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Advancements in Self-Sensing Cementitious Composites: A Review on Smart Pe Fibers Coated with Carbon Nanotubes

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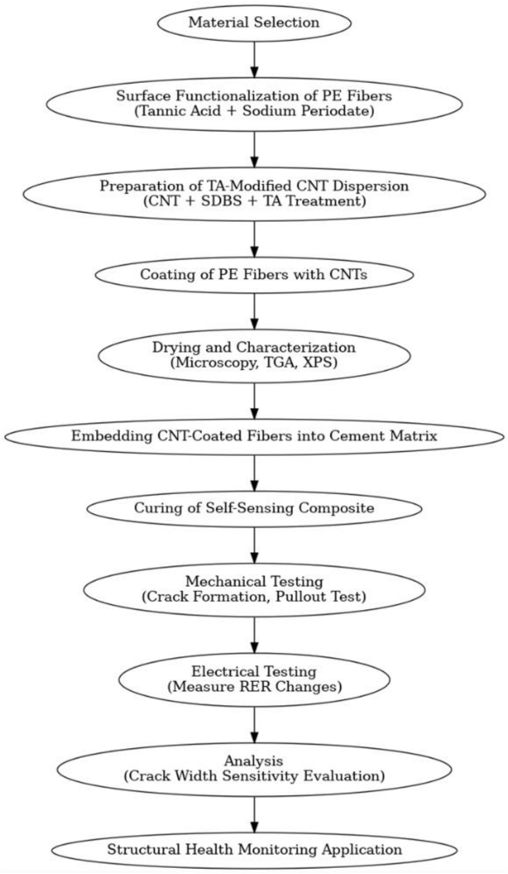
ABSTRACT

The integration of self-sensing abilities in concrete structures represents a significant leap in structural health monitoring (SHM) technologies. Recent studies demonstrate that smart polyethylene (PE) fibers coated with single-walled carbon nanotubes (SWCNTs) exhibit exceptional crack detection capabilities. This review summarizes the methodology, findings, and technological implications of developing highly sensitive cementitious composites, offering relative electrical resistance (RER) changes up to 100,000%. The materials, fabrication strategies, characterization techniques, and performance metrics are critically discussed, along with comparative insights from existing literature. Future directions for scaling and enhancing practical applications are also outlined.

1. INTRODUCTION

Concrete structures are prone to degradation, primarily through crack formation, which compromises their longevity and safety. Traditional SHM methods using external sensors face limitations such as low compatibility with concrete, environmental sensitivity, and high maintenance. The emergence of self-sensing concrete, which monitors its own health via embedded functional components, offers an innovative solution.Smart cementitious composites created with CNT-coated fibers bridge the gap between durability and intelligence in materials. The reviewed work presents a pioneering method to fabricate PE fibers coated with SWCNTs using a tannic acid (TA) mediated surface functionalization and coating process, enabling real-time crack formation and width monitoring.

2. MATERIALS AND METHODS

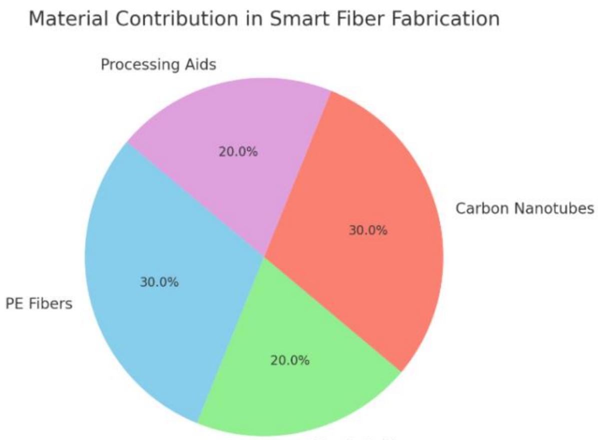


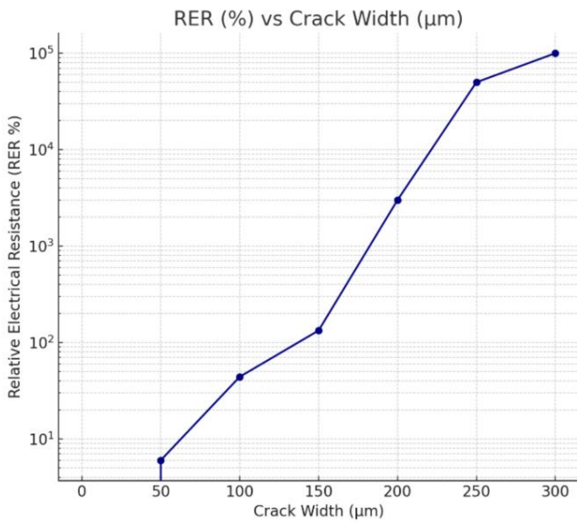
Flowchart**: *Process of Smart Fiber Fabrication and Application***

2.1 MATERIALS USED

Ultra-high molecular weight polyethylene (UHMWPE) fibers were selected for their excellent tensile strength and chemical resistance. However, they are inherently non-conductive. Tannic acid (TA) was used for surface functionalization, with sodium periodate (SP) acting as an oxidant to speed up polymerization. Single-walled carbon nanotubes (SWCNTs) were chosen due to their outstanding electrical conductivity and minimal defects. Surfactants like SDBS and chemicals like ethanolamine aided the dispersion and binding of CNTs. This combination of materials aimed to create conductive, robust fibers capable of monitoring crack formation within a cementitious composite matrix.

Pie Chart: *Contribution of Each Component in Smart Fiber Fabrication*





2.2 FIBER SURFACE FUNCTIONALIZATION

The PE fibers were washed, then immersed in a tannic acid solution with sodium periodate. This process introduced active hydroxyl and carboxyl groups on the otherwise inert fiber surfaces. Ethanolamine was added to enhance fiber surface reactivity. The chemical modification allowed better attachment of CNTs, transforming the fibers from insulating to conductive. This step was crucial in ensuring that the fibers could later act as effective crack sensors when embedded into the cementitious composite, enabling real-time monitoring without compromising the fiber's mechanical strength or chemical durability.

2.3 CNT COATING PROCEDURE

After surface activation, the PE fibers were coated with TA-modified CNTs dispersed in water using SDBS as a surfactant. Sonication helped achieve a uniform CNT dispersion. Fibers were then immersed and mildly shaken to promote even coating. After drying under ambient conditions, a CNT network formed around the fiber surfaces. Microscopic and spectroscopic analyses (SEM, XPS, TGA) confirmed successful CNT deposition. This step ensured the fibers had excellent electrical conductivity, making them sensitive to strain and crack formation. The coated fibers would later be embedded in concrete to test their self-sensing capability.

4. COMPARATIVE ANALYSIS

4.1 COMPARISON WITH DIRECT CNT MIXING

Directly mixing CNTs into cement matrices has challenges like uneven dispersion, high material usage, and increased costs. Additionally, maintaining uniform conductive pathways inside concrete becomes difficult. The reviewed method, using CNT-coated fibers, circumvents these issues by localizing CNTs only where needed. This results in strong, consistent electrical pathways and greatly reduced CNT consumption. The outcome is a cost-effective, highly efficient self-sensing system. Moreover, this fiber-based strategy minimizes adverse effects on concrete's mechanical properties, which is often a drawback when bulk CNTs are used throughout the cementitious material.

4.2 ADVANTAGES OVER STEEL FIBER APPROACHES

Steel fibers have traditionally been used to reinforce concrete but are prone to corrosion, leading to long-term durability concerns. In contrast, CNT-coated PE fibers are chemically stable, lightweight, and corrosion-resistant. Additionally, PE fibers offer excellent flexibility and high strength without significantly altering the concrete's structural properties. The sensory performance of CNT-coated fibers far exceeds that of steel fibers embedded in concrete, particularly in terms of sensitivity to strain and crack width. These advantages make CNT-coated fibers a more sustainable and technologically advanced choice for modern structural health monitoring applications.

4.3 PERFORMANCE METRICS

The CNT-coated fibers exhibited outstanding performance with a relative electrical resistance (RER) change up to 100,000% during crack propagation. Crack width sensitivity reached as high as 1003%/μm, setting a new benchmark among self-sensing cementitious composites. These results outperform previous systems based on either bulk CNT-mixed matrices or steel fiber reinforcement. Not only did the smart composites demonstrate high sensitivity to crack formation, but they also reliably detected progressive crack widening. The ability to achieve such high signal amplitudes while using minimal CNT amounts highlights the efficiency and practicality of the reviewed method.

5. APPLICATIONS AND IMPLICATIONS

5.1 PRACTICAL USE CASES

Smart concrete composites created with CNT-coated fibers can be embedded in bridges, tunnels, dams, and skyscrapers to enable real-time structural health monitoring. Strategic placement of these smart fibers within critical zones allows for early detection of crack initiation and progression. This proactive detection can significantly extend the lifespan of infrastructure, prevent catastrophic failures, and reduce repair costs. Additionally, the use of such composites can support safer designs in earthquake-prone areas by offering early warnings of structural weaknesses before significant damage occurs.

5.2 MONITORING SYSTEMS AND DATA COLLECTION

When embedded in concrete, the CNT-coated fibers can be connected to monitoring devices like oscilloscopes, wireless modules, or Internet of Things (IoT) systems. Data on relative resistance changes can be transmitted in real time to maintenance teams or centralized servers. This enables continuous, remote monitoring of infrastructure health without human intervention. Real-time alerts for crack formation and widening allow maintenance teams to take immediate action. Integrating such systems into civil structures represents a major step toward fully autonomous, intelligent infrastructure management.

5.3 ECONOMIC AND ENVIRONMENTAL IMPACTS

By facilitating early damage detection, smart composites can minimize costly large-scale repairs and extend the service life of structures. This reduces the environmental impact associated with concrete production and construction waste. Furthermore, because the fiber-coating method uses a minimal amount of CNTs, the overall material costs are lower than traditional bulk CNT approaches. Reducing maintenance frequency also lessens environmental disturbances in urban areas. Overall, this technology presents a highly sustainable approach for modern infrastructure, balancing technological advancement with economic and ecological considerations.

Graph: *Relative Electrical Resistance (RER %) vs Crack Width (µm):*

Crack Width (µm)	RER (%)
0	0
50	6
100	44
150	133
200	3000
250	50,000
300	100,000

6. FUTURE DIRECTIONS

6.1 MULTI-CRACK DETECTION

While this study focused on detecting single cracks, real-world structures often experience multiple simultaneous cracks. Future work should investigate the capability of CNT-coated fibers to distinguish between multiple crack events. Developing signal-processing algorithms that can analyze overlapping resistance changes will be critical. Understanding how multiple cracks affect the electrical pathways will help refine the technology for larger and more complex structures. This will broaden the range of practical applications, making smart composites even more versatile.

6.2 ENVIRONMENTAL STABILITY

Environmental conditions such as temperature fluctuations, humidity, and freeze-thaw cycles can affect both concrete and embedded sensors. Future studies should explore the long-term durability and sensory stability of CNT-coated fibers under harsh environmental conditions. Testing performance under accelerated weathering and simulating different climate scenarios will provide insights into the material’s real-world reliability. This is crucial for ensuring that the sensory system remains accurate and dependable throughout the structure's lifespan, particularly in exposed infrastructures like bridges and offshore platforms.

6.3 SCALABLE FABRICATION TECHNIQUES

For widespread adoption, the CNT-coating process for PE fibers must be scalable and cost-effective. Current methods involve manual soaking and drying, which are labor-intensive. Future efforts could develop automated roll-to-roll coating lines or spray deposition systems. Scaling up would also require optimizing CNT dispersion stability and adhesion techniques. Exploring new, faster chemical functionalization methods would make mass production more practical. Achieving scalability without compromising fiber quality and sensory performance is key to industrial adoption of smart concrete composites.

6.4 INTEGRATION WITH IOT PLATFORMS

Integrating smart cementitious composites with IoT platforms could transform infrastructure monitoring. Wireless modules connected to the CNT-coated fibers could transmit crack and strain data in real time to cloud servers. Machine learning algorithms could then analyze this data to predict structural degradation trends. Implementing IoT-based dashboards would allow engineers to visualize health conditions instantly. Such integration would enable predictive maintenance strategies, reducing repair costs and improving safety. Future work should focus on creating standardized interfaces between fiber-based sensors and commercial IoT networks.

7. CONCLUSION

The incorporation of CNT-coated polyethylene fibers into cementitious composites marks a significant advancement in self-sensing concrete technologies. The unique surface functionalization and CNT coating process transformed inert fibers into highly sensitive strain and crack width sensors. This approach provided extraordinarily high relative electrical resistance changes (up to 100,000%) and crack width sensitivities of 1003%/μm, surpassing previous technologies. Furthermore, the minimal CNT usage makes this method more cost-effective and scalable. Compared to traditional steel fiber reinforcement or bulk CNT mixing, the smart fiber strategy offers superior corrosion resistance, better integration with IoT systems, and more sustainable long-term performance. Future studies should explore multi-crack detection, environmental durability, and scalable production techniques. Embedding such smart composites in critical infrastructures opens the path toward intelligent, self-monitoring, and predictive maintenance systems, reducing economic costs and enhancing public safety. Overall, this innovation sets a new benchmark in the field of structural health monitoring and smart materials engineering.

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