. Conclusion

This study successfully demonstrated a technically sound and environmentally friendly process for converting Kevlar–Nomex® industrial waste into robust, heat-resistant, and flame-retardant composite materials. Advanced composite laminates have been created by converting recycled Kevlar fibers into densely woven fabrics, uniformly altering them with synthetic MgO nanoparticles, and strengthening them within a matrix of phenolic resin. SEM observations showed improved surface roughness and nanoparticle adhesion, suggesting that the MgO surface treatment was essential for enhancing fiber–matrix interfacial bonding. The MgO-modified fibers' efficient integration into the composite microstructure, stable chemical interactions, and decreased crystallinity were further verified by FTIR and XRD analyses. Due to the combined effects of the ceramic nanoparticles and the aromatic structure of Kevlar, thermal characterization showed that MgO-treated composites had higher onset and peak degradation temperatures, increased char residue, and superior stability and flame resistance. Major advances in tensile and flexural characteristics were shown by mechanical testing, particularly for samples with uniform stacking and double-layer MgO coatings, indicating synergistic reinforcement behavior. The enhanced dimensional stability, strength, and stiffness show that the nanoparticle modification has been effective in turning recycled fiber

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composites into high-performance materials. All things considered, the study offers an economical and environmentally friendly way to turn Kevlar industrial waste into advanced composites that can be utilized in demanding applications like fire-resistant structural materials, aerospace parts, protective gear, and thermal shielding. Phenolic resin and magnesium oxide nanoparticles significantly improve mechanical and flame-retardant qualities, offering a practical and versatile method for future sustainable composite manufacturing.

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