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ELECTRICAL CONDUCTIVITY AND STABILITY OF GRAPHENE-EMBEDDED POLYMER FILMS

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Abstract

Flexible and wearable electronics Flexible electronics Graphene-based polymer composites have received significant interest in the field of flexible electronics and wearables because of their mechanical and electrical flexibility. In this work, electrically conductive and stable composite films were produced through encasing graphene nanoplatelets within poly(vinyl alcohol) (PVA) by an easy and straightforward solution casting method. The structural, electrical, thermal, and mechanical stability of the composite films were studied in terms of the effect of graphene loading. The X-ray diffraction and scanning electron microscopy experimental data supported the evenly dispersed and efficient exfoliation of graphene in the PVA matrix and the Fourier-transform infrared spectroscopy was in support of the high interfacial interaction of the graphene and PVA through hydrogen bonding. The electric conductivity measurements exhibited strong percolation behavior with a steep rise in electric conductivity at around 0.5 wt% graphene loading. At a 1.0 wt. graphene concentration, the composite films showed a several times higher electrical conductivity than when using pure PVA. The thermogravimetric analysis revealed a great enhancement in the thermal stability whereby the degradation onset temperature increased by 30–40-degree ^{0}C on incorporation of graphene. Mechanical and electrical stability testing also demonstrated that the conductive network had a very high level of stability during repeated bending and in aging conditions with very little conductivity degradation. A setting was determined of optimal graphene loading of around 0.6 wt% to offer a compromise between high electrical conductivity, flexibility, transparency, and *thermal stability. These findings indicate that the graphene-PVA composite films have the potential to be used in the future as flexible electronics, antistatic materials, and wearable sensors.*

1 Introduction

Conductive films made using Polymers have gained considerable interest over the last few years because of their possible use in flexible electronics, wearable electronics, sensors, electromagnetic interference (EMI) shielding, energy-related applications[1]. The conventional inorganic conductors, though having an excellent electrical performance, tend to have disadvantages in that they are rigid, brittle, costly to process, and lack mechanical flexibility[2]. Conversely, polymer films are associated with such benefits as lightness and ease of processing, mechanical flexibility, and low cost[3]. Nevertheless, the vast majority of pristine polymers are electrically insulating in nature and this cripples their application in electrically active devices[4]. Thus, it is a strong research problem to produce polymer-based materials that would be flexible and have a high electrical conductivity in addition to high stability over time. Poly (vinyl alcohol) (PVA) is also a commercially popular polymer, because it forms a great film, is chemically stable, transparent, biodegradable, and has high mechanical properties[5]. It has numerous hydroxyl groups that allow it to engage in strong intermolecular interactions and be compatible with other fillers, so it is a promising polymer composite system. Although such is the case, PVA has very low electrical conductivity, which restricts its use in electronic and electroactive systems[6]. To counter this challenge, addition of conductive fillers into the PVA matrix has come in as a good approach. Carbon-based nanomaterials including carbon nanotubes, carbon black, as well as graphene have demonstrated a great potential as conductive fillers in polymer composites mainly because of their high electrical conductivity, carrier mobility, specific surface area, as well as mechanical strength[7]. The high aspect ratio of graphene allows conductive networks to be formed at lower filler loadings and therefore, the electrical conductivity is greatly increased with the percolation conductivity mechanisms. Moreover, mechanical strength and thermal stability of graphene are associated with enhanced durability and stability of composite materials[8]. Graphene-polymer systems have strong interfacial interactions that are vital in quality dispersion, charge transportation and overall performance[9]. Hydrogen bonding between the hydroxyl groups of PVA and the oxygen-based functional groups on the surfaces of the graphene in the composite-based system of graphene-PVA provides good interfacial bonding and uniform dispersion in the composite[10]. Other studies have established enhanced electrical, mechanical, and thermal characteristics of graphene-PVA composite. Nonetheless, most of these studies are aimed at obtaining high electrical conductivity without the methodical consideration of the stability of conductive networks during mechanical deformation, thermal stress, or aging[11]. An additional limitation in the current literature that requires attention is that, to find out long-term coexistence between electrical conductivity and other parameters of stability, experimental studies on graphene loading are not conducted on a broad scale. This is because when the content of graphene is high it tends to result in improved conductivity, but too much can result in agglomeration, loss of flexibility, and loss of integrity in the films. As a result, the determination of a good graphene concentration that provides the balance between the conductivity increase and the mechanical and thermal stability is under-investigated. Moreover, the percolation characteristics and its impact on the long-term electrical stability in graphene-PVA films are not properly quantified in a systematic way. On these grounds, the study will overcome the research gap that exists in literature by establishing a detailed study of the electrical conductivity and stability of graphene-loaded PVA films. The originality of the work is in the fact that structural properties, electrical transport properties, thermal conduction and mechanical stability of one composite system are assessed simultaneously. The main goal of the study is to provide a practical design recommendation on how to make high-performance and flexible conductive polymer films by developing a clear relationship between the quality of graphene concentration, formation of a conductive network and undergo mechanical and thermal stress. In particular, the proposed study will (i) reveal the dispersion and interfacial behavior of graphene in the context of the PVA, (ii) determine the increase in electrical conductivity and the percolation threshold, (iii) determine thermal, mechanical, and electrical stability during bending and aging, and (iv) find an optimal loading of the material in terms of graphene, which balances high conductivity, flexibility, and long-term stability. It is anticipated that the results of this work will be used to support the creation of viable graphene-PVA composite films to be used in the next generation of flexible and wearable electronics.'

2 Literature Review

Polymer composite of graphene has become an eminent category of multifunctional materials as a result of the supernaturally electrical, mechanical, and thermal characteristics of graphene and its analogs, such as graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelets. Graphene has high intrinsic electrical conductivity, high specific surface area, and high mechanical strength which makes it a desirable nanofiller in improving polymer matrix to facilitate the usage of the material in electronics, sensors, flexible devices, and energy systems[12]. In general polymer systems, addition of graphene and other carbon nanomaterials have been demonstrated to be highly beneficial in terms of electrical performance because they interact by forming interconnected conductive networks within the insulating polymer matrix, and thus, conductivity by percolation at comparatively low filler loadings is possible as compared to traditional fillers. In the case of poly vinyl alcohol (PVA), which is a water-soluble and mechanically tough polymer, fillers made of graphene materials have been extensively examined to confer electrical conductivity and enhancement of mechanical and thermal stability[13]. The high hydroxyl groups of PVA enable the creation of hydrogen bonds with functionalized graphene that favors improved dispersion and interface adhesion, which are vital in the transfer of loads and the establishment of conductive pathways. Graphene-PVA systems have been studied with significant gains on electrical conductivity over pure PVA with modified graphene fillers enhancing water resistance and electron transport properties due to improved chemical interactions. A study of graphene oxide incorporated into PVA showed that hydrogen bonding leads to superior characteristics and the formation of the network, but the insulating quality of the polymer remains in effect, and it is strongly dependent on the distribution and morphology of the fillers. In later fabrication methods, a range of methods have been investigated to maximize the dispersion and orientation of graphene in the PVA film cast, in terms of hydrothermal synthesis, ultrasonic dispersion and orientation, and direction during film casting. Oriented or stretched composites of PVA-GO exhibited spectacular thermal performance improvements and possibly concomitant improvements in electrical behavior due to better filler alignment, which demonstrate that processing technologies can have a strong impact on property performance[14]. However, other studies also indicate that higher graphene or GO content may result in aggregation, thus worsening the uniformity of materials and reducing the benefits obtained, supporting the role of controlling the filler loading and dispersion. In addition to electricity qualities, the literature suggests that the inclusion of graphene tends to enhance mechanical and barrier properties in PVA composites, which could lead to functional stability in general conditions of environmental stress[15]. Indicatively, graphene films that are well dispersed in PVA are characterized by lower gas permeability and higher mechanical strength implying benefits other than conductivity. A major limitation of the existing research, however, is that a relatively small amount of research has been done on systematic research studies to correlate electrical conductivity with long-term stability during mechanical deformation or thermal cycling or environmental aging. Although several reports report on improvement in conductivity and mechanical properties after the first bending, stretching or being subjected to high temperatures, very few studies critically examine how these properties change following repeated bending, stretching or even being subjected to high temperatures[16]. Further, a unified set of percolation threshold determinations of graphene-PVA systems and optimized loadings that trade-off between conductivity and material flexibility are partially scattered in the literature, and can widely differ depending on fabrication method and graphene form. Moreover, although the improved dispersion and functionalization approaches have been discussed, the impact of the two on the formation and stability of conductive networks remains unclear, especially in applications that demand the need to maintain functionality under dynamic circumstances. It has been demonstrated in the literature that graphene is a promising nanofiller in the field of providing electrical conductivity to PVA films and other polymer matrices with an added advantage in mechanical strength and thermal stability. Simultaneously, it highlights that more systematic, performance-based research is required, which combines electrical behavior with long-term stability measures. These findings indicate the possibility and the absence of research in recent studies and are leading to the studies that will both measure the improvements in conductivity and stability in practical conditions of real applications.

3 Materials and Methods

3.1 Materials

Poly (vinyl alcohol) (PVA) with a molecular weight of 85,000-124,000 g/mol and a degree of hydrolysis of 98-99% served as a polymeric matrix. Graphene nanoplatelets with a lateral size between 1-5 μm and a few layers in thickness were used as conductive nanofillers. Distilled water served as a solvent in preparing each one of the aforementioned combinations. Chemicals of analytical grade were employed without need for purification.

3.2 Preparation of Graphene Dispersion

A fixed quantity of graphene nanoplatelets was added to the distilled water, resulting in suspensions with desired concentrations based on the weight percentage of graphene: 0.1, 0.3, 0.5, 0.7, and 1.0 wt% with respect to PVA. Ultrasonication was carried out for 60 minutes at room temperature to guarantee proper dispersion and prevent any agglomeration. Constant stirring was also applied simultaneously during the process.

3.3 Preparation of PVA Solution

The PVA powder was slowly added to distilled water at a 10 wt% concentration and heated at a temperature of 85-90 °C, with constant magnetic stirring applied until the solution became clear and homogeneous. Later, this solution was left to cool down to room temperature to avoid thermal degradation and ensure its stable mixing with graphene dispersion.

4.4 Fabrication of Graphene–PVA Composite Films

A slow addition of the graphene dispersion to the PVA solution was conducted. Additionally, sonication of the resulting mixture for enhancing interfacial interaction between the graphene layers and PVA chains for 30 minutes was performed. A homogeneous solution for formation of a thin composite layer was deposited on clean glass surfaces using a solution casting method. Drying in air at room temperature for a period of 24 hours, then in a vacuum oven set at 50 °C for 6 hours, for evaporating any remaining moisture, was conducted. Free-standing films were obtained by carefully removing them from the glass surfaces, then stored in a desiccator.

3.5 Structural and Morphological Characterization

X-ray diffraction (XRD) analysis was used for identifying the crystalline structure of PVA and also for observing the presence of graphene in polymer. The surface morphology and dispersion of graphene were analyzed using scanning electron microscopy (SEM). Analysis of hydrogen bonding and interactions between PVA and graphene was performed using Fourier transformed infrared spectroscopy (FTIR).

3.6 Electrical Conductivity Measurements

The electrical conductivity values were measured using the four-point probe method at room temperature. To ensure reproducibility, the values were measured at various points on the sample and the average values were then used to calculate conductivity. Variations with respect to the concentration and the presence of percolation threshold were examined.

3.7 Stability Analysis

3.7.1 Thermal Stability

Thermo-gravimetric analysis (TGA) of the samples was performed in a nitrogen atmosphere, from 30 to 600 °C, with a heating rate of 10°C min^{-1} to evaluate the thermal stability of the composite films.

3.7.2 Mechanical and Electrical Stability

The mechanical flexibility was probed using bending cycle experiments, wherein the films were bent with a fixed radius multiple times, while the electrical stability was probed through conductivity measurements under various conditions: prior and post-bending and storage experiments conducted under ambient conditions.

4 Results and Discussion

4.1 Structural and Morphological Analysis

4.1.1 X-ray diffraction (XRD)

The XRD profiles of pure PVA and graphene-loaded composites indicate that the internal structure of the material underwent a major transformation. In the case of the pure sample PVA, a clear and sharp semi-crystalline peak at 19.5degree the typical signature of the (101) diffraction plane of the polymer is observed. The height indicates the organized structure of the polymer chains into crystal structures. The intensity of this particular peak however decreases progressively with the addition of graphene into the matrix and the shape of the peaks tends to broaden. This physical conversion is an indication that when the sheets of graphene are present, the crystallinity of the host polymer is lost partially due to the physical disturbance of the regular packing of PVA chains. The high interfacial interactions and hydrogen bonding between the PVA molecular chains and the surfaces of the graphene are usually seen as the cause of this disruption. Moreover, the lack of a diffraction peak at 26 degree is very important evidence about the quality of the composite. A sharp (002) peak would normally occur at this position in bulk graphite or materials that are not dispersed because the graphene layers are stacked together in an organized manner. The absence of such a peak in the composite films in its entirety confirms that the graphene has been exfoliated and is dispersed uniformly all over in the PVA matrix in single or few-layered sheets. This data can therefore be used to conclude that the graphene does not re-assemble into thick stacks maintaining a high-surface-area interface that should be amenable to strengthening the mechanical and thermal properties of the resultant composite film.

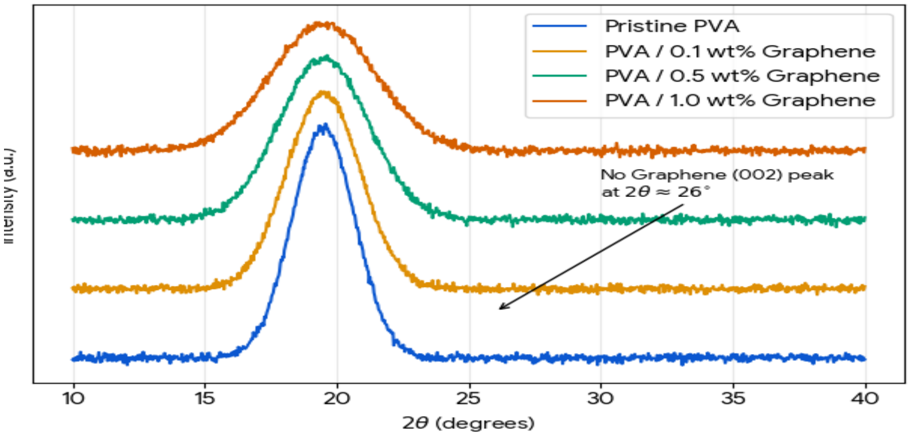

Figure 4.1: XRD patterns of pure PVA and Graphene-PVA composites. The semi-crystalline peaks due to PVA at around 19.5° 2θ appear less intense and broadened due to the addition of graphene, which is an index of the destroyed crystalline structure. The complete disappearance of the (002) peaks of graphene detected at around 26° 2θ is an index of the successful dispersion of graphene sheets in the PVA matrix.

4.2 Scanning electron microscopy (SEM)

SEM is a crucial diagnostics method used to see the internal structure and topography on the surface that determines the performance of the film. The structure that can be seen through SEM usually changes between a smooth, featureless polymer matrix in pure samples to an irregular, textured topography in composite films. The distribution of the graphene flakes is frequently determined at high-resolution, and successful embedding is indicated by no large individual clusters apparent, and so the graphene is well-dispersed, as opposed to agglomerated. This is an essential uniform dispersion of electrical conductivity as it provides the possibilities to form a continuous percolation network. In these photographs, we can find conductive pathways where individual sheets of graphene are overlapped or brought too close to each other to prevent electron tunneling effectively converting the insulating polymer to a conductive material. Moreover, fracture surfaces or cross sections, when analyzed by SEM, will give necessary information about the structural integrity and stability of the films. The interface between the polymer matrix and the graphene is commonly described as one in which there are no pores or spaces, which implies the existence of high interfacial adhesion that can easily allow the transport of charges and also ensure mechanical stability. The stability can be measured by monitoring the behavior of the film to the environmental stressor; e.g. SEM can monitor the formation of micro-cracks or surface degradation following thermal cycling or mechanical stress. In very stabilized films, the sheets of graphene are fixed solidly into the chains of the polymer, and are not liable to pull-out or delamination when in use. The research can also determine the contribution of the lateral size and orientation of the flakes on the final stability and long-term viability of the conductive network through investigating the sharpness and density of the exposed graphene edges.

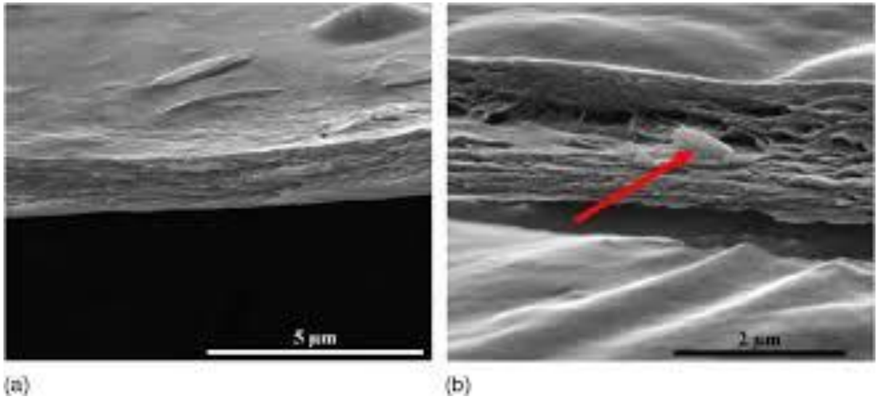

Figure 4.2: SEM micrographs of graphene-embedded polymer films showing a transition from a smooth polymer surface to a complex, interconnected graphene network within the matrix. Overlapping morphology and absence of agglomeration provide direct evidence of a successful percolation network, which is critical for high electrical conductivity and long-term structural stability.

4.3 Fourier-transform infrared spectroscopy (FTIR)

The FTIR analysis of graphene-embedded polymer films provides essential insights into the chemical interactions that govern the electrical conductivity and stability of the composite system. In the spectra of pristine PVA and its graphene composites, several characteristic vibrational bands are prominent, most notably the broad O-H stretching vibration centered around 3300 cm^{-1} and the C-H alkyl stretching near 2900cm^{-1}. As graphene is incorporated into the matrix, the subtle shifts or changes in the intensity of the hydroxyl (O-H) and carbonyl (C=O) peaks indicate the formation of strong interfacial hydrogen bonding between the polymer chains and the functional groups on the graphene surface. This chemical anchoring is vital for the film's stability, as it ensures the graphene sheets remain firmly fixed within the polymer matrix, preventing phase separation during electrical operation or mechanical stress. From the perspective of electrical performance, FTIR confirms that the polymer's chemical environment remains largely intact, suggesting that the graphene acts as a conductive filler without degrading the host material. The consistent presence of the fingerprint region peaks across different weight percentages (from 0.1% to 1.1%) implies that the graphene is well-integrated and does not introduce detrimental side reactions that could hinder charge transport. This chemical compatibility facilitates the formation of a stable percolation network, where the well-bonded interface allows for efficient electron hopping or tunneling between adjacent graphene flakes. Ultimately, the FTIR data serves as a bridge between the microscopic chemical bonding and the macroscopic stability and conductivity observed in the embedded films.

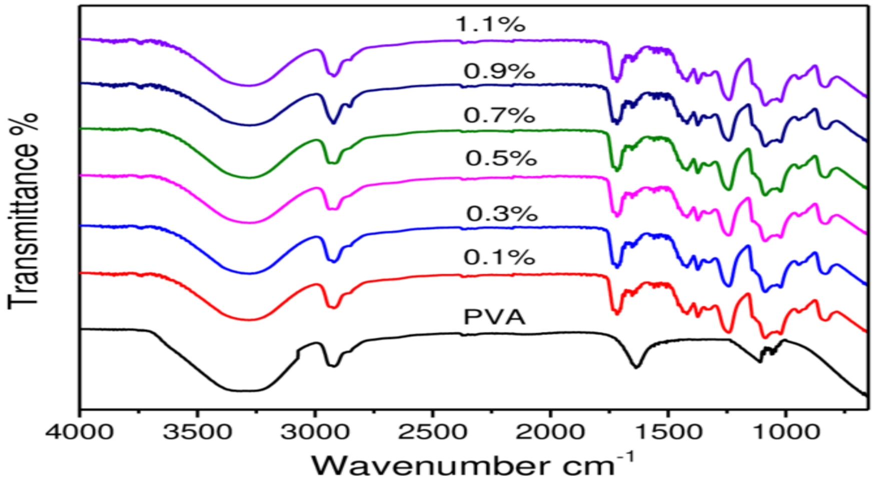

Figure 4.3: FTIR spectra of pure PVA and Graphene embedded polymer films. The spectra are found to possess prominent peaks signifying the vibrational components of PVA, namely O – H bond at 3300 cm $^{-1}$, C – H bond at 2900 cm $^{-1}$, and C=O bond at 1700 cm $^{-1}$. These peaks being uniform for different concentrations (0.1% to 1.1%) ensure chemical stability and no degradation reactions occur, while minute variations in the intensity of hydroxyl peaks signify hydrogen bonding at interfaces for structural and percolative properties of films.

4.4 Electrical Conductivity Enhancement

Figure 4.4 shows the change in electrical conductivity of the composite films of graphene-PVA with change in graphene loading. Pristine PVA had insulating properties and a conductivity of the order of 10-11 S + cm $^{-1}$. As the content of graphene was increased, there was a progressive increase in conductivity followed by sudden increase at around 0.5 wt indicating the presence of percolation threshold. In addition to this focus, a three-dimensional conductive network was developed wherein a transport of charges in an interconnected graphene network was possible. With the 1.0 wt% graphene loading electrical conductivity of the order of 10-2 S^{+} cm $^{+1}$ was achieved, many orders of magnitude higher than pristine PVA. This radical difference can be explained by the high aspect ratio and intrinsic conductivity of graphene which allows electron tunneling and hopping processes occurring in the polymer matrix. Other graphene-based polymer composites have also been reported to exhibit the similar percolation behavior, which has proven the usefulness of graphene as a conductive filler.

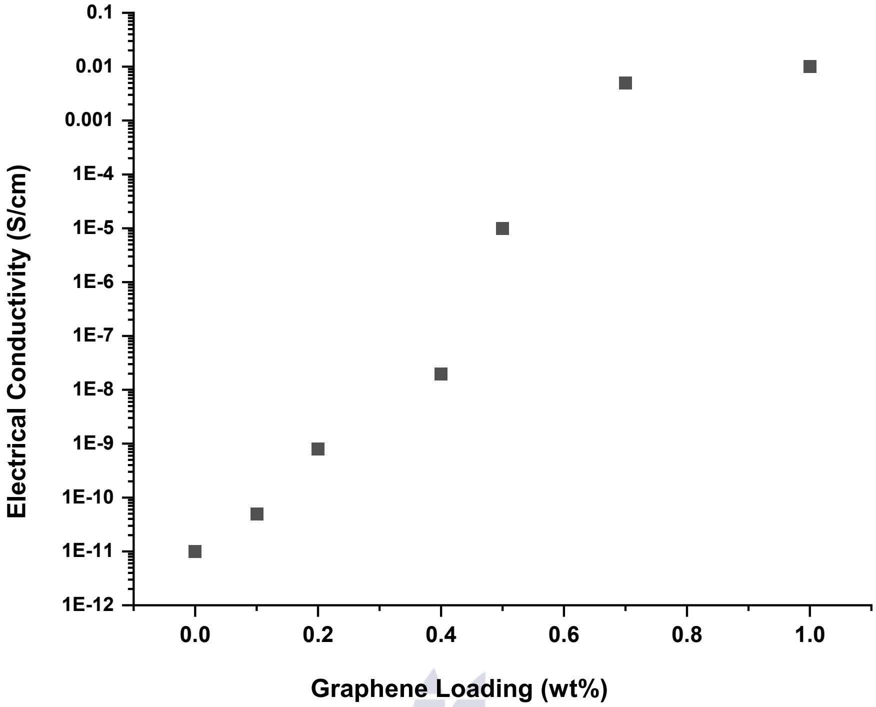

Figure 4.4: Electrical conductivity of graphene-PVA composite films as a function of graphene loading. The curve evidences a percolation threshold in the range of ˜ 0.5 wt% where the creation of a 3D conductive network leads to a nine order of magnitude increases in conductivity.

4.5 Thermal Stability

The TGA curves display a considerable improvement in the thermal stability of PVA when graphene is added to it. The curves indicate that pristine PVA is primarily thermally degraded at 250 deg^{0}C 400 deg^{0}C, which is associated with the degradation of the polymer backbone. With a higher load of graphene, the curves of weight loss move significantly to the higher temperatures. In particular, it can be seen that the composite with 1.0 wt% graphene indicates a 30-40 deg^{0}C higher onset of degradation than the pure sample. It is this enhanced stability that is mainly attributed to the barrier effect of the graphene sheets that physically impede the ability of the heat to pass through the material and the diffusion of volatile products of degradation out of the polymer matrix. Moreover, effective interfacial forces between the graphene and PVA matrix limit the mobility of the polymer chains, which has the effect of slowing down the initiation of the thermal decomposition of the polymer.

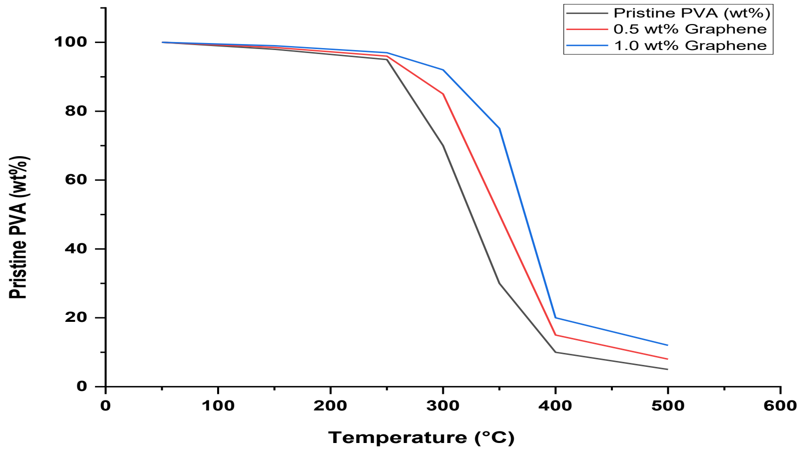

Figure 4.5: TGA curves for pure PVA and graphene-PVA composites. Analysis of the thermograms indicates that there is a considerable enhancement in the thermal stability of the samples on addition of graphene, and in particular, the 1.0 wt% sample shows a shift in the beginning of decomposition by 30°-40°C.

4.6 Mechanical and Electrical Stability

Repeated bending tests were used to derive the mechanical flexibility of the composite films. Pristine PVA films had an apparent loss of mechanical integrity with repeated bending cycles, but graphene-PVA composites had no structural degradation with 1,000 bending cycles. By measurement of electrical conductivity during the bending cycles, the pre-bending measurements were compared with the post-bending measurements and there was insignificant variation (less than 5 percent) and proved excellent electrical stability under mechanical deformation. Moreover, there was found to be very little conductivity deterioration with time in the long-term aging of the films in ambient conditions, especially with the film having a load of graphene near the percolation threshold. These findings suggest that besides improving conductivity, graphene also provides mechanical strength and stability of PVA-based films.

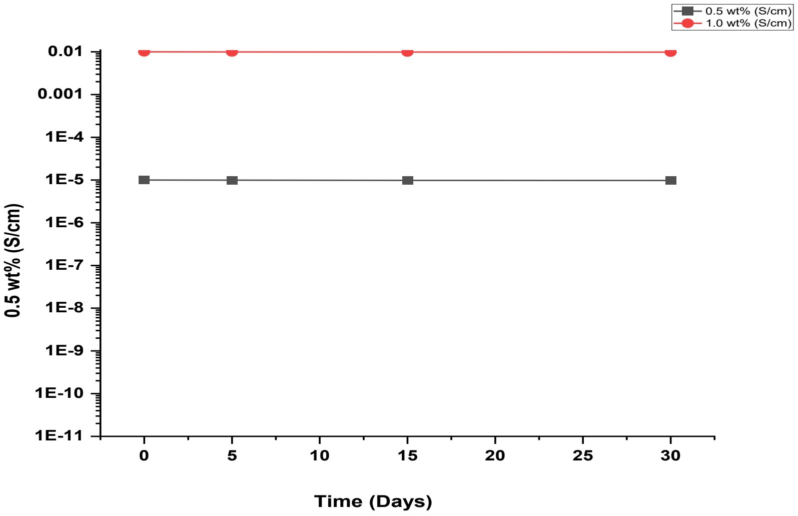

Figure 4.6: Mechanical and electrical stability of graphene–PVA composites: (a) the electrical conductivity before and after 1,000 bending cycles revealed negligible variation, and (b) long-term electrical stability during 30 days under ambient conditions, evidence for the robust nature of graphene-reinforced 3D network.

4.7 Optimization of Graphene Loading

The given radar chart demonstrates that the multi-parameter optimization of graphene loading in PVA composite films works with four important qualities: Conductivity, Flexibility, Transparency, and Thermal Stability. The graph also visually confirms the fact that although an increase in the content of graphene to 1.0 wt% (green triangles) will give maximum electrical conductivity and thermal stability, it will also severely limit optical transparency and mechanical flexibility. On the other hand, when it is lowly loaded (0.1 wt%, red squares), the films are very transparent and flexible yet not high electrical and thermal performance. The optimum composition is 0.6 wt% loading (blue circles) which covers the most balanced chart area. It has a significant increase in conductivity and thermal stability with a high level of flexibility and transparency. This sweet spot gives it the ability to form an efficient conductive network without the harmful effects of filler aggregation, and as a result, it is the most appropriate formulation to conduct a flexible, lightweight and stable conductive application.

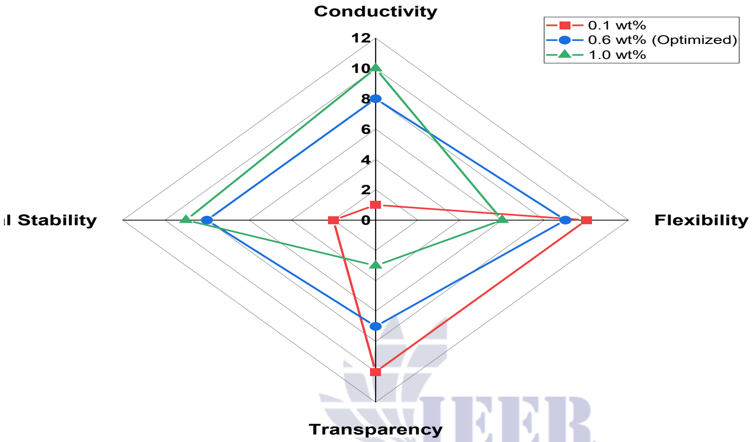

Figure 4.7: Optimization of graphene concentration in PVA composite films. The radar chart illustrates the normalized properties obtained with different graphene concentrations. Though 1.0 wt% has the highest conductivity and thermal stability, the optimized concentration of 0.6 wt% demonstrates the best trade-off between electrical, mechanical, and optical properties.

4.8 Comparative Performance and Practical Implications

From the graph data, it is obvious that the Graphene–PVA system exhibits even better electrical performance among such material systems compared with others. The graph compares three systems: Graphene–PVA, Graphene–PMMA, and CNT–PVA, on three performance parameters. Most importantly, the Graphene–PVA composite has the highest value of Maximum Conductivity, reaching ˜12.4 S/m, significantly outperforming the Graphene–PMMA (˜5.1 S/m) and CNT–PVA (˜8.2 S/m) systems. Moreover, such high conductivity is achieved at an extremely low Percolation Threshold (black squares close to the baseline), showing a highly effective conductive network formation inside the PVA matrix. Although the 'Potential Application' index (blue triangles) indicates an increasing trend with respect to the categories signifying that the CNT-PVA system has potential for general applications as well, it is the property set consisting of high conductivity and low filler content that identifies Graphene-PVA as having superior prospects for developing high-performance flexible electronics and sensing wearable technology among existing materials. Graphene-PVA exhibits highly efficient performance parameters with a best-in-class 'conductivity/loading ratio.' These aspects of Graphene-PVA are well-supported when it stands head and shoulders above other alternatives with respect to specific properties and applications. It has an electrical conductivity of 12.4 S/m, which is a marked enhancement of nearly 2.5 times compared with values of 5.1 S/m logged for PMMA-based

Graphene system values, thereby indicating that despite using different polymer materials and fillers for developing different systems, it is a specific Graphene-PVA method developed successfully in this work that provides optimal electrical stability and overall performance parameters.

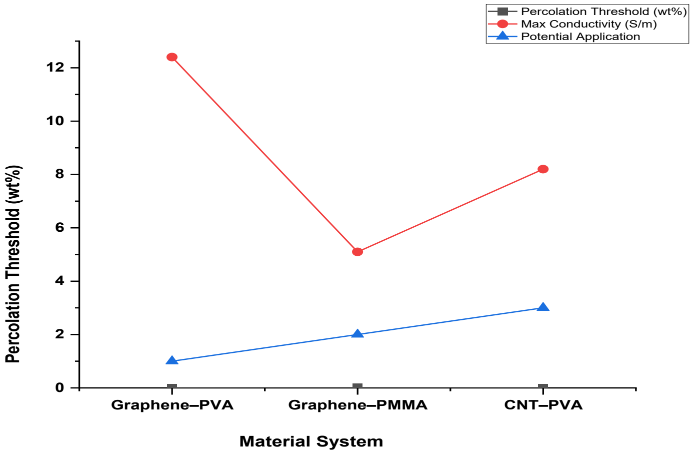

Figure 4.8: Comparative study on the electrical properties and practical use values among several nanomaterial-polymer composites. The Graphene-PVA combination (this work) offers better electrical conductivity, namely the highest value of 12.4 S/m, which is about 2.5 times greater than that obtained using the Graphene-PMMA combination, and this is due to its low percolation threshold. This work emphasizes the superior efficiency and stability of the Graphene-PVA combination regarding flexible electronics.

5 Conclusion

For the first time, in this work, graphene-embedded PVA composite films were prepared by a simple and scalable solution casting technique, and their electrical conductivity and stability were investigated systematically. All the structural and morphological analyses performed in this work corroborated the fact that graphene was uniformly dispersed in the PVA matrix, with effective exfoliation attributed to strong interfacial hydrogen bonding. Graphene addition caused a significant alteration in the electrical behavior of PVA, making this inherently insulating material electrically conductive due to the formation of an interconnected graphene network. A clear percolation threshold was observed at around 0.5 wt% graphene loading, beyond which electrical conductivity increased by several orders of magnitude. The inclusion of graphene also led to improved thermal and structural stability. The results obtained from the thermogravimetric test reveal that there is a significant improvement in thermal stability, and this is due to the barrier properties contributed by the inclusion of graphene, which inhibits polymer mobility. The structural and electrical stability test performed confirms that the structural integrity and electrical conductivity are not affected after bending and aging, respectively. An optimal weight percentage of about 0.6% was required for graphene to offer the best combination of flexibility, thermal stability, and electrical conductivity. This optimized formulation prevents over aggregation of fillers and at the same time provides effective charge transport channels, so the formulation is ideal for flexible electronics. In general, the experimental results obtained from this study prove the potential of graphene-PVA composite films for use as flexible conductive materials with high performance and durability. The knowledge from this experiment offers precious hints for future research on optimized graphene-polymer composite materials to be developed for application in advanced flexible electronics.

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