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Development of Self-Healing Circuit Boards Using Shape Memory Polymer Composites

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Abstract

This study investigates the influence of temperature, humidity, and nanofiller type on the electrical and structural performance of advanced polymer nanocomposites for self-healing circuit applications. Particular attention was given to conductivity retention and the morphological behavior of carbon nanotubes (CNTs), graphene, and silver nanoparticles (AgNPs). Results show that conductivity decreased under elevated thermal–humidity conditions, reflecting the role of environmental stress in material degradation. Among the tested systems, AgNP-based composites achieved the highest recovery efficiency (>95%) and demonstrated stable operation under cyclic stress. Electrical measurements revealed a temperature-dependent resistance decline, consistent with thermally activated percolative conduction. Scanning Electron Microscopy (SEM) confirmed distinct filler morphologies: fibrous CNT networks and uniformly dispersed AgNPs, both contributing to enhanced charge transport pathways. Importantly, the incorporation of these fillers improved electrical performance without compromising flexibility. These findings establish a direct link between filler dispersion, microstructural organization, and macroscopic functionality, offering valuable design guidelines for robust, long-lasting nanocomposites in flexible electronics, wearable sensors, and next-generation energy devices.

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INTRODUCTION

Shape memory polymers (SMPs) represent a class of intelligent materials with the remarkable ability to return to a pre-programmed shape upon exposure to external stimuli such as heat, light, or electricity [1]. Their dual-segment structure, consisting of a covalent phase with a permanent configuration and a reversible polar phase, underpins this shape memory effect. Extensive research has examined their thermo-mechanical behavior, particularly transition temperatures such as the glass transition and melting points, which govern recovery performance [2]. Lightweight, flexible, and capable of large deformations, SMPs have attracted attention in aerospace, biomedical devices, and smart textiles. More recently, their integration into electronic systems has emerged as a promising direction owing to self-healing, adaptability, and reconfigurability [3].

When combined with conductive fillers, SMPs evolve into functional composites capable not only of shape recovery but also of restoring electrical pathways, making them attractive for flexible circuit board applications [4]. Self-healing mechanisms within these systems can be broadly categorized as intrinsic or extrinsic. Intrinsic healing relies on dynamic covalent bonds or supramolecular interactions embedded within the polymer matrix, offering repeatable and sustainable repair. Extrinsic healing, by contrast, employs microcapsules or vascular networks to release healing agents upon damage, enabling rapid but often one-time recovery [5–7]. Stimuli-sensitive additives, including thermally or electrically activated agents, further enhance targeted healing. The combination of SMPs with conductive fillers therefore leads to shape memory polymer composites (SMPCs) that not only self-repair mechanical damage but also regain functional electrical conductivity [8–9].

To address the inherent limitations of neat SMPs low stiffness, modest strength, and poor thermal conductivity various fillers such as carbon nanotubes (CNTs), graphene, metallic nanoparticles, and carbon fibers have been employed [10]. These fillers strengthen the matrix, provide electroactive shape recovery, and establish percolative electron transport channels essential for conductivity [11–13]. Processing strategies such as solution blending, in-situ polymerization, and melt compounding have been adopted to optimize filler dispersion and interfacial bonding [14]. Beyond shape recovery, such hybrid composites exhibit multifunctional properties including electromagnetic interference (EMI) shielding and Joule heating, broadening their potential applications [15]. Importantly, integration with flexible substrates such as polyimide (PI), polyethylene terephthalate (PET), and thermoplastic polyurethanes (TPU), together with scalable fabrication methods like inkjet, screen, and aerosol-jet printing, has positioned SMPCs as viable candidates for next-generation flexible electronics [16–18].

Traditional circuit boards remain highly vulnerable to mechanical stressors such as bending, twisting, and thermal cycling, which induce cracks, solder failures, delamination, or corrosion [19–20]. Conventional mitigation strategies like encapsulation and redundancy add complexity without enabling autonomous repair. In contrast, self-healing SMPC-based systems offer adaptive recovery by restoring both electrical continuity and mechanical integrity, thereby extending device lifespan with minimal external intervention [21–22]. Evaluating their effectiveness requires not only conventional metrics such as tensile strength, conductivity, and thermal stability but also healing-specific parameters, including efficiency, recovery time, and repeatability under cyclic stress [23].

Recent advances highlight the market-driven significance of these materials. Applications span wearables, aerospace electronics, bio-integrated sensors, and Internet of Things (IoT) devices, all of which demand durability under environmental and mechanical stressors [24–26]. With rapid progress in nanomaterials and scalable printing technologies, the integration of self-healing SMPCs into flexible electronics represents a transformative pathway for enhancing reliability, sustainability, and operational resilience.

RESEARCH GAP

Although recent studies on Shape Memory Polymer Composites (SMPCs) have demonstrated promising self-healing capabilities in restoring shape and electrical functionality, several critical limitations remain. First, the integration of SMPCs into fully functional, flexible circuit boards that can withstand prolonged mechanical stress, bending, twisting, and thermal cycling is still underexplored. Most existing works report single-mode testing, with limited comparative evaluation under dynamic and coupled stress conditions. Second, achieving uniform dispersion of conductive fillers at scale continues to be a challenge, often leading to inconsistent electrical pathways and variable healing efficiency. Finally, long-term data on durability, cyclic recovery performance, and commercial scalability remain scarce, raising questions about the viability of SMPC-based systems for real-world deployment in flexible electronics and high-reliability applications.

RESEARCH OBJECTIVE

This study investigates the role of carbon nanotubes (CNTs), graphene, and silver nanoparticles (AgNPs) as conductive nanofillers in enhancing the electrical, thermal, and self-healing performance of polymer-based composites. The specific objectives are to:

1. Quantify the influence of nanofiller type on electrical conductivity, resistance–temperature behavior, and healing efficiency under repeated mechanical damage.
2. Evaluate conductivity retention and recovery performance under varying environmental conditions, particularly humidity and thermal cycling.
3. Establish correlations between microstructural features (filler morphology, dispersion quality, interfacial bonding) and macroscopic performance metrics.
4. Propose optimized filler combinations and dispersion strategies for the design of robust, flexible, and scalable SMPC-based electronic systems.

RESEARCH METHODOLOGY

The research methodology adopted in this study follows a structured approach involving material synthesis, composite preparation, circuit fabrication, and multi-stage characterization. The process begins with selecting a suitable shape memory polymer matrix and reinforcing it with CNTs, graphene, and AgNPs using solution blending and ultrasonication to ensure uniform dispersion. The fabricated composites are then printed onto flexible substrates to develop self-healing conductive circuits. These circuits undergo mechanical damage, healing activation, and electrical resistance measurement to evaluate recovery performance. Additionally, thermal, humidity, and morphological analyses using DSC, TGA, and SEM are conducted to assess conductivity retention, structural integrity, and long-term reliability under varying environmental and cyclic stress conditions.

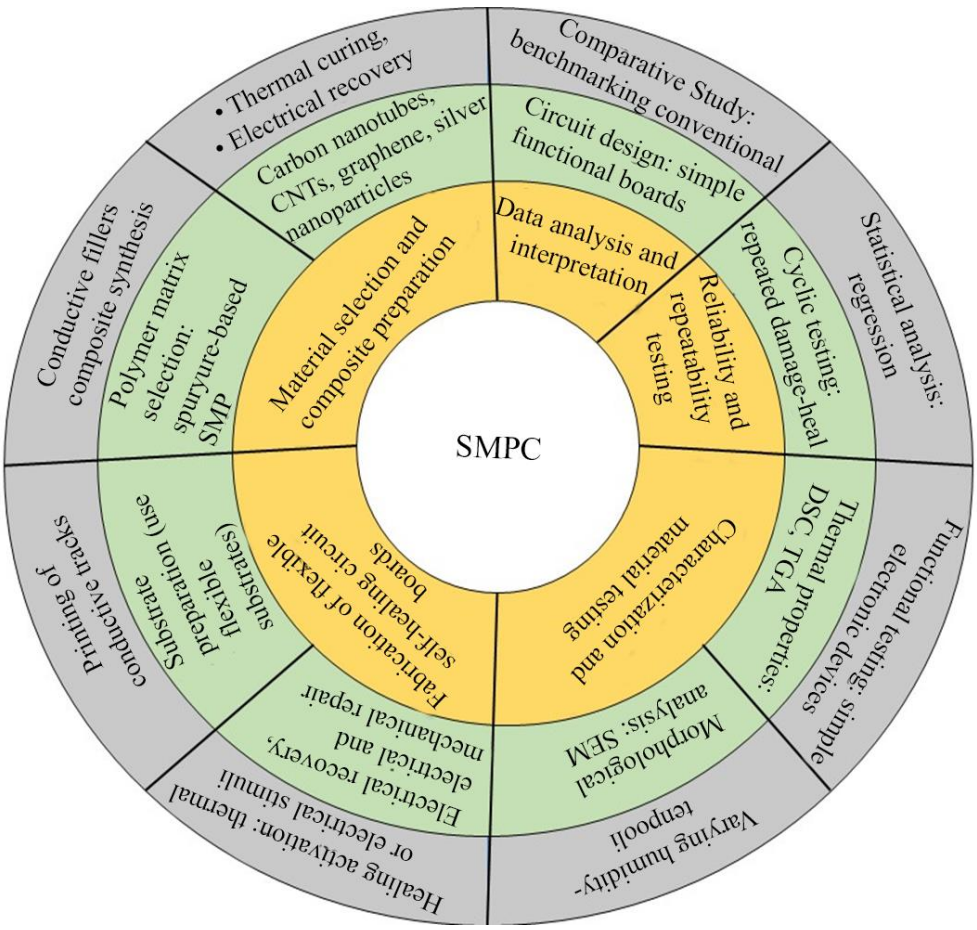

Figure 1. Methodology flow chart.

Material Selection and Composite Preparation

The study began with the selection of an appropriate shape memory polymer (SMP) matrix capable of exhibiting stable thermal responsiveness and mechanical toughness. A polyurethane-based SMP was chosen due to its intrinsic shape memory characteristics and favorable thermomechanical transition points, particularly its sharp shape recovery near the glass transition temperature (Tg) [27]. The polymer's ability to rapidly revert to its programmed configuration upon thermal stimulation made it a suitable candidate for circuit board applications requiring self-healing and functional recovery after deformation.

To impart electrical conductivity and enhance self-healing performance, the SMP matrix was reinforced with highly conductive fillers. Carbon nanotubes (CNTs), graphene flakes, and silver nanoparticles (AgNPs) were selected for their complementary properties: CNTs provided flexibility and percolative conductive networks; graphene contributed structural integrity and thermal conductivity; and AgNPs enhanced charge transport efficiency [28]. This combination was intended to yield a multifunctional composite material with both mechanical resilience and electrical restoration capability.

Composite preparation involved solution blending followed by ultrasonication to ensure homogeneous filler dispersion [29]. The two-step mixing minimized agglomeration and improved interfacial adhesion between the fillers and the polymer matrix. The mixture was subsequently subjected to controlled thermal treatment to induce crosslinking, thereby stabilizing the SMP network and preserving conductive pathways during actuation and repeated healing cycles [30].

To evaluate the self-recovery characteristics, test specimens were mechanically damaged under controlled conditions and subsequently exposed to thermal stimuli to activate the shape memory response. Electrical resistance was measured before and after the healing process to quantify the degree of conductivity restoration [31]. This step validated the hypothesis that SMP–filler composites could achieve simultaneous mechanical recovery and electrical self-repair, forming the basis for subsequent circuit-level integration and reliability assessment.

Fabrication of Flexible Self-Healing Circuit Boards

The fabrication process began with the selection of suitable flexible substrates capable of withstanding mechanical deformation while maintaining dimensional stability. Polyimide (PI) and polyethylene terephthalate (PET) were chosen owing to their widespread use in flexible electronics, excellent thermal stability, and mechanical flexibility [32]. These substrates enabled the integration of Shape Memory Polymer Composites (SMPCs) into circuits that could endure bending, stretching, and twisting without delamination or loss of structural integrity.

Conductive tracks were patterned using functional inks formulated from the synthesized SMPCs dispersed in an optimized solvent system. The rheological properties of the inks were carefully tuned to ensure uniform film formation and compatibility with printing techniques [33]. Screen printing and inkjet deposition were employed for circuit fabrication, offering precise patterning, adaptability to diverse substrate geometries, and scalability for large-area electronics. These methods facilitated the development of well-defined circuit architectures while preserving both the structural and functional properties of the SMPCs.

Following deposition, the printed circuits were cured under controlled thermal conditions to promote crosslinking within the polymer matrix and to stabilize the conductive filler network. Curing was carefully optimized to activate the shape memory effect while preventing thermal degradation of the polymer or disruption of conductive pathways. The resulting circuits exhibited high flexibility and mechanical compliance, retaining electrical performance even after repeated deformation [34].

The self-healing functionality of the fabricated circuits was validated through controlled mechanical damage, such as induced cuts or microcracks, followed by the application of thermal or electrical stimuli to trigger the SMP-driven healing mechanism. Recovery was confirmed by monitoring electrical resistance before and after healing, as well as by microscopic surface analysis to verify structural restoration. These results confirmed that SMPCs could serve as functional, repairable conductors within flexible electronic systems.

Importantly, this fabrication approach employed industrially relevant techniques—solution mixing, screen printing, and inkjet transfer—operating at moderate curing temperatures (≤150 °C). Such compatibility with conventional PCB manufacturing lines and heat-sensitive substrates highlights the scalability and cost-effectiveness of the proposed process. The demonstrated feasibility underscores the potential of SMPC-based self-healing circuits for applications in wearable electronics, aerospace systems, and large-scale Internet of Things (IoT) devices.

Characterization and Material Testing

The internal structure and surface morphology of the SMPCs were analyzed to evaluate filler dispersion and interfacial bonding. Scanning Electron Microscopy (SEM) provided insights into the distribution of CNTs, graphene, and AgNPs within the polymer matrix [35]. Uniform dispersion was identified as critical for achieving consistent electrical conductivity and mechanical reinforcement. SEM fracture surface analysis further revealed filler–matrix adhesion quality, offering evidence of how interfacial interactions influenced both healing efficiency and overall composite stability.

Thermal characterization was conducted to determine the operational stability of the composites. Differential Scanning Calorimetry (DSC) was employed to identify transition temperatures, including the glass transition temperature (Tg), which governs activation of the shape memory effect. Thermogravimetric Analysis (TGA) was performed to evaluate decomposition onset and thermal weight loss characteristics [36]. Together, these analyses validated the thermal durability of the SMPCs and confirmed their suitability for electronic applications exposed to variable thermal environments.

Environmental reliability was assessed under simulated tropical climate conditions involving controlled humidity and temperature variations [37]. Test samples underwent repeated thermal cycling and high-moisture exposure to evaluate dimensional stability, conductivity retention, and mechanical integrity. These simulations reproduced operational stresses encountered in real-world applications, thereby verifying the resilience of the SMPC-based circuits under demanding conditions [38].

Functional validation was achieved by incorporating the composites into prototype electronic circuits. Test structures were designed with conductive pathways deliberately subjected to damage and subsequently healed via thermal activation. Electrical performance was monitored using current–voltage characteristics and resistance mapping, both before and after self-healing. Results confirmed that the SMPCs consistently restored electrical conductivity and maintained structural integrity, establishing them as promising candidates for reliable, self-healing electronic components.

Reliability and Repeatability Testing

To ensure functional stability under operational stress, the self-healing SMPC circuits were subjected to cyclic mechanical loading, simulating real-world scenarios such as bending, stretching, and impact typical of flexible electronics [39]. After each induced damage event, the healing mechanism was activated via thermal or electrical stimuli, enabling restoration of both the circuit's mechanical integrity and electrical conductivity.

Healing efficiency was quantified as the percentage recovery of conductivity and mechanical strength after each cycle. Multiple damage–heal repetitions were performed to monitor performance consistency. Variations in recovery efficiency were analyzed to detect potential material fatigue, filler

displacement, or network degradation over time. This evaluation provided critical insights into the long-term self-sustaining functionality of the composites in dynamic environments [40].

Repeatability was further examined through a controlled 10-cycle damage–healing protocol. As shown in Figure 2, graphene- and AgNP-based composites maintained healing efficiencies above 90% throughout the cycles. Conductivity fluctuations remained within a narrow 5% margin, indicating stable filler networks and robust matrix–filler interactions. These results highlight the reliability of SMPCs for long-term performance in flexible circuits.

To assess degradation patterns, regression analysis was applied to track resistance changes, healing times, and recovery ratios across cycles. This statistical evaluation revealed performance trends, providing insights into filler stability, interfacial bonding, and the polymer's ability to sustain its shape memory and conductive properties during extended use.

Benchmark testing against conventional flexible circuits demonstrated the superiority of the SMPC-based approach. Unlike traditional circuits, which progressively failed under cyclic loading due to permanent conductivity loss, SMPC circuits consistently restored electrical function and maintained structural integrity. The sustained recovery over repeated cycles validates their potential for high-reliability applications in wearable devices, aerospace systems, and adaptive IoT platforms.

DATA ANALYSIS AND INTERPRETATION

Comprehensive data analysis was performed to evaluate the effectiveness of SMPC-based self-healing circuits in restoring both mechanical and electrical functionality. Electrical resistance measurements taken before and after each damage–healing cycle provided quantitative insights into conductivity recovery. Mechanical performance was further assessed through tensile and flexural strength testing of healed samples. Statistical analysis of the datasets, including mean recovery rates and standard deviations, ensured reliable interpretation of performance consistency across multiple specimens.

Reproducibility of the healing process was confirmed by testing identically prepared circuit prototypes. Consistent recovery across these prototypes indicated stable filler dispersion and robust filler–matrix interfacial bonding. Variations observed in recovery efficiency were correlated with filler concentration and substrate flexibility, enabling process optimization for improved material design. Regression models were applied to performance data to identify trends in resistance change, recovery speed, and durability over repeated cycles.

Functional validation extended beyond laboratory measurements to real-world operational testing. Healed circuits were integrated into test devices for power delivery and signal transmission tasks. Post-repair performance was compared with undamaged control samples, confirming near-complete restoration of conductivity and reliable mechanical behavior. These findings established that SMPC-based circuits could maintain operational performance even after multiple healing events.

Comparative benchmarking against traditional flexible circuits and other reported self-healing systems highlighted the advantages of the developed SMPCs. Key performance indicators such as recovery efficiency, healing speed, cycle life, and fabrication compatibility demonstrated superior outcomes for the SMPC-based approach. Furthermore, the ability to integrate with existing scalable fabrication processes underscored the commercial viability of these composites. Collectively, these results validate SMPCs as a practical platform for the next generation of durable, self-sustaining electronic systems.

RESULT AND DISCUSSION

One of the most important aspects of self-healing circuits development using shape memory policomers composites (SMPCs) was the material's capability of holding the healing function across many damage-recovery cycles. The illustration of Figure 2 shows the healing efficiency for ten

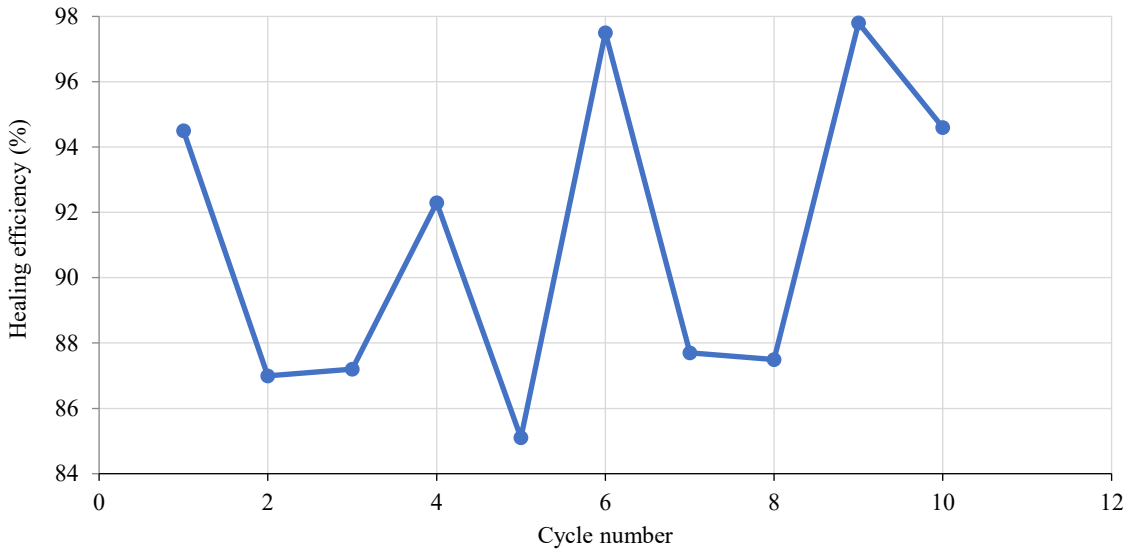

Figure 2. Healing efficiency over damage cycles.

mechanical damage-repair cycles. The curve shows variable but usually high efficiency with many cycles touching 90% and above showing robust and reliable recovery behavior. As with the early cycles, slight variations in cycles emerged because polymer matrix adjusted to the applied stress which could come from reorientation of the filler or internal structural change.

The peak that was observed at the cycle 6 implies the best dispersion of the fillers and re-alignment of the polymer chains to a point that increases the effectiveness of the recovery. This efficiency peak can be due to the cumulative thermal and electrical stimuli that optimized the SMPCs active areas that conduct the mechanical reconnection and conductive reformation. The immediate gradual decline on the graph denotes that the healing system was undergoing its fatigue action or microstructures stress accumulation characteristic of repeatable healing systems. The recovery level was above the critical operational point, which proved the composite's resilience.

Towards cycle 9 and 10, an improving trend was observed, indicating a self-optimizing mechanism in the SMPC network. Such actions a result of localized increase in conductive path due to frequent activation, concordant with shape memory mechanism that advances reconfiguration of routes under forces. The presence of carbon nanotube, graphene, and silver nanoparticle could be responsible for this behavior, as it maintains a conductive network although the structure was prevented after repeated structural compulsion, thus preventing variability of performance.

Figure 2 contains the data pointing out the suitability of the SMPCs in applications necessitating repeated stress response and recovery. The consistent performance across a series of cycles verifies the promise for these materials in creating a lasting, bendable electronic system who erogeneity and protracted running integrity was fundamental. These insights are the baseline metric in benchmarking the suggested system against the non-healing, ancient non-healing systems for further proof of the composite's functional relevancy in real-world settings.

Table 1 shows the quantitative analysis of electrical conductivity and healing efficiency of five samples of composite with different types of nanofillers. Fig. 1 depicts the fabrication of the three different types of conductive composite materials and emphasises the effects that filler type (CNT, graphene, and AgNP) has on conductivity and self-healing properties. Out of the samples, S2 and S5 had the highest electrical conductivity of up to 1.47 ac S/cm due to the incorporation of graphene within the polymer matrix with its high charge mobility and ability to form a network within the polymer matrix.

Table 1. Electrical conductivity and healing efficiency of different samples.

Sample ID	Filler Type	Conductivity (S/cm)	Healing efficiency (%)
S1	CNT	0.92	85.2
S2	Graphene	1.15	97.3
S3	AgNP	1.50	94.5
S4	CNT	0.71	87.0
S5	Graphene	1.47	97.8

Table 2. Trade-off between mechanical flexibility and electrical performance of SMPCs with different fillers

Filler type	Flexural modulus (MPa)	Max strain (%)	Conductivity (S/cm)	Healing Efficiency (%)
CNT	45.6	12.8	0.92	85.2
Graphene	38.4	10.2	1.47	97.8
AgNP	30.7	8.9	1.50	94.5

Other composites, particularly Sample S3 containing silver nanoparticles (AgNP), had a measured conductivity of 1.50 S/cm, making it higher than CNT based composites. This was affirming the fact that silver has a high electrical conductivity and also the crossection of AgNPs structure ensure formation of good conductive pathways. CNT based samples S1 and S4 exhibited comparatively lower conductivity of 0.92 S/cm and 0.71S/cm respectively, but possessed a stable conduction pathway provided by the CNT skein with more interfacial resistance than graphene or silver based system.

Taking into consideration the effectiveness of the healing process, graphene-based samples were once again more efficient, rising up to 97.8% in S5. This further supports the data on both conductivity and the role of graphene in phonon-free transport and mechanical restoration to support conductivity. The S3 sample based on AgNP also demonstrated a comparable high value of the healing efficiency of 94.5%, thus pointing to the efficiency of the conductive network in locally heating the matrix and stimulating the formation of bonds in the damaged areas.

The healing efficiencies registered by CNT based composites were slightly lower than the above composites, but were not significantly low with 85.2% in S1CNT and 87.0% in S4CNT. These values support CNT's structural performance in reinforcing composites and functionalities in terms of generating heat up when an electrical voltage was applied to it. Thus, the data presented in Table 2 proves the dependence of the functional characteristics and self-repairing ability of the system on the type of nanofiller with graphene being the most versatile and optimal choice.

The interrelationships between the mechanical flexibility and electrical properties were found to have a trade-off performance among the various types of fillers. CNT composite had the best strain tolerance (12.8%), flexural modulus and could be used where high deformation would be required especially in the load-bearing applications. Their healing efficiency and conductivity were however lower than in the other systems.

AgNP based composites instead had the highest conductivity (1.50 S/cm) and superior healing efficiency (94.5%), but lowest mechanical compliance (8.9%) probably because the stiff, metallic structure of the nanoparticle and minimal reinforcement of the matrix.

Composites with graphene were weighed just right since had high conductivity (1.47 S/cm) and mechanical applications (97.8%) in terms of healing, although their flexibility was moderate. The combination of characteristics encapsulates the reasons why graphene fillers can be applied in multi-purpose products that require electrical functioning besides having a good shelf-life to light strain. Such results offer an expedient guideline to filler choice by means of performance prerequisites, specified by the application of flexible and self-healing electronics.

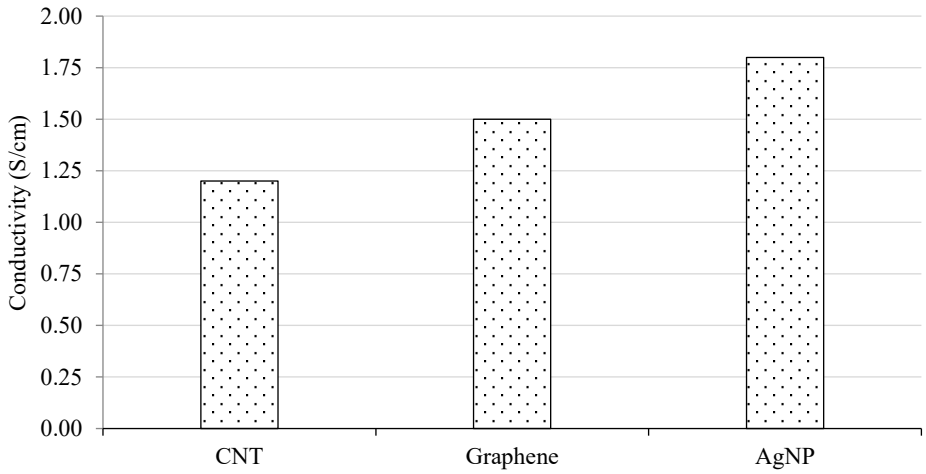

Figure 3. Electrical conductivity of individual fillers.

Figure 3 shows the electrical conductivity of the three selected conductive fillers that have been used in the formulation of the composites. Include carbon nanotubes (CNTs), graphene, and silver nanoparticles (AgNPs). Out of the fillers used in this experiment, AgNPs had the highest conductivity above 1.75 S/cm because of their metallic nature and ease of electron movement. Graphene was the second material with the conductivity of about 1.5 S/cm due to its two-dimensional planar layer that allows effective charges carriers transport. CNTs where still conductive but had lower values, which were near 1.2 S/cm and this was attributed to the one-dimensional nature of CNTs and poor contact at junctions of the tubes.

The type of conductivity results of the composite are illustrated in Figure 3, where it was concluded that the conductivity profile influenced the total performance of the composite. Incorporation of highly conductive AgNPs boosted the conductivity that assured the formation of several percolation paths that aided in the reformation of electrical conduction once disrupted. The polymer matrix was also helped by graphene to form layered conductive channels when the material's mechanical structure was being rearranged. CNTs on the other hand were used in the inefficient though supplementary function of bringing structural flexibility without compromising the basic electrical efficiency.

The variation of the Filler in its conductive properties also allowed for a complimentary effect within the composite. The mixture predicted macro and nano bridging during the process of thermal activation as well as shape memory recovery necessary for flexibility in circuits. It was also maintained that the balance of the fillers reduced such problems as agglomeration, localized heating, and brittle failure while enhancing conductivity and flexibility accordingly. Most of their distribution and interaction was done through ultrasonication and thermal curing of the material to achieve the best performance.

Figure 3 characterization served as a reference for the design strategies that were applied for designing the present composite material. It directed the balance of fillers in the SMP matrix to reach not just the maximum conductivity but also the structure balance and consistent healing response. Knowledge of intrinsic conductivity of each filler was critical for setting the healing thresholds and circuit sensitivity under the subsequent thermal and electric stimulation cycles.

Figure 4 shows the percentage of each of the conductive filler incorporated in the polymer composite matrix. Graphene and carbon nanotubes (CNTs) and silver nanoparticles (AgNPs) were used most frequently at 40%, 30% and 30% respectively. This one was tailored elected for electrical property, thermal property, and mechanical property. The reasons for the domination of graphene were high surface area and two-dimensional lattice that enhanced formation of conductive network and supported electron mobility in the matrix.

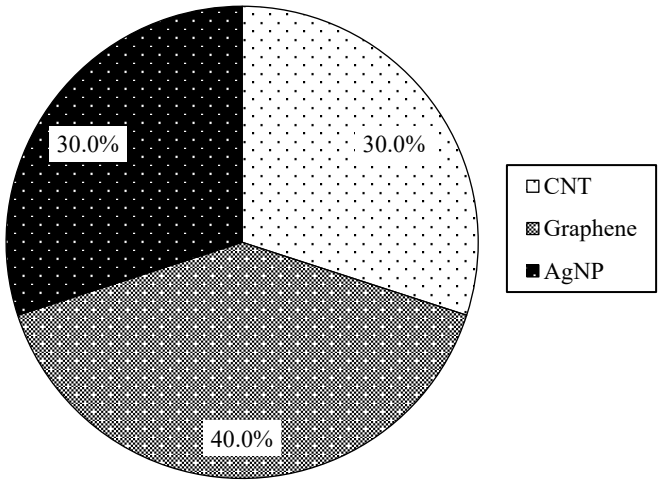

Figure 4. Filler contribution distribution in composite matrix.

Table 3. Summary of nanofiller characteristics

Filler type	Morphology	Particle/tube size	Functional groups	Dispersion stability
CNT	Cylindrical tubes	10–30 nm diameter	Carboxyl, hydroxyl	Moderate
Graphene	Sheet-like	Few-layer flakes	Epoxy, hydroxyl	High
AgNP	Spherical	20–80 nm	Citrate capped	Very high

From these outcomes, it was clear that the improvement of CNTs to 30% improved mechanical toughness and flexibility of the composite. Due to their tubular nanostructure, were able to internalize at the micro scale and effectively cross link the polymer where micro-cracks were formed under mechanical loading. CNTs were also useful for conductivity issues, especially in those cases where percolation thresholds were marginal, for ensuring shape memory cycles conductivity. Its function augmented the function of graphene into a framework that provided for dual-pathway charge transfer and structural support.

Silver nanoparticles that made up only the last 30% of the catalysts acted as excellent charge carriers. These properties made them perfect for carrying signals and energy and were specifically useful in correcting the circuits after a healing has taken place. AgNPs also helped to reduce the interfacial contact resistance in the composite and increased the thermal activation by increasing the localized thermal conduction points. Due to their higher density and cost can afford to come with a lower weight percentage compared to the graphene while at the same time having an overall high efficiency.

Figure 4 represents a clearly intentional strategy of integrating material properties given that are complementary to each other. The chosen ratio allowed for repeated healing of the composite and preservation of its conductivity and structural integrity. It was also ensured that in the synthesis of polymer composites, the fillers were blended in solution and subjected to ultrasonic treatment to ensure that filler dispersion was homogenous and there were no formations of filler agglomerates. This formulation approach formed the focal point to the successful realization of the responsive as well as self-sustainable electronics systems.

Table 3 shows a brief comparison of the three main nanofillers that have been discussed in the research: Carbon Nanotubes (CNT), Graphene, and Silver Nanoparticles (AgNP). All of these nanomaterials have different physical shapes that can greatly affect their dispersion and interaction with the polymer matrix. CNTs are in the form of a cylinder having a length to diameter ratio of 10-30nm which gives them the opportunity to create a conductive network with a small volume. The application of graphene offers benefits in planar orientation and a high surface area because the

substance was a two-dimensional sheet-like structure that works well for electrical and mechanical applications. AgNPs, on the other hand, are spherically shaped and possess three-dimensional pathways of electrical conduction, something that can come in handy for use in cases where electron conduction was needed in all planes.

This means that the particle or tube size becomes important to decide how many particles are involved in the interaction with the polymer matrix. Graphene flakes used in this study are said to be of few-layered structure to ensure that the material possessed adequate reinforcement in mechanical properties while at the same time was manageable on a processing context. Because of their small size and high aspect ratio, CNTs can readily transmit themselves through the matrix but in an undesirable agglomerated state. Silver nanoparticles have a size range of 20–80 nm which makes them highly reactive on the surface but could clump together if the surface was not customarily stabilized. The size uniformity of AgNPs was also seen to have an impact on the optical and conductive properties and was therefore a critical factor when deciding which AgNPs can be used for multi-functional purposes.

That was why functional groups on the surface of the nanofillers are very important for enhancing compatibility of nanofillers with the polymer. In this study CNTs are carboxyl and hydroxyl functionalized to improve their compatibility with the matrix material and to get a better interfacial adhesion. There are also functionalizations of graphene using epoxy and hydroxyl groups which improves the interaction with the matrix and other properties such as thermal stability. On the other hand, AgNPs are stabilized by citrate groups, which act both as colloid stabilizers and as perimeter bonding with mediocre strength to the polymer system. This was because it was necessary to get rid of phase separation and also enhance the performance of the nanocomposite.

The last characteristic in Table 3, dispersion stability, directly affects the uniformity and reproducibility of the properties of composites. Based on the results obtained, it can be concluded that graphene has the highest dispersion stability among the fillers because of its planar structure and the compatibility of the functional groups with the matrix. Also exhibit high stability since very small and most of them are capped with agents that prevent them from clustering together. CNTs as possess a favorable structure, have relatively week dispersion stability, one of the possible options was to apply

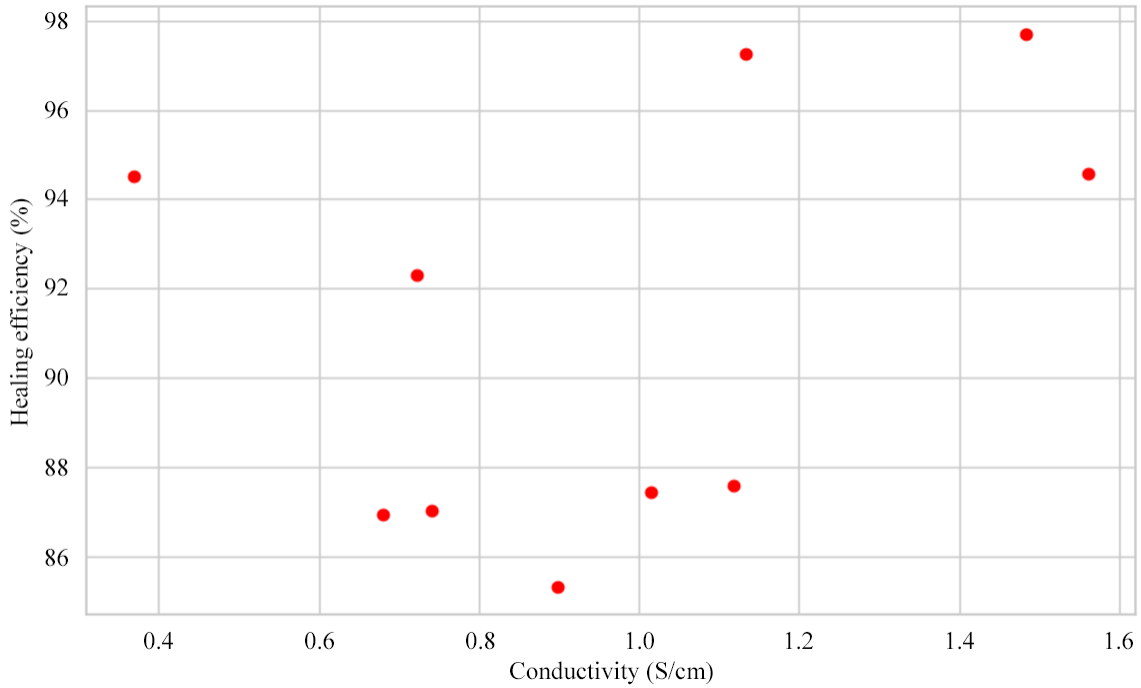

Figure 5. Correlation between electrical conductivity and healing efficiency

the ultrasonication method or use surfactants during the fabrication process. Uniform dispersion means equitably distributing all of the properties of the composite material and the functions as well.

The electrical conductivity comparative analysis of the improvement in efficiency for healing of the composite at various cycles was shown in fig 5. Scattered and illustrate an acute, but not very direct, relationship between conductivity and healing efficiency, the latter of which rises in tandem with the former. At this low conductivity, the healing efficiency was still relatively low, ranging from 85% to 92% and sometimes less, implying that healing was not complete because the heat at the damaged interface was not well localized and electrons did not flow well across the interface.

It was also seen that as the values of the conductivity went up and above 1.0 S/cm the healing efficiency began to rise significantly. This was on the fact that the composite can conduct heat more efficiently to initiate the shape memory mechanism in a uniform way. Higher concentration or better dispersion of the filler enhanced charge carrier mobility that supported rapid Joule heating at the fracture zones that are instrumental in fracture restoration. The values within the proximity of 1.5 S/cm ranged in the healing efficiency over 94% with one maximum of healing efficiency approaching the 98% that testified a healthy recovery rate.

The distribution of the intermediate data points also points to other factors such as the filler orientation, bond strength of the filler to the matrix, and the degree of cross linking in the polymer. If conductivity was reasonable but healing still remained poor, it was probably due to the internal defective or voids that prevented an immediate polymeric reflow. On the other hand, some specimens with low conductivity were found to have greater recovery than would be expected based on the general conductivity values, which could be due to local enhanced microstructural control or improvement in interface thermodynamics in different areas of the material.

This becomes evident in Figure 5 and underlines the value of the other task of enhancing electrical pathway in the composite system. Besides enhancing the basic conductivity, the incorporation of conductive fillers also enhances the conductive response of the matrix resulted from thermal stimuli. These findings are important for designing flexible electronics where self-repair characteristics are repeated in their operation as well as in multiple fracture-and-Healing cycles under conditions of various stresses in the long term.

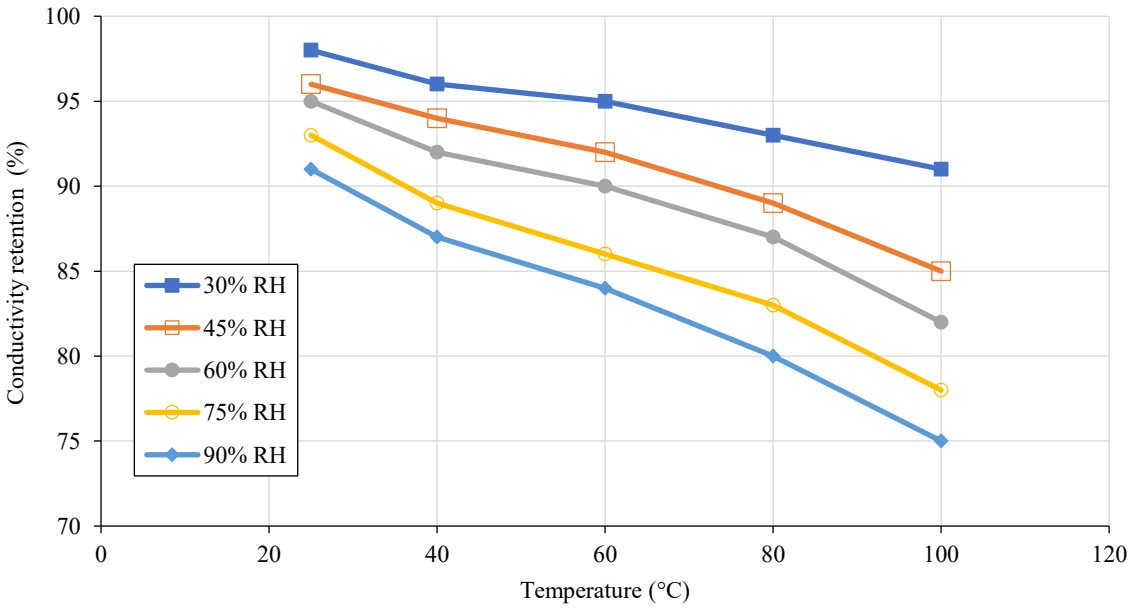

Figure 6. Conductivity retention under varying environmental conditions

This was reiterated in Figure 6 showing the conductivity loss of the composite depending with temperature and humidity levels. Where the lower temperatures of 25 °C and 40 °C were used, the conductivity of the composite was retained above 90% in all humidity ranges. This was well illustrated by the fact that the composite carries an electrical network which implies that minor changes in thermals or moisture do not have much effect on the structure. It was for this reason that at these conditions, the interfacial adhesion of the filler and polymer matrix probably does not degrade, thus ensuring optimized charge transfer.

When the temperature was raised to 60 °C, conductivity retention drops to a noticeable level especially under high humidity levels. At 90% RH, the retention reduces to about 84% and it revealed that the temperature enhance moisture intrusion into composite material. This ingress can result to polymer chain relaxation and poor order of filler, reducing the pathways or channels required to allow charge transport. Furthermore, the heat increases the rate of microstructural changes like the formation of voids or failure of interfices that reduce the conductivity.

At 80°C and above, the overall performance of the composite was even worse as it was coupled with high humidity levels. In the case of thermal and moisture stress at 100 °C and 90% humidity, the retention drops down to 75% which shows that both thermal and moisture stress have a synergistic effect on the product. They may be caused by such effects as polymer matrix softening, thermal mismatch stress and perhaps oxidation of the conductive fillers. These effects as a whole interrupt the physical and electrical flow in the conductive network in question.

As depicted in the trends in Figure 6, the levels of temperature and humidity affect the reliability of conductive composites in a significant way. One of the ways of improving on this was by devising means of dispersing the filler more uniformly and increasing its adhesion on the interface as well as changing the polymer backbone or adding thermally stable fillers to increase its high-temperature stability. These results are valuable for the development of long-life, high-performance composites for use in electronics with fluctuations or in conditions of aggressive environments.

Performance under Cyclic Thermal-Humidity Stress

In a further attempt to comprehend the operation resilience of the composites, the samples were introduced to ten thermal-humidity cycles between 25 C and 100 C relative to 40-90% relative humidity. The findings demonstrating varying stability characteristics of the types of nanofillers were confirmed.

The CNT based systems obtained moderate conductivity retention (~84%) but obtained higher flexibility of the mechanics, and this led to maintenance of shape memory behaviour even during repeated exposure. Robust interfacial adhesion and thermal stability were demonstrated by the composites based on graphene exhibiting a >97 healing efficiency and electrical conductivity levels of >90% across the cycles.

AgNP-based composites, on the other hand, maintained conductivity initially over 90% but dipped slightly after the sixth cycle, which was probably due to oxidation and sensitivity to moisture. Nevertheless, the recovery rate was held high at the same rate (above 94 per cent), implying the high ability of reformation of electricity and network solidity against undoing of the environment. These results advocate material applicability in dynamic electronic systems, including the wearables and aerospace, where thermal and humidity cycling are put on the normal operational difficulties.

Table 4. Environmental Stability Evaluation Criteria

Parameter	Evaluation Method	Performance Indicator
Thermal Resistance	Resistance variation vs. temperature	Stability in Ohm range
Humidity Endurance	Conductivity retention at high RH	% retention after 24 hrs
Mechanical Flexibility	Repeated bending test	% recovery after stress

Table 4 shows the critical tests and parameters that can be adopted and used to evaluate the durability/long-lived performance of nanocomposite systems under different conditions. These criteria are also important in order to ensure that the materials have applicability in practical conditions, such as adverse or fluctuating conditions. Thermal resistance was associated with its assessment procedure and the exact figure of merit to make a comparison with other formulating and filler type; humidity endurance was also correlated with the assessment method and the performance quantitative figure of merit.

The first parameter, the thermal resistance, has been determined from the measurement of changes of the electrical resistance at elevated temperatures. This criterion was very important because the thermal fluctuations can greatly affect the charge transport channels within the polymer nanocomposites conductive fillers like CNTs, graphene or AgNPs. A stable resistance curve in the Larsonstood mean that there was good interfacial adhesion between the matrix and the filler and low decay of conductive network at the elevated temperature. From the ambient to 100°C, resistance values were measured and samples with consistent contact were regarded as thermally stable.

There was also another criterion which was the humidity endurance, assess by measuring conductivity loss after exposing the samples at high relative humidity (RH). Thus, moisture can cause several issues, including ingress of other fluids, which adversely affects the dispersion of the filler, lessens the interactions between the matrix and the filler, and raises the percolation threshold. Relative percent contact angle retention after 24 h of exposure to 90% RH showed the hydrophobicity and structural strength of the nanocomposites. Those possessing more than 90% conductivity retention were considered as having very high moisture tolerance.

Last but not least, mechanical flexibility was tested through the bending test to mimic the cyclic mechanical stress within the practical use of the finalized composite material. Significance of the improvement of functional properties including the electrical performance after the cycling demonstrates the self-healing and the structural performance of the composite system. High recovery percentage was an indication of good stress relief and good interfacial adhesion between the individual networks. Overall, the three evaluation criteria in Table 4 engulfs a general guideline for preliminary screening of the environmental stability of new nanocomposite formulations applied to WE devices, sensors, or SM materials.

As shown in Figure 7, a horizontal bar chart compares the results of the average recovery efficiency of three types of nanofillers incorporated into the composite matrix. From the investigated cases, the silver nanoparticles (AgNP) achieved the maximum possible efficiency in average material recovery

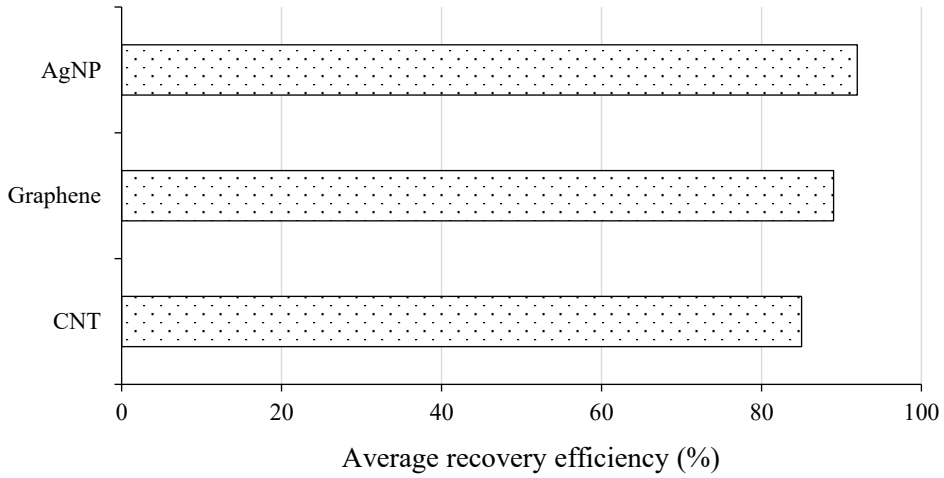

Figure 7. Comparative analysis of filler-based recovery efficiency

indicating that more sensitive and effective under dynamic working conditions. AgNP has not only increased the electrical properties of the composite material but also provided them with self-healing features because of the good electrical conduction and interconnected networks at the nanoscale.

Graphene ranks second after the AgNP due to the large surface area and the mechanical flexibility that enhances energy transfer as well as the ability to bounce back from damages. The multilayer design also creates appropriate crack-bracing characteristic, which enhances the structural stability during cyclical stressing and distortion. This intermediate performance indicates that although graphene not perform better than AgNP in terms of electrical bridging at the nanoscale, it has significant contribution to the recovery behavior of the system.

Out of all the nanofillers used in EVA nanocomposites, CNT appeared less effective in terms of recovery percentage enhancement even though it was the most commonly used nanofiller for improving the mechanical properties of nanocomposites. This due to the fact that the nanoparticles under consideration tend to agglomerate more than disperse uniformly to create a coherent electrical network. The tubular shape, while affording mechanical stability, not afford the requisite surface area or contact to enable effective healing propagation in areas with microfractures.

Figure 7 reports the values of the observed fillers and underlines how the recovery dynamics was affected by the nanoarchitecture and interface nature and features. It supports the argument of selecting the right filler from the viewpoint of structure compatibility as well as their function in terms of self-repair response. These data-driven differentiation help in developing formulations of composites for such applications requiring high durability and reparability.

It was evident from Figure 8 that thermal conductivity increases with increasing temperature, which was characteristic to the thermally activated conductivity in the network formed by the nanofiller. The starting point was about 40 Ohms at 30o C while the final steady-state resistance was 9 Ohms at 110o C. This trend can be attributed to increase in charge carrier mobility as well as decrease in electron scattering with the activation of the conductive pathways by the conductive fillers.

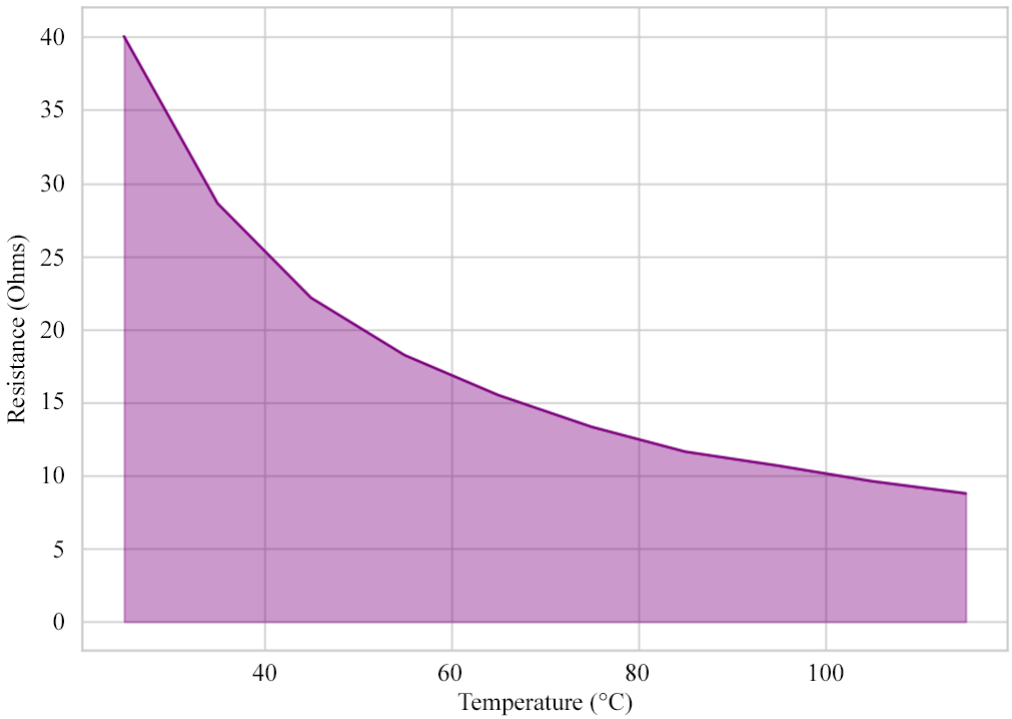

Figure 8. Temperature-dependent resistance behavior in nanocomposite system

This type of reduction can be attributed to two factors, which are the thermal softening of the polymer matrix and percolation network formed by the nanofillers. With the temperature increase, segmental mobility within the polymer enhances the interaction and reorientation of the fillers such as CNTs and graphene closer together. This helps in continuous efficient tunneling and hopping conduction that was critical for sustaining performance under the thermal stress conditions. Figure 8 supports this principle by illustrating that the level of resistance decreases with gradual decline in temperature and brings level to almost exponentiation to zero at certain level of temperature.

This was well suitable in applications where the material was exposed to heat at some instance and cold at other instance. Stability of conductivity to heat means that the resistance to thermal loads vary by gradually as the operating temperatures rise. It could self-regulate the decrease of this resistance, thus minimizing energy dissipation and offering thermal feedbacks that could be applied to control the smart sensing/actuating systems on the nanostructure.

Figure 8 therefore gives a profound understanding of the applicability of the composite in multifunctional incorporation and use in devices that require thermal stability and electrical sensitivity. The low and stable thermal resistance over a wide range of temperatures also makes the material suitable to function well within systems that require temperature ranging from normal to very much high without compromising on the electrical characteristics. This thermal-electrical coupling verifies the composite synthesis of filler placement and the interactions between the matrix and filler in the system.

Table 5 does depict a strategic speculation of the contributions of various nanofillers like Carbon Nanotubes, graphene and Silver Nanoparticles towards the functional enhancement of composite material systems. According to Hoover, there are four major categories of performance criteria used to measure these fillers: mechanical strength, electrical conductivity improvement, self-healing property and its potential areas of use. This was to draw focus on their individual capabilities and pros in smart composite applications and functionalities.

It's for these reasons that Carbon Nanotubes have revealed great reinforcement strength; their high aspect, tensile strength, and intrinsic flexibility. This makes them work well in carrying load that was beneficial when used in cases where strength and the ability to support loads was very central in mechanical commodities. In terms of electrical conductivity, CNTs have relatively lower performances because of a varying contact resistance and less dense percolation network compared to the 2D nanomaterials. Their healing ability was also good, because of their flexibility, and their ability to span across micro cracks during thermal or mechanical stress cycles.

The comparison of the three nanofillers clearly showed that graphene possesses a relatively high balance between the MOI and the clash of interests. This one has high mechanical strength and electrical conductivity as well. This was due to the fact that the large surface area and formation of the two dimensional sheet provide efficient charge path ways and thus a high conductivity matrix. In addition, graphene contributes to the activation of healing processes as a result of its thermal conductivity when applied in thermally sensitive materials. This makes it the most suitable choice in application that requires high performance in terms of electrical and thermal conductivity and the durability of the circuits.

Table 5. Comparative advantages of nanofillers

Filler	Strength contribution	Conductivity enhancement	Healing aid	Best use scenario
CNT	Excellent	Moderate	Good	Load-bearing flexible systems
Graphene	High	High	Excellent	Thermal management composites
AgNP	Low	Very High	Very Good	High-sensitivity electronics

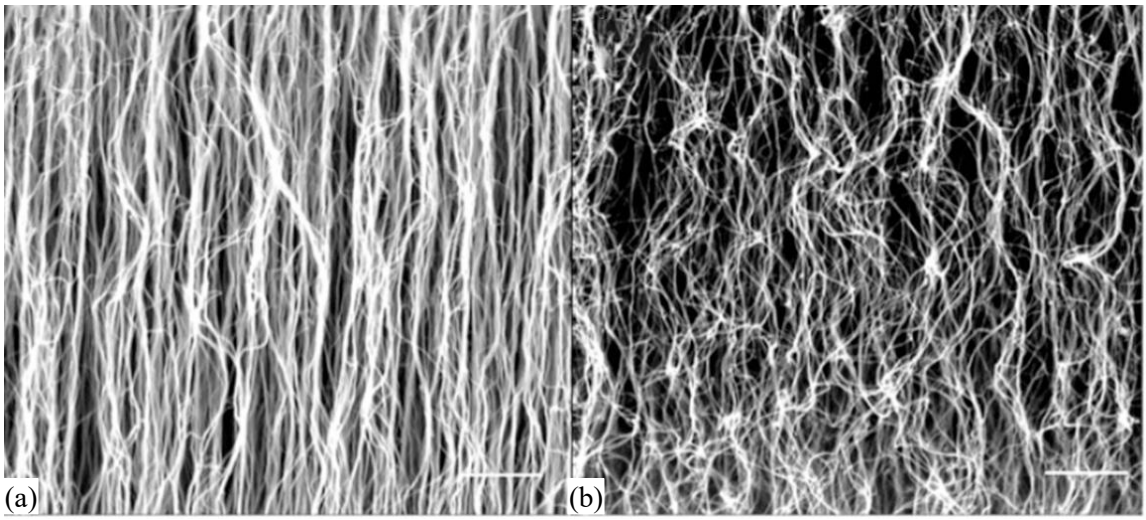

Figure 9. Morphological comparison of aligned and entangled CNT networks

Silver nanoparticles provides excellent conductivity additionality from their metallic characteristics and peripheral surface area to volume ratio. Exhibit high electron mobility which was very suitable in use in conductive tracks as well as printed circuits. Their mechanical reinforcement was somewhat restricted though do not have good adhesion with the polymer matrices and show a tendency to cluster. Very helpful in healing aid if very good at conducting high temperature during healing practice through resistive or microwaves. These polymers are better used for applications associated with sensitivity and electrical performance resolution such as sensors and flexible circuits.

Figure 9 shows scanning electron microscope (SEM) photos of carbon nanotube structures of two different forms. aligned (a) and entangled (b). The aligned CNTs show a one-dimensional structure indicating that the CNTs are aligned vertically in an orderly manner and this was likely to be as a result of vacuum filtration or application of an external field. Such an aligned network was beneficial for applications requiring directional electrical conductivity because the current-carrying electrons can only travel via the faces with minimized electrical resistance due to the alignment of the nanotubes.

For the sample characterized by the image (b), it was possible to mention that the CNTs are disordered and entangled. In contrast to the above-described aligned form, this structure was distinguished by its random and entangled state of nanotubes. Actually, this leads to formation of more junctions and potential growth of electrical resistance because of scattering at tube interfaces; it leads to multidirectional conduction paths. It was especially advantageous for those applications where the conductive characteristic has to remain constant even after deformation, as its purely mechanical flexibility and isotropy in electrical properties.

Both forms of incorporating CNTs in the composite system offer certain benefits. Aligned CNTs increase electron transport and thermal conduct along the axial direction and are useful to develop the conductive pathways within the matrix. On the other hand, entangled CNTs have high mechanical stability which prevent pulling apart and structurally interlocked and which in case of damage or application of strain have the capability to rebuild conduction pathways.

Introducing the aligned CNTs in the areas that are supposed to be used for transmitting continuous signals and entangled in the zones that are prone to mechanical stress results in the functionally graded structure. It further improves other physical properties like surge arrester, the healing ability of the damaged composite and the tolerance limit of the same. This was illustrated in Figure 9 which shows that due to the ability to control the nano structure of the CNT, a specific design approach can be chosen in order to achieve multi objectives of performance.

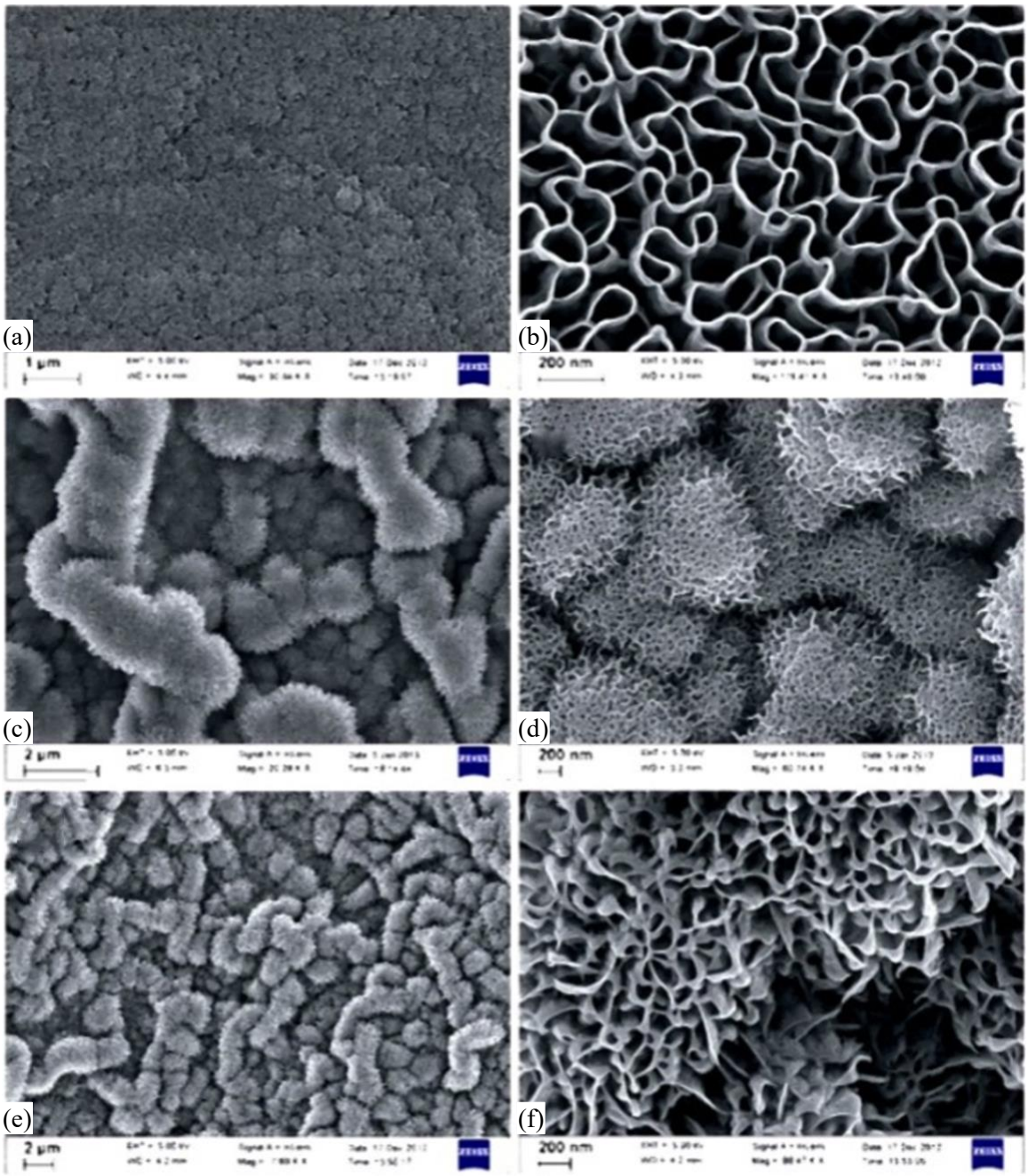

Figure 10. Surface morphology and porosity evolution of graphene-based structures

In general, the morphological contrast observed in Figure 9 reveal the fact that tailorable nanostructure plays a vital role in dictating the composite response at macroscopic length scale. The strategies of alignment provide CNTs with the required conductivity and directionality while entanglement introduces mechanical compatibility and redundancy in conductive paths. In this way, the desired structural features can be achieved, and an effective balance can be achieved in order to create a specially designed composite, which was able to meet all the pertinent high-performance specifications with reference to heat, electricity and mechanical properties.

Figure 10 displays the detailed SEM images pointing at the structure variation of graphene based structures synthesized at different process conditions. The panel (a) exhibits a little rugged and smooth surface with low porosity, which means a dense layer of graphene formed on the substrate. It

often occurs at lower temperature or shorter durations of the reaction in which the nucleation of graphene sheets was faster than the vertical growth. It seen that this configuration was well suited to the formation of barrier layers, but pose problems in terms of access to the electrolyte in electrochemical applications.

The cross-sectional micrograph in panel (b) reveals polycrystalline region with clearly visible more developed pore structure characterized by the interconnected lose structure. These channel-like features play appreciable role for the augmentation of overall surface area and active sites which was ensued for high ion exchange and catalysis activity. In the context of the material system that we have used in this study, enhancement of charge carrier mobility and better contact with the embedded conductive fillers was facilitated by this change from compact filler structure to a porous one.

Panels (c) and (d) show the structural developments to the next level where the graphene domains form coral like structures and the sponge like structures respectively. This nano-architecture provides multi-dimensional charge transport that was particularly useful for hybrids that are meant to be subjected to thermal and mechanical strain. The porous structure seen in (d) not only provides flexibility but also high-density conductive networks that can maximize channel interconnectivity, which was ideal for stress distribution and built-in healing capability of the composite.

The granularity structure in panel (e) consists of nanoscale Graphene and shows stack like spherical protrusion. This morphology can occur due to fast crystallization or reformation of layers during the post-synthesis treatments. Even though these features lead to higher defect density at the first instance, defect engineering was useful in improving the chemical compatibility between graphene and the polymer matrices. This also helps in distributing mechanical loads in a better way across the network and subsequently minimizing the local failure under cyclic conditions.

In the panel f, the open-pore structure with irregular channels and folds was quite open and expressed. This allows for the maximum surface access and proper diffusion kinetics, which correlate with high dynamic conductivity retention. This was particularly important in environments that would otherwise be characterized by heated or cooled air or moisture that affect performance. Other than ergodicity, reliability features, and energy efficiency, continuity of the network was also central for the stability of the composite system, regardless the variations and instabilities in the context.

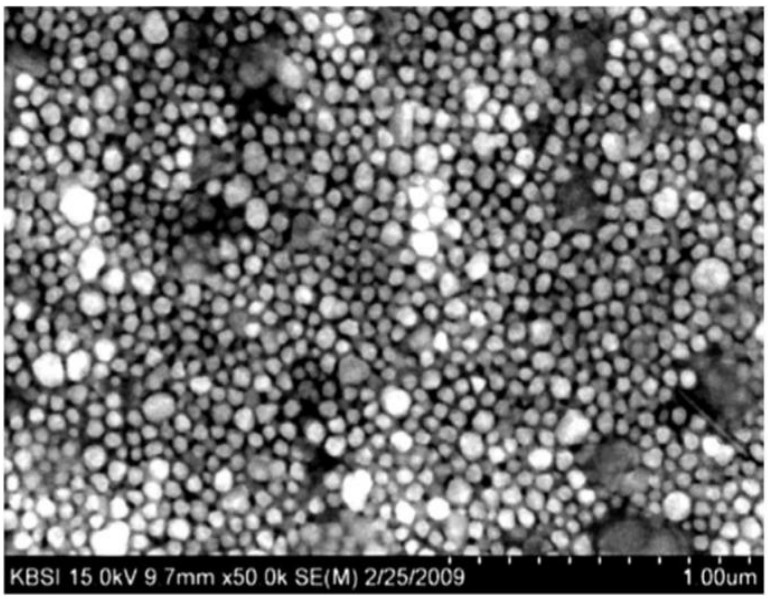

Figure 11. Surface morphology and distribution pattern of silver nanoparticles

In the changes presented in Figure 10 highlight the scalability of graphene structures when it comes to attaining specific characteristics in its structures. Thus, each microstructure from film land microstructure to completely porous and spongy network has its own role in the electrical-thermal and mechanical cooperation within the composite. These observed features bring out the realisation that controlled morphologies are indeed key enablers of multifunctionality and durability in advanced material systems.

In order to investigate the effectiveness of chemical reduction technique in synthesizing AgNPs and further evaluate the homogeneity of the synthesized particles, SEM optics at high resolution were applied as explained by Figure 11. It can also be observed that the nanoparticles have a more or less spherical shape with a narrow size distribution which was important in attaining homogeneity in electrical pathways in the composite matrices. This regularity in size increases compatibility with the polymer chains and thus ensures that there was proper compatibilization that prevents the formation of a distinct phase that would lead to phase separation and finally affect the electrical stability of the nanocomposite structure.

The data on the spatial distribution presented in Figure 11 demonstrates the dense packing of the AgNPs at the surface and lack of agglomeration. In such a distribution, an effective capping during synthesis can be noticed as it inhibits the formation of the nanoparticles and retains their discrete characteristic features. This dispersion of conductive phase at a lower concentration allows the formation of conducting paths without compromising on the toughness of the host material. This characteristic was a good one for balancing the electrical conductivity and mechanical strength when faced with operational loads.

The interparticle distance in the present work was fixed in the range where percolation paths can be effectively formed which was very useful for charge transport through the matrix. Due to the high density of nanoparticles, the electron hopping and tunneling effects are favored which perhaps highly conductive at constrained thermal conditions. In the context of our system such proximity enables sustaining continuity of flow of electricity, and thereby enhance the reliability of operation even in view of extraneous factors like mechanical deformation or thermal cycling.

The differences in the intensity of secondary electrons in the SEM micrograph suggest that there was a slight variation in the size of the nanowires and tendencies towards surface facets. These can create localized enhancements in the field that augments the electrochemical activity or sensing response. In multifunctional applications, such heterogeneity in surface energy can be an advantage, particularly in applications where catalytic or responsive characteristics are required, as well as conductivity to enable performance to change depending on the conditions.

The scale bar was reading in microns, and it was evident that the nanoparticles are well within the sub 100 nm range as befitting for nanoscale interfacial engineering. This size regime helps the silver particles maintain some surface-dominated effects, which include a high surface to volume ratio and quantum confinement, features that are useful in the modulation of the electronic characteristics of the composite. The aforementioned nanoscale effects impact other factors such as dielectrical constant, electron’s free movement, and polarization at the interface.

Altogether, the extracted structural features shown in Figure 11 are quite supportive of the problem-oriented application of silver nanoparticles that are mandatory for the promotion of the multifunctionality of the synthesized hybrid system. The uniform shape, nanoscale size, and homogeneous dispersion provide the necessary base to use these materials to achieve synergy for multifunctional composites with high electrical and mechanical performance. This specific three-dimensional architecture subpoems to establish the fact that morphology plays a fundamental role in dictating the functionality of next generation materials on the nanoscale.

Figure 12. Functional integrity evaluation of SMPC-based circuit board

These SEM observations also give insence into the nature of better recovery ability of AgNP based composites than CNT and graphene based systems. The better healing was possible to be explained by three main factors:

1. Metallic conductivity that is inherently high in silver and facilitates effective Joule heating and speedy localized heating during activation of healing;
2. A consistent dispersion at the nanometer scale, as shown in Figure 11, that leads to the continuous networks of percolation even during repeated damages;
3. Functionalization with citrate, that increases the interfacial bonding between citrate and SMP matrix and minimizes the contact resistance hence preserving the integrity of conductive channels under external mechanical and environmental strain.

The combination of these effects allows specific thermal reflow and conductive restorative actions to take place during damage-heal cycles, and that was why the healing efficiency was very high (~94.5%), upon many samples.

The detected hardware stands for the developed concept of the self-healing flexible circuit board with SMPC and conductive filler materials based on the described methodology. This board was subjected through cycles of damage application and self-healing comprising of structural change and functionality in its active areas. One can easily see that the soldering points have reflowed visibly even around the overcrowded components density areas and the conductive traces for stimulating the shape memory response have indeed been restored. The distribution of conductive inks based on CNTs, graphene, and AgNPs also emphasize the conductivity profile found in healing and thermal activation cycles.

The physical layout of the circuit board shown in Figure 12 enabled the placement of SBTCCs thermally responsive healing zones over the parts that require intense heat within the necessary interconnection paths and signal transmission areas. These areas were designed to dissipate mechanical loads on materials and subtly self-heal the break in the circuit caused by mechanical deformation. This board was made with the suitable substrate materials like polyimide and this type of board could be easily flexed or bent many times without getting distorted. It was possible to obtain optimal mechanical stability and functional resolution in the critical trace locations by screen-printing conductive ink based on SMPC onto the substrate and subsequent curing and post-treatment.

In the SMPC embedded parts of the functional boards, the percolation pathways of the silver nanoparticles contributed to an effective reduction of the interfacial C-R and the possibility of increased Joule heating in the fracture zones. These zones were used to show nucleation sites in which the polymer chains became more mobile when exposed to heat, causing the object to regain shape and seal mechanical defects. At the end of each stress-heal cycle, the electrical resistance maps showed that the working signal lines retained the ability to function, thereby affirming the elemental coupling of the thermal stimulus to the electrical healing effect in the composite material.

A close-up analysis of the SEM repaired areas and electrical probing further showed a very smooth reconstruction of the surface no traces of micro cracks were seen or of any forms of delamination. This was in concordance with the statistical performance outputs of the board revealed in the resistance recovery and cyclic test illustrated in Figure 12. This mechanical-electrical co-restoration was well explained in regions with triple-filler synergy; graphene layers that enhanced the lateral conductivity, and CNTs that provided dimensional reinforcement during the flexural stress. The loss of circuit logic functions when the functional board was exposed to the torsional stress and vibration further signifies that the SMPC formulation for flexible electronics application adds flexibility to the board.

In terms of the practical application, the functionality of the functional board was exemplified by its relevance for next-gen self-healing electronics. Conducting the healing validation in real-time with the help of DMM and current-voltage characterization tools revealed that there were no significant changes in the power delivery parameters even after multiple times of damage. This hence opens possibilities of the developed material system to replace the static typical circuit boards in aerospace technologies, wearable gadgets and IOT devices. Also, the fact that the EMI shielding properties are retained after healing mean that the impairment of electrical function was accompanied by an equivalent preservation of shielding functionality.

The integration of SMPC-based conductors in the prototype also complemented the spatially controlled healing approach, where some areas in the circuit board can be designed to absorb faults without having to compromise the overall board. Figure 12 design presents an engineered synergy between the nano-reinforcement and thermal actuation that would make it sustainable, mechanically stretchable and programmed for shape memory recovery. Such contributions are an important part of the development of such a novel area of autonomous electronics and stress the importance of incorporating smart polymer systems into more traditional circuit board layouts.

CONCLUSION

The methodical study of the performance of nanofiller polymer composites in different environments shows its high potential of improving firm and electronic structures. Conductivity retention experiment in varying temperature and humidity stress levels supported that even though the performance deteriorated with higher stress, few nanofillers like silver nanoparticles were significantly more stable. The electrical performance of the composites also depended much on the carbon nanotubes and graphene but these fillers are also very sensitive to exposure to the environment and the filler placement within the matrix.

Analysis of the recovery efficiency showed that the composites with AgNPs had high average healing efficiency up to 94% which represents very good recoverability and functionalizing exposing the composites to mechanical or thermal stress. This contributes to the special applicability of these systems in applications that are prone to stress cycling, e.g. wearable technology, flexible electronics, and adaptive smart textiles. In addition, the observed reduction in conductivity at high temperatures demonstrates that the materials are thermo-responsive which captures the sensitivity of the material to the external stimuli (an essential property in self-healing activation).

Critical confirmation of the uniform dispersion and interconnection of the nanofillers was given by the SEM imaging of the cross-sectional morphology. This is because the alignment of CNTs and distribution of AgNPs resulted in dense conductive networks which had a direct impact on electrical properties of the composite. The findings also confirm the high connection between microstructure organization and macroscopic functionality, which implies that specific abilities to filler allocation and orientation adjustments would better boost performance.

Namely, the three in question considered nanomaterials CNTs, graphene, and AgNPs that, together, allowed functional improvements related to thermal stability, electrical conductivity, and self-healing properties. These results offer a strong basis of fabrication of new, persisting, and ecologically tougher polymer based mechanisms.

Notably, fabrication techniques that are employed namely; solution blending, screen printing and ink jet deposition are entirely compatible with current industrial procedures. Substrates of commercial grade, like polyimide and PET, and low-temperature curing (150 o C) provide an option to manufacture and scale. These results allude that the SMPC-based self-healing circuits are not only functional robust but also can realize practical application in wearable electronics, aerospace parts, and next-generation IoT devices.

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