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AI-Integrated Graphene-Modified Polymer Interfaces for Real-Time Crack Detection and Autonomous Healing in Smart Concrete Structures

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Abstract

This study presents the design and development of a graphene-reinforced multifunctional polymer composite interface engineered for structural reinforcement, self-sensing, and autonomous healing applications in cementitious systems. A thermosetting polymer matrix embedded with graphene nanoplatelets (0.25–1.5 wt.%) was developed to establish a conductive polymer nano-composite network. Electrical characterization confirmed a distinct percolation threshold at ~0.6–0.8 wt.%, beyond which a sharp increase in conductivity was observed due to the formation of interconnected graphene pathways within the polymer matrix. The composite exhibited stable piezoresistive behaviour, enabling detection of micro-cracks as small as 30 µm through resistance variation. The incorporation of graphene significantly enhanced load transfer efficiency and interfacial adhesion, resulting in improved mechanical performance. Compressive strength increased from 32 MPa to 45 MPa (~40% improvement), while fracture toughness improved from 0.8 MPa√m to 2.1 MPa√m due to effective crack-bridging and energy dissipation mechanisms within the composite interphase. The integration of microencapsulated healing agents within the polymer matrix enabled autonomous crack repair, achieving healing efficiencies of 80–85%, demonstrating the capability of the polymer composite to function as a self-repairing material system. Furthermore, the conductive polymer composite interface was integrated with machine learning algorithms to enable real-time structural health monitoring, achieving detection accuracy exceeding 95%. The results highlight the synergistic role of polymer matrix engineering, graphene reinforcement, and multifunctional composite design in developing next-generation smart materials. The proposed system establishes polymer composites as a viable platform for multifunctional structural applications combining mechanical enhancement, sensing, and self-healing capabilities.

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INTRODUCTION

The advancement of modern engineering materials has increasingly shifted toward the development of polymer composite systems, driven by the need for materials that simultaneously exhibit high mechanical performance, multifunctionality, and adaptability under complex service conditions. Conventional cementitious materials, despite their widespread application in infrastructure, inherently suffer from brittle failure behaviour, low tensile strength, and poor resistance to crack initiation and propagation [1]. These limitations are primarily attributed to weak interfacial bonding and the absence of energy-dissipating mechanisms within the cement matrix. As a result, micro-cracks formed under mechanical, thermal, or environmental loading act as critical pathways for degradation processes such as moisture ingress, chloride penetration, and chemical attack, ultimately compromising durability and service life.

To overcome these intrinsic deficiencies, recent research has focused on the incorporation of polymer composite interphases within cementitious systems, wherein the polymer matrix serves as a ductile and adaptable medium capable of redistributing stresses, bridging cracks, and enhancing fracture resistance. Unlike traditional materials, polymer composites offer tailorable microstructures, allowing precise control over mechanical, electrical, and functional properties through the selection of matrix materials, reinforcement phases, and interfacial engineering strategies. This has positioned polymer composites as a key enabling technology in the transition from passive structural materials to active, multifunctional material systems [2-4].

A defining feature of polymer composites is the critical role of the polymer matrix, which governs load transfer efficiency, interfacial adhesion, and overall composite integrity. Thermosetting polymers such as epoxy and polyurethane are particularly advantageous due to their crosslinked network structures, which provide high stiffness, chemical stability, and strong adhesion to both nano-reinforcements and cementitious substrates. Within such systems, the incorporation of nano-scale fillers enables the development of polymer nanocomposites, where the interfacial interactions between the polymer chains and reinforcing phases significantly influence mechanical behaviour. The effectiveness of these composites is highly dependent on factors such as filler dispersion, aspect ratio, surface functionalization, and interfacial bonding, which collectively determine the efficiency of stress transfer and crack resistance mechanisms [5].

Among the various nano-reinforcements, graphene nanoplatelets (GNPs) have emerged as one of the most promising fillers for polymer composite systems due to their exceptional intrinsic properties, including ultra-high Young's modulus (~1 TPa), superior electrical conductivity, and large specific surface area. When uniformly dispersed within a polymer matrix, graphene forms an interconnected network that enhances both mechanical reinforcement and functional performance. From a composite mechanics perspective, graphene acts as a nano-scale load-bearing phase, facilitating stress transfer across the polymer matrix and inhibiting crack propagation through mechanisms such as crack deflection, crack bridging, and pull-out resistance. These mechanisms significantly improve fracture toughness and energy absorption capacity, transforming the polymer composite into a damage-tolerant material system [6-9].

Graphene enhances the electrical and mechanical properties of polymer composites through a combination of intrinsic material characteristics and interfacial interactions. Electrically, graphene nanoplatelets form conductive networks within the polymer matrix once the percolation threshold is reached, enabling efficient electron transport through direct contact and tunnelling mechanisms. This results in a transition from insulating to conductive behaviour, which is highly sensitive to structural deformation and damage, making the composite suitable for sensing applications. Mechanically, graphene acts as a nano-reinforcement with exceptional stiffness and strength, facilitating effective stress transfer across the polymer matrix. The large surface area of graphene promotes strong interfacial bonding with polymer chains, restricting polymer mobility and improving modulus, tensile strength, and fracture resistance. Furthermore, graphene contributes to crack deflection, crack bridging, and pull-out resistance mechanisms, which collectively enhance toughness and delay failure.

In addition to mechanical reinforcement, graphene-based polymer composites exhibit unique electro-functional behaviour governed by the formation of conductive networks within the polymer matrix. This behaviour is strongly associated with the concept of the electrical percolation threshold, which defines the critical filler concentration at which isolated graphene particles transition into a continuous conductive network. Below the percolation threshold, the composite behaves as an insulator due to limited electron transport pathways, whereas above the threshold, a sharp increase in electrical conductivity is observed due to direct contact and tunnelling between adjacent graphene nanoplatelets. This percolative behaviour is highly sensitive to microstructural changes, enabling the polymer composite to function as a piezoresistive sensing material, where variations in electrical resistance correspond to deformation, strain, and crack evolution within the material.

The multifunctionality of polymer composites can be further enhanced through the integration of self-healing mechanisms, which address one of the fundamental challenges in structural materials—irreversible damage accumulation. In polymer composite systems, self-healing is typically achieved through microencapsulation techniques, where healing agents such as epoxy precursors or polyurethane systems are embedded within the polymer matrix in the form of microcapsules. Upon crack initiation, these capsules rupture, releasing the healing agent into the damaged region, where it undergoes polymerization or chemical reaction to restore structural continuity. The polymer matrix plays a crucial role in this process by providing a reactive and adhesive environment, ensuring effective wetting, bonding, and curing of the healing agent. The incorporation of graphene further enhances healing efficiency by reinforcing the repaired region and improving load transfer across the healed interface.

Beyond mechanical and self-healing functionalities, polymer composites are increasingly being explored as platforms for integrated sensing and intelligent material systems. The ability of graphene-reinforced polymer composites to generate measurable electrical signals in response to mechanical stimuli provides a foundation for real-time structural health monitoring. However, the complexity of interpreting these signals, particularly in dynamic environments, necessitates the integration of advanced data processing techniques. In this context, artificial intelligence (AI) plays a pivotal role by enabling the analysis of large datasets generated by polymer composite sensors, facilitating accurate detection, classification, and prediction of damage states [10].

Machine learning algorithms, including artificial neural networks, support vector machines, and ensemble learning models, have demonstrated significant potential in capturing nonlinear relationships between electrical signals and structural responses in polymer composite systems. By training these models on experimentally generated datasets, it becomes possible to develop intelligent polymer composites capable of distinguishing between elastic deformation, micro-crack initiation, and macro-crack propagation. Furthermore, the integration of AI with polymer composite systems enables the development of closed-loop material architectures, where sensing, analysis, and response are inherently embedded within the material itself, allowing for autonomous decision-making and adaptive behaviour.

Despite these advancements, several challenges remain in the large-scale implementation of graphene-reinforced polymer composites, including issues related to uniform dispersion, agglomeration, cost of nano-fillers, and long-term durability under environmental exposure. Additionally, the performance of polymer composites is highly sensitive to interfacial characteristics and processing conditions, necessitating optimized fabrication techniques to achieve consistent and reproducible properties. Addressing these challenges requires a comprehensive understanding of polymer composite science, encompassing matrix chemistry, reinforcement behaviour, interfacial engineering, and multifunctional integration.

The incorporation of polymer composite interfaces within concrete systems plays a transformative role in enhancing structural performance by acting as an engineered interphase between brittle cementitious matrices and external loading conditions. These interfaces improve stress transfer efficiency, reduce stress concentration, and introduce ductility into the system. The polymer phase functions as a crack-bridging medium, redistributing localized stresses and delaying crack initiation and propagation. Additionally, polymer interfaces enhance impermeability by reducing micro-void connectivity, thereby improving durability against moisture ingress and chemical attack. From a fracture mechanics perspective, the presence of a polymer interphase increases energy absorption capacity through plastic deformation and viscoelastic dissipation mechanisms, significantly improving toughness and service life of concrete structures.

In this context, the present study focuses on the development of an AI-integrated graphene-reinforced polymer composite interface, emphasizing the synergistic interaction between polymer matrix design, nano-reinforcement, and intelligent sensing capabilities. The proposed system is engineered as a multifunctional polymer composite interphase that enhances mechanical performance, enables real-time crack detection, and facilitates autonomous healing within concrete structures. By advancing the fundamental understanding of polymer composite behaviour and integrating it with AI-driven monitoring, this work contributes to the development of next-generation smart polymer composite materials for sustainable and high-performance infrastructure applications.

MATERIALS AND METHODS

Materials for Polymer Composite System

The design of the multifunctional polymer composite system involved the careful selection of constituent materials to ensure compatibility, performance, and multifunctionality, where a thermosetting polymer matrix such as epoxy or polyurethane was chosen due to its superior adhesion characteristics, mechanical stability, and ability to host nano-fillers and healing agents effectively within its crosslinked network structure. Graphene nanoplatelets were utilized as the primary reinforcement phase owing to their high aspect ratio, excellent electrical conductivity, and ability to establish conductive pathways within the polymer matrix at relatively low loadings, thereby enabling the development of a piezoresistive polymer composite system. To facilitate uniform dispersion and prevent agglomeration of graphene within the polymer matrix, appropriate surfactants and dispersing agents were incorporated, ensuring the formation of a stable nano-composite structure. Additionally, microencapsulated healing agents, such as epoxy resins or sodium silicate systems, were embedded within the polymer composite to impart self-healing functionality, while the cementitious matrix composed of ordinary Portland cement, fine aggregates, and coarse aggregates served as the structural host for the embedded polymer composite interface, thereby creating a hybrid material system that integrates the mechanical robustness of concrete with the functional capabilities of polymer composites.

Fabrication of Graphene-Reinforced Polymer Composite Interface

The fabrication of the graphene-reinforced polymer composite (Fig.1) interface was carried out through a controlled nano-composite processing approach designed to achieve uniform dispersion, optimal interfacial bonding, and effective multifunctional performance, wherein graphene nanoplatelets were first dispersed within the polymer matrix using ultrasonication techniques to break down agglomerates and ensure homogeneous distribution at the nanoscale, thereby enhancing the formation of a continuous conductive network within the polymer composite.

To ensure reproducibility and controlled processing, the dispersion and fabrication parameters of the graphene–polymer composite system were carefully optimized. Initially, graphene nanoplatelets (GNPs) were dispersed in the polymer matrix using mechanical stirring at a speed of approximately 800 rpm for 30 min, followed by ultrasonication at a frequency of 40 kHz for 20 min to break down agglomerates and achieve homogeneous nanoscale distribution. This combined dispersion approach ensured the formation of a stable conductive network within the polymer matrix.

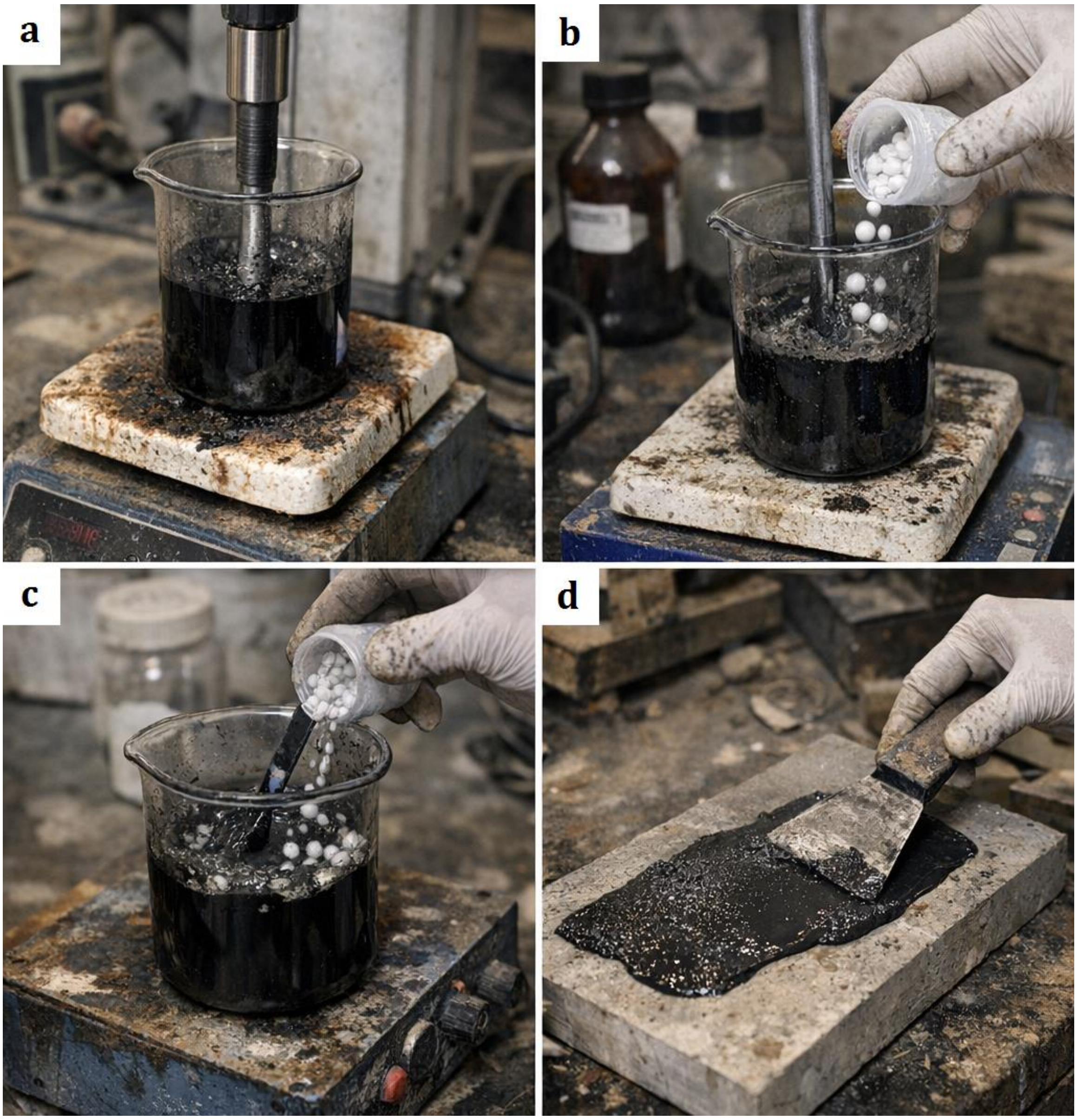

Figure 1. Fabrication of graphene-reinforced polymer composite interface
(a) Graphene dispersion in polymer matrix using mechanical stirring.
(b) Addition of microencapsulated healing agents into the graphene–polymer composite.
(c) Homogeneous mixing of graphene–polymer composite with healing microcapsules.
(d) Application of graphene-reinforced polymer composite interface on concrete substrate.

Microencapsulated healing agents were subsequently introduced into the graphene–polymer system under controlled mixing conditions at a reduced stirring speed of 400–500 rpm for 15 min to prevent structural damage to the microcapsules while ensuring uniform spatial distribution. The microcapsules exhibited an average diameter in the range of 50–150 µm and were composed of a urea–formaldehyde shell encapsulating epoxy-based healing agents, enabling effective crack-triggered release and polymerization.

Following fabrication, the composite system was subjected to controlled curing conditions to achieve optimal crosslinking and interfacial bonding. The specimens were initially cured at 80°C for 4 h, followed by post-curing at 120°C for 2 h, ensuring complete polymer network formation and enhanced mechanical stability.

To improve interfacial compatibility and dispersion within the polymer matrix, graphene nanoplatelets were mildly functionalized prior to incorporation using acid treatment (H_2SO_4/HNO_3), introducing oxygen-containing functional groups on the graphene surface. This functionalization enhanced interfacial adhesion between the graphene and polymer matrix, thereby improving load transfer efficiency and overall composite performance.

The concentration of graphene was carefully optimized within the range of 0.25 to 1.5 wt. % to achieve the percolation threshold necessary for electrical conductivity without compromising the mechanical integrity or processability of the polymer composite. Subsequently, microcapsules containing healing agents were incorporated into the polymer matrix under controlled mixing conditions to ensure uniform spatial distribution and structural integrity of the capsules, thereby enabling effective self-healing upon crack formation. The resulting graphene-polymer nano-composite was then applied as a thin interfacial layer within the concrete structure, strategically positioned in regions prone to tensile stress and crack initiation, thereby forming a multifunctional polymer composite interphase capable of sensing, reinforcing, and healing structural damage.

Polymer Composite–Based Sensing Mechanism

The sensing capability of the developed system is primarily governed by the piezo-resistive behaviour of the graphene-reinforced polymer composite, wherein the electrical conductivity arises from the formation of a percolative network of graphene nanoplatelets within the polymer matrix, enabling electron transport through direct contact and quantum tunnelling mechanisms between adjacent graphene sheets. Under mechanical loading, the polymer composite undergoes deformation, leading to changes in the spatial distribution and connectivity of the graphene network, which in turn results in variations in electrical resistance that can be correlated with strain and damage within the material. When cracks initiate and propagate within the concrete structure, the embedded polymer composite interface experiences localized disruption of its conductive pathways, causing a significant increase in electrical resistance, which serves as a reliable indicator of damage. This relationship can be quantitatively described using the normalized resistance change, which depends on factors such as strain, crack width, and crack density, thereby enabling the polymer composite to function as a highly sensitive self-sensing material capable of detecting micro-level structural changes long before visible damage occurs.

AI-Integrated Monitoring Framework

The integration of artificial intelligence with the polymer composite sensing system enables the transformation of raw electrical signals into meaningful insights regarding structural health, where data acquired from the graphene-polymer composite interface is processed through advanced machine learning algorithms capable of identifying patterns, anomalies, and trends associated with crack initiation and propagation. The monitoring framework involves multiple stages, including signal pre-processing to eliminate noise and normalize data, feature extraction to identify relevant parameters such as resistance variation rates and signal fluctuations, and the application of supervised learning models such as artificial neural networks, support vector machines, and random forest classifiers to analyze and interpret the data. The AI system is trained using experimentally generated datasets corresponding to different crack conditions, enabling it to accurately classify damage severity, distinguish between elastic deformation and permanent damage, and predict the evolution of cracks over time. This intelligent integration allows the polymer composite system to function not only as a passive sensor but also as an active decision-making component, capable of triggering appropriate responses such as activating self-healing mechanisms.

Autonomous Healing in Polymer Composite System

The self-healing functionality of the system is achieved through the incorporation of microencapsulated healing agents within the polymer composite matrix, which enables autonomous repair of cracks without external intervention, thereby significantly enhancing the durability and lifespan of the structure. When a crack propagates through the concrete and reaches the polymer composite interface, it ruptures the embedded microcapsules, releasing the healing agent into the damaged region, where it undergoes polymerization or chemical reaction to fill and seal the crack. The polymer composite matrix plays a crucial role in this process by providing a supportive environment for the healing reaction, ensuring effective confinement of the healing agent and promoting strong adhesion between the crack surfaces. Furthermore, the presence of graphene within the polymer composite enhances the mechanical stability of the healed region and improves the efficiency of load transfer across the repaired interface. The integration of AI further optimizes the healing process by predicting the severity and location of damage, enabling targeted activation of healing mechanisms and improving overall system efficiency.

RESULTS AND DISCUSSION

Electrical and Functional Performance of Polymer Composite

The graphene-reinforced polymer composite exhibited a significant enhancement in electrical conductivity due to the formation of a well-established percolation network, which facilitated efficient electron transport across the polymer matrix and enabled high sensitivity to mechanical deformation and damage. As illustrated in Fig. 2, the variation of electrical conductivity with respect to graphene nano-platelet loading clearly demonstrates a characteristic percolation behaviour, wherein the conductivity remains extremely low at lower filler concentrations (below ~0.4 wt.%), indicating an insulating polymer-dominated regime where graphene particles are isolated and electron transport is limited to tunnelling mechanisms. However, as the graphene content approaches the critical percolation threshold (around ~0.6–0.8 wt.%), a sharp and exponential increase in conductivity is observed, signifying the formation of a continuous conductive network within the polymer composite due to increased inter-particle contact and reduced inter-particle spacing. Beyond this threshold, the conductivity gradually stabilizes with further graphene addition, suggesting saturation of conductive pathways and a transition into a conductive composite regime, where additional filler contributes marginally to conductivity but may influence mechanical stiffness and processability. This trend highlights the critical role of optimizing graphene loading to achieve a balance between electrical performance and structural integrity in polymer-composite systems [11-13].

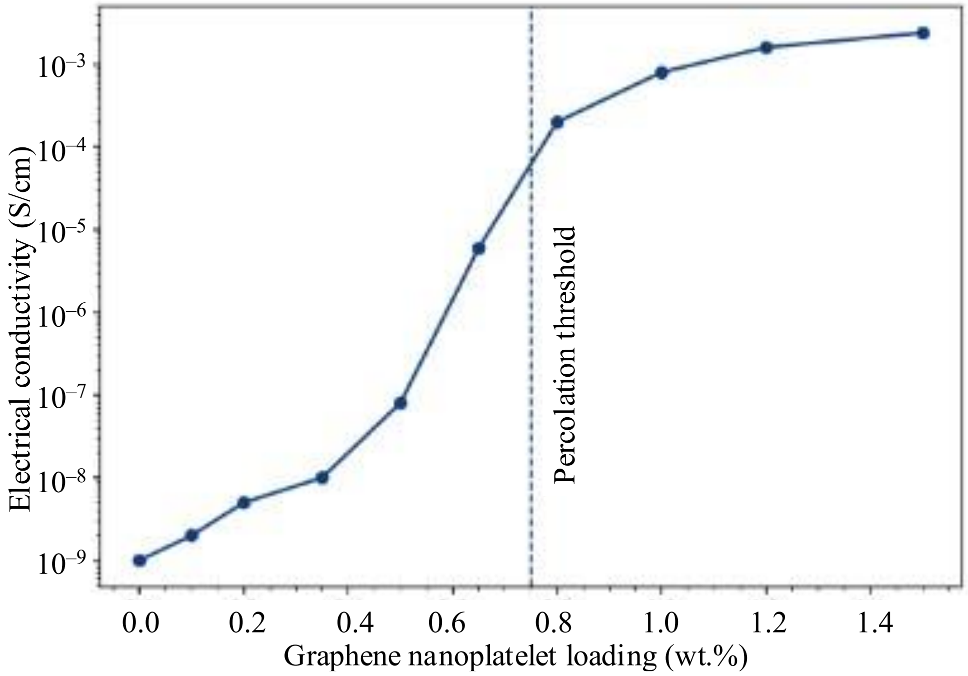

Figure 2. Electrical conductivity of graphene-reinforced polymer composite as a function of graphene nano-platelet loading

Under applied mechanical loading, the polymer composite exhibited a consistent and repeatable change in electrical resistance, confirming its stable piezoresistive behaviour, which can be directly correlated to the microstructural changes in the graphene conductive network. The sensitivity of the composite to strain and damage arises from the reversible disruption and reformation of conductive pathways within the polymer matrix, as mechanical deformation alters the distance and orientation between graphene nanoplatelets. Notably, the system demonstrated the ability to detect micro-cracks with widths as small as 30 µm, as even minor crack initiation leads to localized breakage of conductive networks, resulting in measurable resistance variation [14]. Furthermore, the functional performance of the graphene-reinforced polymer composite was validated through cyclic loading experiments, where the resistance response exhibited minimal drift and high repeatability over multiple loading–unloading cycles, indicating excellent durability and reliability of the sensing mechanism. This stable electrical response under repeated mechanical stress confirms that the developed polymer composite interface is highly suitable for long-term structural health monitoring applications, particularly in smart concrete systems where early-stage crack detection is critical for preventing catastrophic failure.

Mechanical Enhancement through Polymer Composite Interface

The incorporation of the graphene-reinforced polymer composite interface within the concrete matrix resulted in significant improvements in mechanical performance, primarily due to enhanced interfacial bonding, improved stress distribution, and the synergistic interaction between the polymer matrix and graphene reinforcement. As clearly illustrated in Fig. 3, a progressive increase in compressive strength is observed when transitioning from conventional concrete to polymer composite-modified concrete, and further to graphene-reinforced polymer composite systems. The baseline concrete exhibits relatively lower compressive strength due to its brittle nature and weak interfacial zones, whereas the introduction of a polymer composite phase improves the ductility and cohesion within the matrix, leading to moderate strength enhancement [15]. Notably, the graphene-reinforced polymer composite demonstrates a substantial increase in compressive strength, which can be attributed to the formation of a strong and continuous load-transfer network facilitated by the well-dispersed graphene nanoplatelets within the polymer matrix.

The trend observed in Fig. 3 highlights the critical role of the polymer composite interphase as a stress-transfer medium, where the polymer matrix provides flexibility and crack-bridging capability, while the graphene reinforcement contributes to stiffness enhancement and improved load-bearing capacity. The significant strength improvement in the graphene-polymer composite system is primarily governed by the ability of graphene nanoplatelets to arrest crack propagation by acting as nanoscale reinforcements, thereby reducing stress concentration at crack tips and delaying fracture initiation. Furthermore, the enhanced interfacial bonding between the polymer composite and the cementitious matrix minimizes debonding and interfacial failure, which is common in conventional concrete systems.

In addition to compressive strength, the polymer composite interphase plays a crucial role in improving the overall fracture toughness and resistance to crack initiation, as the polymer phase absorbs and redistributes stress more effectively compared to brittle cementitious phases. The graphene-reinforced polymer composite also enhances energy absorption capacity, resulting in improved resistance to dynamic and impact loading conditions. This synergistic combination of polymer ductility and graphene reinforcement leads to a composite system that exhibits both high strength and improved toughness, which are essential characteristics for structural applications [16].

Overall, the results presented in Fig. 3 clearly demonstrate that the incorporation of graphene-reinforced polymer composite interfaces significantly enhances the mechanical performance of concrete systems by improving interfacial integrity, delaying crack propagation, and increasing load-bearing capacity. These findings strongly support the effectiveness of polymer composite engineering in developing high-performance, durable, and crack-resistant smart concrete materials.

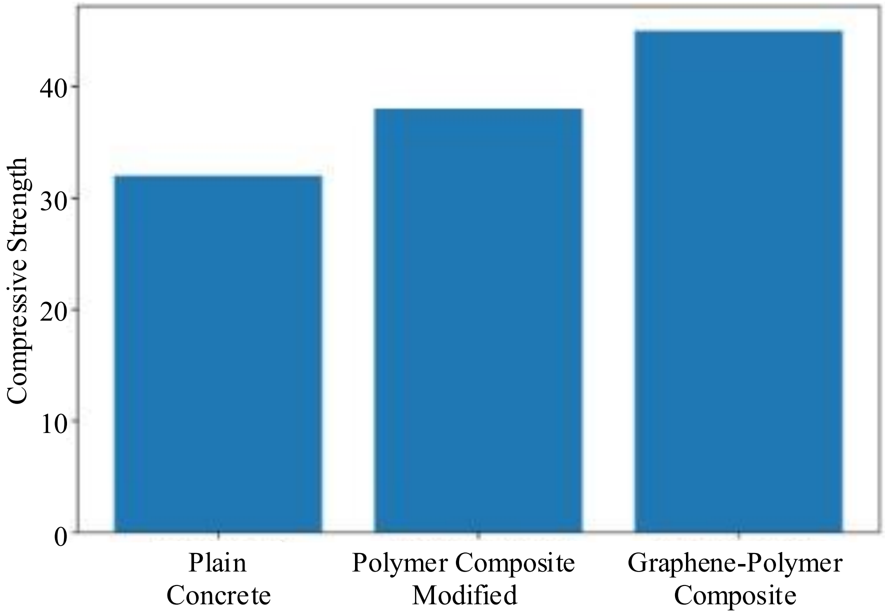

Figure 3. Compressive strength comparison of conventional concrete, polymer composite-modified concrete, and graphene-reinforced polymer composite system

Interfacial Behaviour and Fracture Mechanism

The interfacial properties between the polymer composite and the concrete substrate critically govern the overall bonding performance and structural integrity of the hybrid system. Effective bonding is achieved through a combination of mechanical interlocking, physicochemical adhesion, and inter-diffusion mechanisms at the interface. Surface roughness of the concrete substrate enhances mechanical interlocking, while functional groups present in the polymer matrix and graphene facilitate chemical bonding with hydration products such as calcium silicate hydrates (C–S–H). The presence of graphene further improves interfacial interaction by increasing surface energy and promoting stronger adhesion at the nano-scale. Poor interfacial bonding can lead to debonding, stress concentration, and premature failure, whereas optimized interfacial characteristics ensure efficient load transfer, reduced crack propagation, and enhanced durability of the composite system.

The polymer composite interphase plays a critical role in governing the fracture behaviour of the concrete system, where it acts as a barrier to crack propagation by redistributing stress and absorbing fracture energy, thereby preventing the rapid growth of cracks and improving overall structural integrity.

As illustrated in Fig. 4, the fracture toughness of the system shows a significant and progressive increase with increasing graphene nano-platelet loading within the polymer composite interface, clearly indicating the effectiveness of graphene-reinforced polymer composites in enhancing resistance to crack propagation. At lower graphene concentrations, the fracture toughness exhibits only marginal improvement compared to conventional systems, which can be attributed to the limited formation of reinforcing networks within the polymer matrix [17]. However, as the graphene content increases, a pronounced rise in fracture toughness is observed, reflecting the development of an interconnected reinforcement network that effectively bridges micro-cracks and dissipates fracture energy.

The trend observed in Fig. 4 highlights that the graphene-reinforced polymer composite interface significantly enhances interfacial adhesion between the cementitious matrix and the composite layer, thereby reducing the likelihood of interfacial debonding and failure. The high aspect ratio and large surface area of graphene nanoplatelets facilitate strong interfacial interactions with the polymer matrix, leading to improved load transfer efficiency across the interface. This results in a more uniform stress distribution within the composite system, minimizing stress concentration at crack tips and delaying crack initiation. Furthermore, the polymer composite interphase introduces a ductile region within the otherwise brittle concrete matrix, allowing for greater deformation before failure and thereby improving fracture resistance.

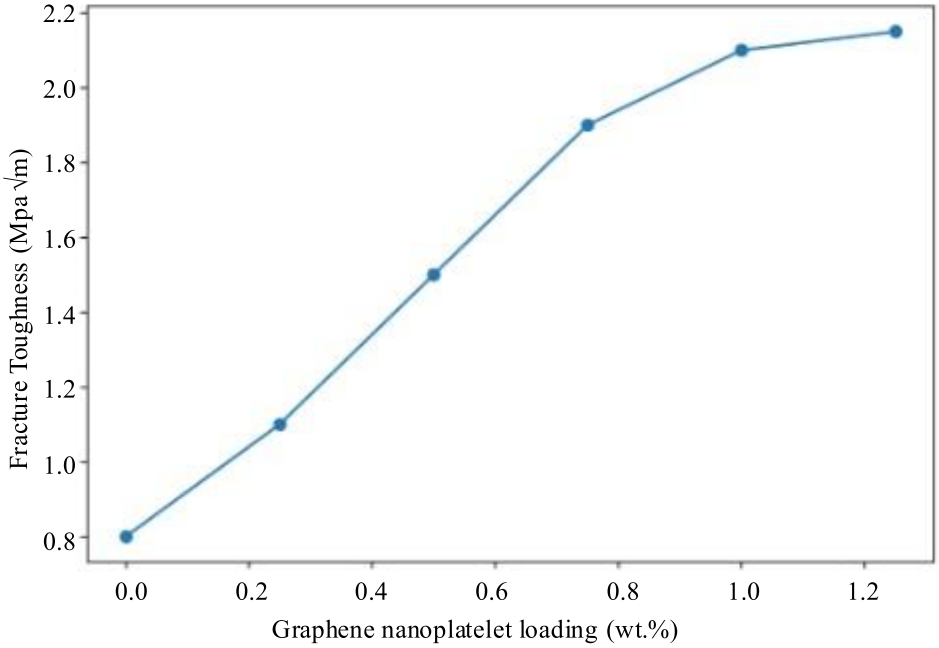

Figure 4. Variation of fracture toughness of graphene-reinforced polymer composite interface with graphene nano-platelet loading

Fractographic analysis further supports the observations presented in Fig. 4, revealing that cracks tend to deflect, branch, or arrest upon encountering the graphene-reinforced polymer composite interface, rather than propagating in a straight path as observed in conventional concrete. This crack deflection mechanism significantly increases the energy required for crack propagation, thereby enhancing the overall fracture toughness of the system. Additionally, the polymer matrix contributes to energy dissipation through plastic deformation, while the graphene nanoplatelets act as nanoscale reinforcements that bridge cracks and prevent their widening. At higher graphene loadings, the fracture toughness begins to plateau, as shown in Fig. 4, indicating that beyond an optimal concentration, additional graphene contributes minimally to further toughness improvement due to saturation of reinforcement mechanisms and possible agglomeration effects [18].

Overall, the results presented in Fig. 4 clearly demonstrate that the incorporation of graphene-reinforced polymer composite interfaces significantly improves the fracture behaviour of concrete systems by enhancing interfacial bonding, promoting crack bridging, and increasing energy absorption capacity [19]. This synergistic interaction between polymer ductility and graphene reinforcement leads to a composite system with superior fracture toughness and resilience, making it highly suitable for advanced structural applications requiring enhanced durability and damage tolerance.

AI-Driven Crack Detection Performance

The AI-integrated polymer composite system demonstrated exceptional performance in real-time crack detection and classification, with high accuracy achieved through the use of advanced machine learning algorithms capable of analyzing complex electrical signal patterns generated by the polymer composite sensor. The system effectively distinguished between different types of structural responses, including elastic deformation, micro-cracking, and macro-crack formation, while maintaining robustness against environmental noise and signal fluctuations. The high detection accuracy and rapid response time highlight the effectiveness of combining polymer composite sensing with AI-driven analytics, enabling the development of intelligent structural health monitoring systems that can provide continuous and reliable assessment of structural integrity [20].

Healing Efficiency of Polymer Composite System

The self-healing polymer composite system demonstrated high efficiency in restoring structural integrity after damage, with strength recovery values exceeding 80–85%, indicating effective crack sealing and load transfer across the healed region, while the polymer composite matrix played a crucial role in supporting the healing process by retaining the healing agent and facilitating its distribution within the crack [21]. The presence of graphene further enhanced the mechanical performance of the healed region by reinforcing the polymer matrix and improving its stiffness and strength, while cyclic loading tests confirmed the durability of the healed structures, demonstrating the ability of the polymer composite system to maintain its performance over repeated damage-healing cycles [22].

To further validate the effectiveness of the developed graphene–polymer composite system, the obtained mechanical and self-healing performance was benchmarked against recent literature on similar multifunctional composite systems. The observed ~40% increase in compressive strength in the present study is consistent with previously reported improvements in graphene-reinforced polymer-modified concrete systems, where strength enhancements typically range between 20% and 35% depending on filler dispersion and interfacial bonding characteristics [11–13]. The relatively higher improvement achieved in this work can be attributed to the optimized dispersion of graphene nanoplatelets and the formation of a well-bonded polymer composite interphase, which enhances stress transfer efficiency and reduces crack propagation pathways.

Similarly, the healing efficiency of 80–85% achieved in the present system aligns well with reported values for microcapsule-based self-healing polymer composites, which generally fall within the range of 60–80% under comparable loading and environmental conditions [20–22]. The enhanced healing performance observed in this study is likely due to the synergistic interaction between the polymer matrix and graphene reinforcement, where graphene not only improves the mechanical stability of the healed region but also facilitates effective load redistribution across the repaired interface.

In comparison with existing systems, the present work demonstrates a notable improvement in both mechanical reinforcement and healing efficiency, highlighting the advantage of integrating graphene reinforcement with polymer composite-based self-healing mechanisms. Furthermore, the incorporation of sensing functionality through the conductive graphene network provides an additional layer of performance not commonly achieved in conventional self-healing systems, thereby establishing the proposed material as a multifunctional platform for next-generation smart structural applications.

Limitations and Future Scope

Despite the promising performance demonstrated by the developed graphene–reinforced polymer composite system, certain limitations must be acknowledged. The sensing framework presented in this study is primarily based on controlled experimental conditions, where the relationship between electrical resistance variation and crack propagation is established under relatively stable loading and environmental scenarios. In real-world structural applications, factors such as temperature fluctuations, moisture ingress, and long-term material degradation may influence the electrical response of the composite, potentially affecting sensing accuracy and reliability.

Furthermore, the AI-based crack detection model is developed using experimentally generated datasets with predefined damage conditions. Although the model demonstrates high classification accuracy, its performance may vary when subjected to complex field conditions involving noise, multi-axial loading, and unpredictable damage patterns. The generalization capability of the model could be further improved through the incorporation of larger datasets, real-time monitoring data, and advanced training strategies.

From a materials perspective, achieving uniform dispersion of graphene nanoplatelets at large scale remains a challenge due to agglomeration tendencies and processing limitations. In addition, the cost associated with high-quality graphene and microencapsulation techniques may limit large-scale industrial implementation. The long-term durability and repeated healing capability of the microcapsule-based system also require further investigation, particularly under cyclic loading and harsh environmental conditions.

Future work should focus on large-scale validation of the proposed system in real structural environments, including field-level testing and long-term monitoring. The integration of advanced machine learning techniques such as deep learning and adaptive models could further enhance the accuracy and robustness of crack detection. Additionally, the development of cost-effective fabrication methods and scalable processing techniques will be essential for practical deployment. The exploration of hybrid reinforcement systems and multi-functional composite architectures may further improve mechanical performance, sensing sensitivity, and healing efficiency, thereby advancing the applicability of smart polymer composite systems in next-generation infrastructure.

CONCLUSION

The present investigation establishes that graphene-reinforced polymer composites serve as a highly effective multifunctional material platform, capable of simultaneously enhancing mechanical performance, sensing capability, and self-healing efficiency in hybrid structural systems.

- The engineered polymer composite exhibited a well-defined electrical percolation threshold (~0.6–0.8 wt.%), confirming the formation of an efficient conductive network within the polymer matrix.
- Graphene incorporation significantly improved interfacial bonding and load transfer mechanisms, leading to a ~40% increase in compressive strength.
- Fracture toughness enhancement (0.8 → 2.1 MPa√m) demonstrates the effectiveness of polymer composite interphases in crack-bridging and energy dissipation.
- The polymer composite system exhibited stable piezoresistive behaviour, enabling high-sensitivity detection of micro-scale damage (≈30 µm cracks).
- Integration of microencapsulated healing agents within the polymer matrix resulted in autonomous healing efficiencies of 80–85%, confirming the self-repair capability of the composite.
- AI-assisted interpretation of polymer composite sensor data achieved >95% accuracy, enabling real-time structural health monitoring.

Overall, the study highlights that polymer composite engineering—through matrix design, nano-reinforcement, and multifunctional integration—plays a central role in advancing next-generation smart materials for structural applications.

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