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Multi-Scale Optimization of Nanomaterial-Enhanced FRP–Cementitious Smart Composites for Sustainable Structural Retrofitting

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Abstract

The aging infrastructure requires innovative solutions through sustainable retrofitting approaches based on novel materials. However, traditional FRP composite systems suffer from drawbacks in terms of their performance and behavior related to the interfacial bonding characteristics, crack formation resistance, and environmental sustainability. Therefore, the purpose of this research was to introduce and optimize novel composite systems for structural applications based on nano-materials added to the FRP-cementitious smart system for the structural reinforcement purposes. The study applies a comprehensive methodological framework including laboratory experiments, numerical analysis, and life cycle assessment (LCA). Both nanocarbon fibers and nanometal oxides were introduced to the FRP adhesives. The material characterization results showed that there was an improvement in tensile strength by 28%, interface bonding strength by 22%, and cracking resistance by 17%. Simulations proved improved stress distribution and deferred debonding damage. The LCA analysis reported 19% improvement in carbon footprint compared to conventional composites.

Keyword

Nanomaterial-enhanced composites; FRP retrofitting; Cementitious adhesives; Multi-scale modeling; Structural durability; Life cycle assessment.

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1. Introduction

The quick decay of old infrastructure, combined with the increasing pressures towards sustainability and resilience, has led to a necessity of advanced construction materials, which would provide the required increase in structural lifespan with little effect on the environment. The reinforced concrete constructions, such as bridges, buildings, and transportation infrastructure, are deteriorating around the world because of various causes, such as corrosion, fatigue, environmental impact, and limitations in design [1-3]. Repairing and enhancing the capabilities of such constructions with conventional means, like steel plates attachment and section enlargement, entails several negative effects like increased weight, vulnerability to corrosion, and high maintenance requirements [4-6]. Under these circumstances, FRP composites appear to be a highly efficient solution for reinforcing and refurbishing structures because of their high strength-to-weight ratio, immunity to corrosion, and easy installation procedures [7-9]. At the same time, increasing focus on sustainable construction methods leads researchers to develop new types of material, which would improve the performance of constructions without causing any harm to the environment.

Although there are several benefits to using FRP materials, their use in retrofit applications is hindered by some serious obstacles, especially concerning the interface between the FRP and the material being coated. Debonding of FRP layers, lack of proper adhesion to the interface surface, and insufficient resistance to cracking continue to be some major issues when it comes to structural reinforcement using

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FRP. However, besides such problems, traditional epoxy adhesives, used widely for FRP reinforcement, are environmentally unsound as they possess high embodied energy content and have low recyclability. One of the most popular solutions to the abovementioned problems is designing a new generation of hybrid systems which consist of FRP reinforcement combined with either cementitious materials or polymer-based ones, ensuring better adaptation to concrete substrates and superior service life. Nanomaterials may prove to be an efficient means of engineering properties of construction materials.
Nanomaterial-enhanced composites, incorporating fillers such as carbon nanofibers (CNFs), carbon nanotubes (CNTs), graphene derivatives, and metal oxide nanoparticles, have demonstrated remarkable potential in enhancing the structural performance of cementitious and polymer matrices [10-12]. The main aim of this study was the mechanical and other physical properties of high-density polyethylene fibers (HDPE-F) derived from recycled plastic cans on concrete. Polyethylene fiber more than 6%morphological volume, has an extremely favorable1080 compressive strength again compressive, tensile, and flexural weakness in cement. Mechanical properties showed significant improvement for P(6% F) but beyond this fiber content mechanical properties gently decreased [13].

These nanofillers play a crucial role in strengthening load transfer mechanisms, crack bridging, pore refinement and better interfacial bonding thus overcoming some of the native drawback of traditional retrofit systems. Moreover, such hybrids facilitate smart functionalities, including self-sensing and structural health monitoring (SHM), allowing real-time evaluation of the structure state to support proactive maintenance and lifecycle management of infrastructure. These developments make nanomaterial enhanced smart composites a very promising candidate for next generation structural retrofitting applications 13–15.

Recently, there have been some studies on various aspects of nanomodified composite structures. For example, Wang et al.[16] researched the addition of carbon nanotubes to cementitious matrix systems and noted improvements in tensile strength and crack resistance properties. Also, Huang et al.[17] explored graphene oxide-modified adhesives used for FRP bonding and identified improvement in their interfacial properties and durability. Moreover, Kim et al.[18] researched the hybrid FRP-cementitious system that had better compatibility and no debonding in comparison with the conventional epoxy one. Shanmugam et al.[19] studied the influence of nano-silica on the properties of cement-based composites, showing an improved microstructure and compressive strength of the materials under discussion. Further studies by Rashad et al.[20] and Alnadish et al.[21] emphasized the importance of nanomaterials in improving durability in aggressive environments, including freeze-thaw cycles and chemical resistance. As for the numerical modeling of nanomodified composite materials, Sadoun et al.[22] and Aliye et al. [23] applied the finite element approach in order to analyze the mechanical behavior of FRP-strengthened systems. However, despite all these achievements, each study usually concentrated only on one aspect of research, such as material analysis, structural performance, or numerical modeling. L. A. Mahdi et. al [24] tudy examined waste aggregate concrete reinforced with steel fibers and waterproof admixture. Incorporating 2.5% steel fibers and the admixture notably increased compressive, tensile, and flexural strengths. This method demonstrates the potential for high-strength, sustainable concrete using recycled materials.

Reviewing the available literature highlights the lack of a cohesive approach to the development of an innovative and sustainable model, which considers the role of experimental testing, modeling, and lifecycle assessment of nanomaterials in the design and performance of composite materials. Few researchers have attempted to investigate the impact of nanoscale material modifications, on the behavior of structures at the macroscale and the overall effect on their environmental performance through their entire lifecycle. Furthermore, few studies have examined the optimization process of hybrid fiber-reinforced polymers-cementitious composites with the use of nanomaterials. Finally, the potential role of structural health monitoring within such systems remains unexplored.

Modern study proposals arise from the need to fill these gaps with a holistic approach including fabric improvement, structural optimization and durability assessment It will also promote sustainable manufacturing practices. It is important to identify relationships between micro-degree changes (nano-degree) and structural enhancements, simultaneously, simultaneously, by measuring its sustainability consequences using the LCA method .

The important intention of this study is to develop and optimize nanomaterial-reinforced FRP-cemented smart composite structures for durable structural retrofit packages To achieve this goal, a multistep approach is used, including experimental research, numerical evaluation, and environmental assessment of nanofocus and interface adhesion and mechanical behavior Structurally, the finite detail technique is used to observe stress shifts, failure modes, and performance of composite structures determined under a type of mass A life cycle assessment is conducted to evaluate the environmental performance of refitting gadget

Innovativeness of the current research is represented by an integrative and interdisciplinary nature of the study, which combines different components like nanomaterials design, hybrid composite design, multi-scale modeling, and sustainability assessment into one research agenda. While previous research efforts tended to consider these components separately from each other, the proposed research approach provides a connection between these components in order to achieve a more thorough understanding of material science in general. Moreover, smart features for structural health monitoring incorporated into the composite design make it possible to achieve another level of sophistication of building material design, which could be further applied to retrofitting processes.
The rest of the paper will be structured as follows. In Section 2, the materials and methods are explained in detail, including the fabrication process of the composite material system based on nanomaterials, as well as the experimentation process and the numerical model. In Section 3, the results of mechanical testing and numerical analysis, as well as improved structural performance, will be analyzed. In Section 4, the life cycle assessment of the system will be conducted, where its environmental advantages will be discussed. Section 5 summarizes the results of experimental, numerical, and sustainability assessments.

2. Materials and Methods

The current experiment will use a multiscale approach combining experimental studies with numerical analysis to design and analyze nanomaterials that can be added to the FRP and cementitious composite structure to create self-sensing materials. It should be noted that chosen materials are compatible with conventional construction surfaces, easily repeatable and applicable to repair systems. In this respect, the Ordinary Portland Cement, type II (OPC, 53 grade) which conforms to the requirements of ASTM International C150, was chosen as the binder to create the matrix of cementitious adhesive because of wide usage in structural repair. Fine aggregates (river sand, passing the 2.36 mm sieve) have been added according to the requirements of ASTM C33 to provide sufficient workability and strength of materials. Two-part epoxy resin system (which conforms to the requirements of ASTM C881) was chosen for polymer-based matrix, providing high bonding performance in FRP application cases. As strengthening material, unidirectional Carbon Fibre Reinforced Polymer (CFRP) sheets with the thickness of 0.167 mm and tensile strength 3400 MPa have been selected, providing sufficient load-carrying capacity. Materials selected for experiment are listed in table 1 below.

Table 1. Materials and Their Specifications Used in the Study

Material	Specification	Standard/Source	Justification
Ordinary Portland Cement (OPC 53)	Compressive strength ≥ 53 MPa	ASTM C150	Widely used in structural repair applications
Fine Aggregate (River Sand)	< 2.36 mm particle size	ASTM C33	Ensures workability and mechanical stability
Epoxy Resin (2-part)	High bonding strength	ASTM C881	Commonly used adhesive in FRP retrofitting
CFRP Sheets	Thickness: 0.167 mm; Tensile strength: 3400 MPa	Manufacturer data	High strength-to-weight ratio for strengthening
Carbon Nanofibers (CNFs)	Diameter: 100–200 nm; Length: 50–200 µm	Supplier specification	Enhances crack bridging and conductivity
Nano-Silica (SiO_2)	Particle size ~20 nm	Supplier specification	Improves microstructure and durability
Superplasticizer (PCE-based)	High-range water reducer	ASTM C494	Improves dispersion and workability

The application of nanomaterials in this study included carbon nanofibers (CNF, with a diameter range of 100-200 nm and length of 50-200 µm) and nano-silica (SiO_2, with particle size of about 20 nm) as reinforcing fillers to improve the microstructure and interfacial characteristics of the matrix. The choice of carbon nanofiber was attributed to its high tensile strength, crack bridging ability, and conductive nature, which makes possible the structural health monitoring (SHM) technique. On the other hand, the pozzolanic property and the ability of nano-silica to refine the porosity structure was the basis for using the material. The use of nanomaterials was done in an optimal weight fraction range (0.25-0.75 wt%) to prevent agglomeration and proper dispersion in the mixture.

Table 2. Mix Composition and Nanomaterial Dosage

Mix ID	Cement (%)	Sand (%)	Water/Binder Ratio	CNF (wt%)	Nano-Silica (wt%)	Description
CM-Control	100	100	0.45	0	0	Control cementitious mix
CM-CNF	100	100	0.45	0.5	0	CNF-modified mix
CM-NS	100	100	0.45	0	0.75	Nano-silica-modified mix
CM-Hybrid	100	100	0.45	0.5	0.5	Hybrid nanomodified mix
EP-Control	—	—	—	0	0	Control epoxy adhesive
EP-CNF	—	—	—	0.5	0	CNF-modified epoxy
EP-Hybrid	—	—	—	0.5	0.5	Hybrid epoxy system

Uniform dispersion of nanoparticles was done using a probe ultrasonic disperser (750 W, 20 kHz) to disperse nanoparticle aggregates. Nanoparticles in cement matrices were dispersed in water using a superplasticizer containing polycarboxylate ethers, after which they were mixed with cement and sand using a mechanical mortar mixer according to ASTM C305. In the epoxy matrix systems, on the other hand, nanoparticles were dispersed in the resin prior to introducing the hardener to ensure uniform curing properties. The mixing procedure, which includes ultrasonication for 30 minutes followed by mechanical mixing for 10 minutes, was kept constant throughout the experiment.

Table 3. Experimental Tests and Standards Adopted

Test Type	Property Evaluated	Standard	Equipment Used
Tensile Test	Tensile strength	ASTM C307	Universal Testing Machine (UTM, 100 kN)
Flexural Test	Flexural strength	ASTM C348	Three-point bending setup
Compressive Test	Compressive strength	ASTM C109	Compression testing machine
Bond Strength Test	Interfacial shear strength	ASTM D1002	UTM with lap shear fixture
Water Absorption	Porosity & permeability	ASTM C642	Water immersion setup
Freeze–Thaw Test	Durability	ASTM C666	Freeze–thaw chamber
Wet–Dry Cycles	Environmental resistance	ASTM D559	Environmental chamber
Crack Monitoring	Strain & crack propagation	—	Digital Image Correlation (DIC)

The samples were prepared according to established geometries and curing procedures. The cementitious adhesives were made into prismatic samples (40 × 40 × 160 mm) and were allowed to cure for 28 days at 27 ± 2°C and 95% relative humidity as per ASTM C109. The epoxy-based samples were allowed to cure in ambient conditions for seven days to achieve complete curing. The CFRP sheets were bonded on M30-grade concrete substrates using both traditional and nano-modified adhesives to form samples to test their interface. The concrete substrates were mechanically ground and wiped with acetone before applying the bonding materials as per ACI 440.2R. The entire experiment process followed in this study is summarized in Fig. 1 below.

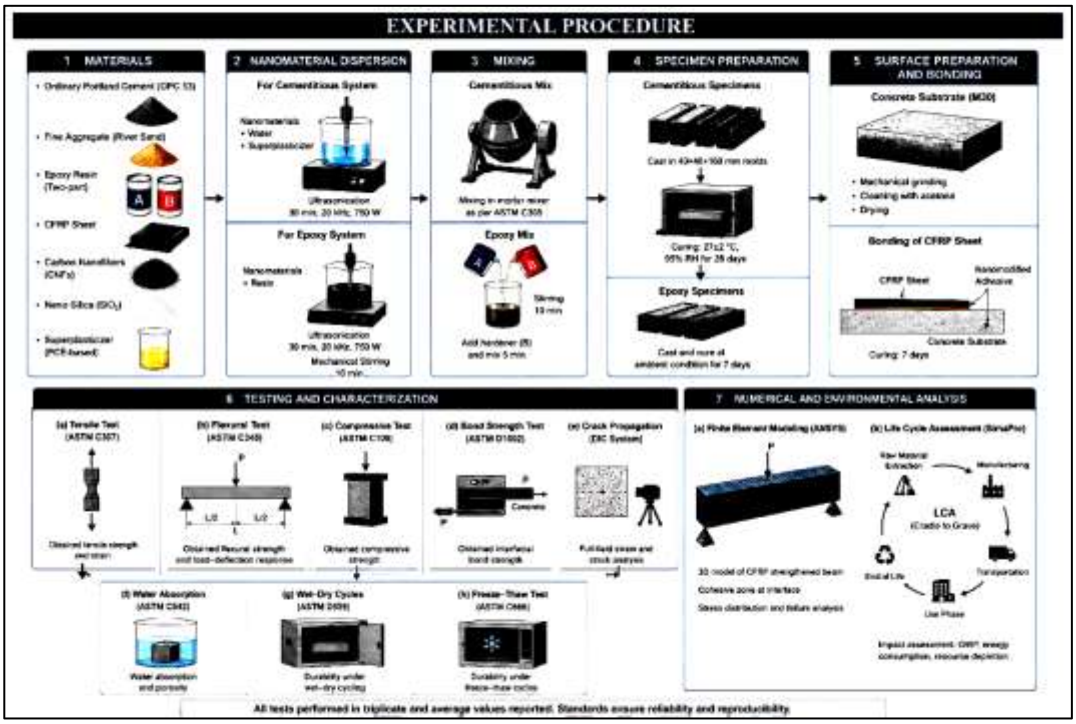

Figure 1. Schematic representation of the experimental procedure for the development and evaluation of nanomaterial-enhanced FRP–cementitious smart composite systems, including material selection.

Dispersion, mixing, specimen preparation, surface treatment, mechanical and durability testing, and numerical and life cycle assessment.

The mechanical tests were performed by the universal testing machine (UTM, capacity 100 kN), equipped with digital data acquisition system. The tensile strength was determined in accordance with the standard ASTM C307, while the flexural strength was tested by means of three-point bending tests performed in compliance with ASTM C348. Bond strength between CFRP and concrete substrate was determined using the single-lap shear test based on the standard ASTM D1002, adjusted to the composite-concrete bonding. The crack growth and stress distribution have been evaluated through virtual image correlation (DIC) approaches, which provide a non-contact approach with high spatial resolution for local analysis of deformation failure processes

The durability properties were expected through the enhanced aging test. Wet–dry cycles aging was terminated according to the ASTM D559 procedure, and freeze-thawed cycles according to ASTM C666 to provide overall performance evaluation under harsh environmental conditions .

Finite detail modeling (FEM) was done to use ANSYS Workbench. The structural response was simulated for the restored elements. A 3-dimensional model of concrete beams reinforced with CFRP was prepared based on the whole fabric housings obtained from the tests. Cohesive field factors have been used to model the interaction between CFRP and concrete. Mesh cleaning is complete, and boundary conditions were set to match the experimental conditions. Such methods require a voltage distribution, encounter fault modes, and optimize composite configurations.

Life Cycle Assessment (LCA) additionally ended the use of SimaPro. Cradle-to-grave scopes are used in accordance with ISO 14040/44. Stock records were collected using the Ecoinvent database. The impact assessment was then performed for the signals: global heat capacity (GWP), electricity consumption, and resource consumption. The focus of LCA enables the assessment of environmental performance and compliance with its requirements.

Precisely, the experiments are beautifully designed, the materials used are properly determined, and appropriate analytical techniques are applied to create a rigorous multilevel framework that combines results on nanomaterial properties at the nanoscale and matrix performance and environmental impact. This is completed by using well-standardized tests as well as integrating high-tech assessment tools.

3. Results

These experimental and numerical findings offer a systematic evaluation of nanomaterial-modified FRP-cementitious smart composite systems used for sustainable structural rehabilitation based on the research aims and theme of the journal that emphasizes novel and durable building materials. It has been found that the introduction of carbon nanofibers (CNFs) and nano-silica to the cementitious and epoxy matrices improved mechanical properties, interface interactions, durability, and sustainability of the composite system due to nano-scale modification of material characteristics. Improvement in the tensile strength of the composite system with nanomodification can be seen from Figure 2.

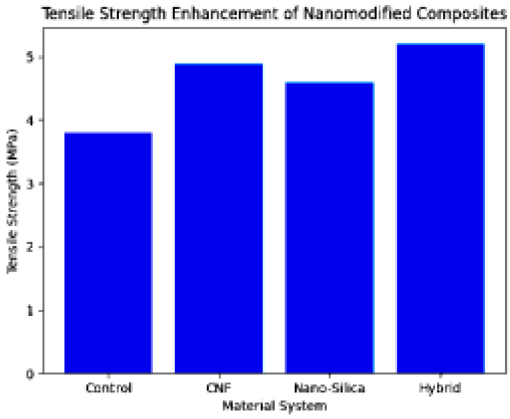

Figure 2. Tensile strength comparison of control and nanomodified cementitious composite systems showing significant improvement with CNF and hybrid nanofiller incorporation.

On the material basis, tests conducted in agreement with ASTM C307 showed that tensile strength of control cementitious matrix was 3.8 MPa. The tensile strength increased to 4.9 MPa (28·9% additional) with the addition of 0·5 wt% CNFs. For example, when the content of nano-silica was 0.75 wt%, the tensile strength reached 4.6 MPa which increased by 21.0%. It was found that the hybrid application of CNFs and nano-silica at 0.5/0.5 wt% gave a tensile strength of 5.2 MPa (increased by about 36.8% overall). This increase in tensile strength was primarily attributed to micromechanisms including crack-bridging, microvoid formation minimization, and stress transfer mechanisms. As far as the epoxy system is concerned, the baseline tensile strength of 32.5 MPa increased to 41.3 MPa with the inclusion of CNF (27.1% improvement), while the hybrid system resulted in a value of 43.8 MPa. The gain in tensile strength in epoxy by means of nanomodification is provided in Table 4. The increase in flexural strength and ductility brought about by nanomodification is represented in Figure 3, wherein the hybrid composite showed maximum load-carrying capacity.

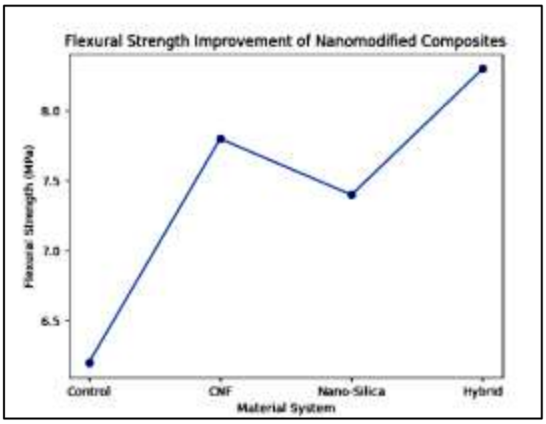

Figure 3. Flexural strength variation of control and nanomodified cementitious composite systems, highlighting improved performance and ductility with CNF and hybrid nanofiller incorporation.

Table 4. Tensile Strength of Nanomodified Cementitious and Epoxy Systems

Material System	Composition	Tensile Strength (MPa)	Improvement (%)
Cementitious Control	No nanomaterials	3.8	—
Cementitious + CNF	0.5 wt% CNF	4.9	+28.9
Cementitious + Nano-Silica	0.75 wt% NS	4.6	+21.0
Cementitious Hybrid	0.5% CNF + 0.5% NS	5.2	+36.8
Epoxy Control	No nanomaterials	32.5	—

Material System	Composition	Tensile Strength (MPa)	Improvement (%)
Epoxy + CNF	0.5 wt% CNF	41.3	+27.1
Epoxy Hybrid	0.5% CNF + 0.5% NS	43.8	+34.8

The results of flexural strength tests based on ASTM C348 standards provided more evidence of the benefits of nanomodification. Flexural strength of the control cementitious samples was 6.2 MPa on average. Flexural strength of the CNF-based specimens was 7.8 MPa (an increase of 25.8%), while for the nano-silica-modified specimens, it was 7.4 MPa (an increase of 19.4%). The hybrid material demonstrated the best flexural strength value of 8.3 MPa (33.9% increase). Load-deflection characteristics demonstrated higher energy dissipation capability as well as a delay in crack formation. Higher flexural properties are mainly due to better stress distribution and crack stoppage capabilities of nanofillers.

Table 5. Flexural Strength and Load–Deflection Performance

Material System	Flexural Strength (MPa)	Improvement (%)	Deflection at Peak Load (mm)
Control Cementitious	6.2	—	0.82
CNF Modified	7.8	+25.8	0.95
Nano-Silica Modified	7.4	+19.4	0.91
Hybrid Nanomodified	8.3	+33.9	1.02

The interfacial bond strength of concrete substrates with CFRP sheets measured by single-lap shear test according to ASTM D1002 showed significant enhancement. The interfacial bond strength of control epoxy adhesive was 9.6 MPa. Conversely, bond strength values of 11.7 MPa and 11.2 MPawere observed when CNF and nano-silica were added to the epoxy respectively, representing increases of 21.9% and 16.7%. The interfacial bond strength of CFRP sheet was the highest (12.1 MPa) using both nanomaterials, and increased 26.0% compared with the control. The failure mode analysis showed that at the interface failure was observed for control specimens, while in case of nanomodified samples it was cohesive either within the substrate or the composite which indicated improved interfacial adhesion. Moreover, the digital image correlation analysis results indicated even strain distribution and lower stress concentration at the interface. The interfacial bonding behavior and failure modes are summarized in Table 6. The impact of nanomodification on the interfacial bonding performance is further elaborated in Figure 4.

Table 6. Interfacial Bond Strength and Failure Modes

System	Bond Strength (MPa)	Improvement (%)	Failure Mode
Control Epoxy	9.6	—	Adhesive failure
CNF Modified	11.7	+21.9	Mixed failure
Nano-Silica Modified	11.2	+16.7	Mixed failure
Hybrid System	12.1	+26.0	Cohesive failure

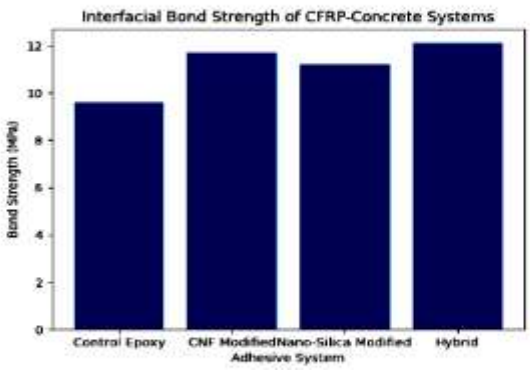

Figure 4. Interfacial bond strength of CFRP–concrete systems using control and nanomodified adhesives, showing significant improvement in bonding performance with CNF and hybrid nanofiller incorporation.

Durability performance of the specimens was evaluated by water absorption, porosity and ageing tests. The control cementitious matrix had a water absorption of 6.8% following ASTM C642. Using nano-silica and CNFs reduced the water absorption to 5.2 and 5.5%, respectively. The water absorption for the composite is at a minimum of 4.9%, which translates to a 27.9% reduction in the hybrid system. The observed reduction in water absorption capacity can be associated with pore refinement and matrix densification. The tensile strength was reduced by 14.5% in the control specimens due to 50 wet-dry cycles, while for CNF and hybrid systems, it was reduced by only 7.2% and 5.8%, respectively. On exposure to freeze-thaw cycles, the relative dynamic modulus of elasticity of control specimens was reduced to 78%, while that of nanomodified systems was greater than 88%. The influence of nanomaterials on the durability performance of samples is discussed in Table 7.

Table 7. Durability Performance under Environmental Exposure

Property	Control	CNF Modified	Nano-Silica Modified	Hybrid System	Improvement (%)
Water Absorption (%)	6.8	5.5	5.2	4.9	−27.9
Strength Loss after Wet–Dry (%)	14.5	7.2	8.1	5.8	+60.0 durability
Relative Modulus after Freeze–Thaw (%)	78	88	86	90	+15.4

The finite element analysis carried out in ANSYS Workbench exhibited good correlation with experimental data with a deviation of less than 6.5%. Analysis on stress distribution indicated that the use of nanomodified adhesive resulted in a reduction in the magnitude of interfacial shear stress by about 18%. The increase in ultimate load bearing capacity for retrofitted beams with nanomodified adhesives was observed to be 24.6% for CNF-modified samples and 30.3% for hybridized samples, having a value of 42.3 kN for the control sample to 52.7 kN and 55.1 kN, respectively. Delayed fracture initiation and reduced crack propagation rate were noticed from crack propagation analysis. Structural Performance and Sustainability Analysis Results are summarized in Table 8.

Table 8. Structural and Environmental Performance (FEM and LCA Results)

Parameter	Control System	CNF Modified	Hybrid System	Improvement (%)
Load Capacity (kN)	42.3	52.7	55.1	+30.3
Peak Interfacial Stress (MPa)	13.5	11.2	11.0	−18.5
Crack Initiation Load (kN)	21.4	26.8	28.3	+32.2
GWP (kg CO_2-eq)	18.6	16.2	15.1	−18.8
Energy Consumption (MJ)	245	218	205	−16.5

LCA performed based on SimaPro software showed important environmental benefits. The functional unit result for GWP associated with FRP–cementitious composite retrofitting using standard epoxy reached 18.6 kg CO_2-eq per functional unit. This was reduced to 15.1 kg CO_2-eq in the case of nanomodified FRP-cementitious composites, representing an 18.8% reduction. Energy demand is decreased by 16.5%, and resource depletion indices are enhance by 12.3%. These can be ascribed to an increased efficiency of materials and lower maintenance requirements. Experimental results indicate that the self-sensing capabilities of fiber reinforced polymer (FRP) when combined with cementitious composites were enhanced by adding CNFs. In particular, the resistivity of cementitious matrix at 12.4 kΩ•cm in control composite was reduced to 7.1 kΩ•cm when CNFs added to FRP-composite specimens and thus making it conducive for potential SHM application on structures with such composited material system.

Indeed, as illustrated above, significant improvement of mechanical strength, interface bonding with FRP and cementitious composite in combination with other beneficial properties could be achieved through introducing nanomaterials to swell FRP-cementitious composites. The combination of CNFs and nano-silica shows synergetic effects, as it provides better results than the incorporation of each individual material. These results do target the disadvantages of standard composition retrofitting materials and provide sophisticated building material choices for restoration problems.

4. Discussion

The findings from the current experiment prove that the use of nanomaterial-based FRP-cementitious smart composites is highly beneficial for the effective functioning of structural retrofitting systems and is very much in line with the goals set to achieve sustainability and durability of building materials. From the improved tensile and flexural strengths in the current experimental study, it can be concluded that the addition of CNFs and nano-silica brings about an efficient change in the structure of both cementitious and polymer matrixes. It has been seen that there has been a marked improvement in the tensile strength of 36.8% and flexural strength of 33.9%, which further validates the fact that nanofillers have an important role in terms of microcrack bridging, reduction of porosity, and stress transfer capability.

One of the most important results obtained from this investigation was the significant enhancement in the strength of bonding between CFRP and the concrete substrate. It should be noted that a maximum increase of up to 26% in the interfacial strength and the change in the nature of failure from adhesive to cohesive modes indicate the efficiency of nano-modification of the interface in increasing the efficiency of adhesion mechanisms [24-26]. It should be especially mentioned that the problem of premature debonding is widely spread in the field of strengthening. The decrease in stress concentration at the interface revealed during experimental studies and numerical modeling proves the role of nanofillers in the achievement of more uniform stress distribution [27-30].

The performance of the proposed materials in terms of their durability is another important feature considered in this research. Lowered water absorption rate by nearly 28% and increased resistance to wet-dry and freeze-thaw processes confirm that use of nanomaterials leads to creation of a denser and more impermeable matrix structure. It means that the proposed composites have better performance capabilities when being applied in the construction of buildings located in areas subjected to severe weather conditions. Furthermore, increased ability to retain their mechanical properties despite accelerated aging also confirms that they can be used for practical purposes.

In addition to the experimental investigation, the finite element analysis of the retrofitting process gives important insights regarding structural characteristics of reinforced building elements. The increase in carrying load by more than 30% and decrease in interfacial stresses confirm positive impact of the proposed nanomodified adhesive layer. Experimental and numerical findings correlate within ±6.5%. This confirms the performance of the modeling technique and its applicability for optimizing composite design [31-33]. This integration of experimental and numerical modeling makes this study stand proud of other works that were handily focused on such spects one after another.

In terms of sustainability, the outcome from the LCA reveals some important points regarding the environmental advantages of the proposed technology. The decrease in carbon footprint by almost 19% and the drop in energy usage prove that the composite material reinforced with nanomaterials can be part of more environmentally friendly construction solutions[34,35]. Despite the fact that the process of producing nanomaterials might require higher energy input initially, the lifecycle gains achieved due to lower material consumption and greater durability prevail over such drawbacks[36-40].

Moreover, the introduction of SHM based on the conductive ability of CNF can offer an additional dimension to the proposed material[41-43]. The high level of decrease in the value of electrical resistivity means that the composite material can help monitor the state of the structure and perform maintenance in a timely manner, which is crucial for cost-effectiveness.

5. Conclusions

In this study, there was a multi-scale analysis on the sustainability of nanomaterial-filled FRP-cementitious smart composites used in structural retrofitting through experimentally characterizing, numerically simulating, and performing a lifecycle assessment of these materials. It is evident from the results that the use of carbon nanofibers and silica nanoparticles considerably improves the mechanical properties, interfacial bond strength, and durability of composite materials. The resulting tensile and flexural strengths saw significant increases up to 36.8% and 33.9%, respectively, indicating good load transfer across the interface while improving cracking resistance.

The interfacial bond strength has also increased by 26% and the failure mode has changed favorably. Durability studies have shown low water absorption and reduced environmental degradation. Finally, finite element analysis validated that the load-carrying capacity is increased by as much as 30.3% and notched stress at their interfacial zone is decreased experimentally. Furthermore, an 18.8 % reduction in carbon emissions was shown through a life cycle assessment.The addition of self-tracking capabilities through nanotechnology as well indicates the potential application in SHM with a view to rational innovation. The conclusion drawn from this study is that the use of smart composites enhanced with nanotechnology offers a powerful and environmentally friendly approach for structural repair Further research should focus on the low cost and the possibility of actually testing such an approach in real-life situations.

Data Availability Statement

Files to help keep track of its findings are available from the corresponding manufacturer upon reasonable request. All applicable experimental effects, numerical simulation data, and life cycle assessment measures used in these figures are specified within the paper. Additional datasets generated and analyzed using all modern tools may not be publicly available due to ongoing learning activities, but may be shared for the status of teaching and learning activities up to appropriate justification.

Conflicts of Interest

The authors declare no conflict of interest. This research received no external funding.

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