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Design and Development of Carbon Fiber–Reinforced Geopolymer Cement Supercapacitors for Durable and Energy-Integrated Smart Infrastructure.

Ali Ajwad
Department of Civil Engineering, University of Management and Technology, Lahore, Pakistan. Email: Ali.ajwad@umt.edu.pk

Omar J. Alkhatib (Corresponding Author)
Professor of Civil and Structural Engineering, Department of Architectural Engineering, United Arab Emirates University, United Arab Emirates. Email: Omar.alkhatib@uaeu.ac.ae

Salman Jafar
College of Architecture and Environment, Sichuan University, Chengdu, Sichuan, China. Email: salmanjafar2002@gmail.com

Muhammad Nawaz
Department of Industrial and Manufacturing, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Sindh, Pakistan. Email: muhammadnawaz@quest.edu.pk

ABSTRACT

The growing need for sustainable and energy-efficient infrastructure has accelerated the development of multifunctional construction materials capable of integrating structural performance with energy storage capabilities. This study presents the design and development of a carbon fiber–reinforced geopolymer cement (CFGPC)–based structural supercapacitor for durable and energy-integrated civil infrastructure. Geopolymer cement, derived from industrial by-products such as fly ash and slag, serves as an environmentally friendly alternative to conventional Portland cement, while carbon fiber reinforcement enhances mechanical strength and electrical conductivity. The proposed composite material is engineered to simultaneously function as a load-bearing structural element and an electrochemical energy storage device. A comprehensive experimental methodology is employed to evaluate both mechanical and electrochemical properties. The addition of carbon fibers forms conductive networks within the geopolymer matrix, enabling efficient charge storage and transfer. Key performance indicators, including specific capacitance, energy density, power density, and compressive strength, are systematically analyzed under varying material compositions. Electrochemical characterization is conducted using cyclic voltammetry, charge–discharge testing, and impedance spectroscopy. Results indicate that the optimized CFGPC composite achieves enhanced electrical

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conductivity and improved energy storage performance while maintaining sufficient structural integrity. The material demonstrates stable electrochemical behavior and durability under operational conditions. Furthermore, the study highlights the balance between mechanical strength and electrochemical efficiency, offering insights for optimal design. This research contributes to the advancement of smart and sustainable infrastructure by transforming conventional construction materials into energy-storing systems, paving the way for next-generation multifunctional civil engineering solutions.

Keywords— Geopolymer Cement, Carbon Fiber Reinforcement, Structural Supercapacitors, Energy Storage Materials, Sustainable Infrastructure, Electrochemical Performance, Smart Civil Systems, Multifunctional Materials.

1- Introduction:

The rapid expansion of urban infrastructure and the increasing global demand for sustainable energy solutions have created a pressing need for innovative construction materials that can perform beyond traditional structural roles. Conventional civil engineering materials, particularly ordinary Portland cement (OPC)-based concrete, are primarily designed for load-bearing applications and lack the capability to store or manage energy. At the same time, the construction industry is responsible for a significant portion of global carbon emissions, largely due to the production of OPC. This has led to growing interest in environmentally friendly alternatives such as geopolymer cement, which is synthesized from industrial by-products like fly ash and ground granulated blast furnace slag [1]. Geopolymer materials not only reduce carbon emissions but also exhibit superior durability, chemical resistance, and thermal stability. In parallel, recent advancements in material science have introduced the concept of multifunctional materials, particularly structural energy storage systems such as supercapacitors. Supercapacitors are known for their high power density, rapid charge–discharge capability, and long cycle life, making them suitable for integration into smart infrastructure systems. However, conventional supercapacitors are typically fabricated using lightweight polymeric or carbon-based substrates, which lack the mechanical strength required for structural applications [2]. This limitation has motivated the exploration of cementitious materials as potential candidates for structural energy storage. One promising approach is the incorporation of conductive fillers into cement-based matrices to enable electrochemical functionality. Among various conductive materials, carbon fibers are particularly attractive due to their high electrical conductivity, excellent mechanical properties, and compatibility with cementitious systems. When embedded within a geopolymer matrix, carbon fibers form conductive networks that facilitate efficient charge transport and storage. This enables the development of carbon fiber–reinforced geopolymer cement (CFGPC) composites capable of acting as structural supercapacitors [3]. Despite these advancements, achieving an optimal balance between mechanical strength and electrochemical performance remains a critical challenge, as excessive conductive filler content may degrade structural integrity. To better understand the research landscape, a comparison of existing materials and approaches is presented in Table 1.

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Table 1: Comparison of Conventional and Emerging Materials for Structural Energy Storage

Material/System	**Mechanical Strength**	**Electrical Conductivity**	**Energy Storage Capability**	**Sustainability**	**Limitations**
OPC-Based Concrete	High	Very Low	None	Low	High carbon emissions, no energy function
Polymer-Based Supercapacitors	Low	High	High	Moderate	Poor structural strength
Carbon Nanotube Cement Composites	Moderate	High	Moderate	Moderate	High cost, dispersion issues
Graphene-Based Cement Materials	Moderate–High	Very High	High	Moderate	Expensive, scalability challenges
Geopolymer Cement (without fillers)	High	Low	None	High	No conductivity
Carbon Fiber–Reinforced Geopolymer (Proposed)	High	Moderate–High	Moderate–High	High	Optimization required

Building upon these developments, this study proposes the design and development of a carbon fiber–reinforced geopolymer cement (CFGPC) system that functions as a structural supercapacitor for energy-integrated civil infrastructure. The research focuses on evaluating both mechanical and electrochemical performance through a systematic experimental framework. Key parameters such as compressive strength, electrical conductivity, specific capacitance, energy density, power density, and durability are analyzed under varying material compositions. Furthermore, this work investigates the influence of carbon fiber content on the trade-off between structural integrity and energy storage efficiency. By optimizing the material composition, it is possible to achieve a balance that satisfies both mechanical and electrochemical requirements [4]. The integration of such multifunctional materials into civil infrastructure has the potential to transform conventional passive structures into active energy-storing systems, supporting applications in smart buildings, self-powered sensors, and intelligent transportation networks. The main contributions of this study

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include: (i) the development of a sustainable geopolymer-based structural supercapacitor, (ii) enhancement of electrical conductivity and energy storage performance through carbon fiber reinforcement, and (iii) demonstration of the feasibility of energy-integrated infrastructure systems. This research provides a foundation for next-generation multifunctional materials that bridge the gap between civil engineering and energy storage technologies.

2- Structural Supercapacitors and Energy Storage Materials:

Structural supercapacitors represent an emerging class of multifunctional materials that simultaneously provide mechanical load-bearing capability and electrochemical energy storage functionality. This dual-purpose approach is gaining significant attention in modern engineering due to its potential to reduce system weight, improve energy efficiency, and enable the development of self-powered infrastructure systems. Unlike conventional energy storage devices, which are typically external to structural components, structural supercapacitors are directly embedded into load-bearing materials, thereby transforming passive structures into active energy storage systems. Supercapacitors, also known as electrochemical capacitors, are characterized by their high power density, rapid charge–discharge capability, and long operational cycle life, making them highly suitable for applications requiring fast energy delivery [5]. However, their energy density is generally lower than that of batteries, which has motivated ongoing research toward enhancing their performance through advanced material design. Early developments in supercapacitor technology primarily relied on polymer-based substrates and carbonaceous materials, including activated carbon, graphene, and carbon nanotubes (CNTs), due to their high surface area and excellent electrical conductivity. Despite their superior electrochemical performance, these materials suffer from limited mechanical strength and structural integrity, restricting their application in load-bearing systems. To address this limitation, recent research has focused on the development of structural supercapacitors, particularly in aerospace and automotive sectors, where weight reduction and multifunctionality are critical. In such systems, reinforcing materials such as carbon fibers are integrated with electrochemically active components to form composites capable of both structural support and energy storage [6]. A comparative overview of different energy storage technologies for structural applications is presented in Table 2, highlighting the advantages of structural supercapacitors in terms of mechanical strength, integration capability, and multifunctional performance.

Table 2: Comparison of Energy Storage Technologies for Structural Applications

Parameter	**Batteries**	**Conventional Supercapacitors**	**Structural Supercapacitors**
Energy Density	High	Moderate	Moderate
Power Density	Low–Moderate	Very High	High
Charge–Discharge Speed	Slow	Very Fast	Fast
Cycle Life	Limited	Very Long	Long

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Mechanical Strength	Very Low	Low	High
Structural Integration	Not Possible	Limited	Fully Integrated
Weight Efficiency	Low	Moderate	High
Application Domains	Electronics, EVs	Electronics	Aerospace, Civil, Automotive

The comparison in Table 2 clearly demonstrates that structural supercapacitors offer a unique balance between electrochemical performance and mechanical functionality. While batteries provide high energy density, they lack structural capability, and conventional supercapacitors, although excellent in power delivery, do not possess sufficient mechanical strength. Structural supercapacitors effectively bridge this gap by integrating both functionalities within a single system, making them highly suitable for advanced engineering applications. A conceptual representation of a structural supercapacitor system is illustrated in Figure 1, which provides insight into its architecture and working mechanism.

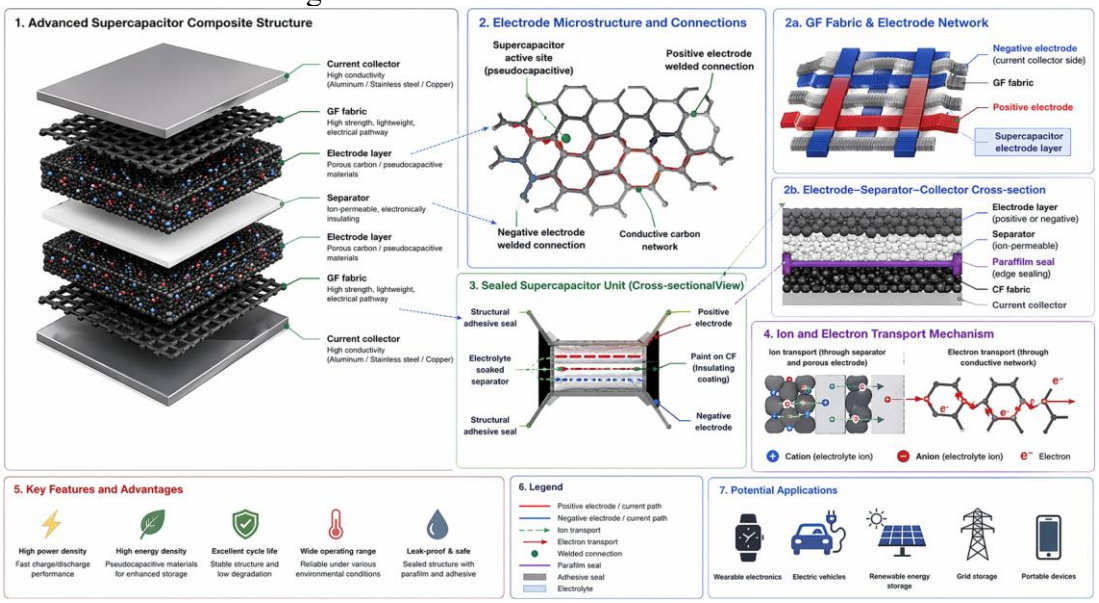


Figure 1: Conceptual Architecture of a Structural Supercapacitor

Structural supercapacitors represent a transformative approach in the field of multifunctional materials by merging structural performance with energy storage capability. Their ability to reduce system weight, enhance efficiency, and enable distributed energy storage makes them highly attractive for applications in aerospace, automotive, and civil infrastructure. However, challenges related to optimizing material composition, improving energy density, and ensuring long-term durability under real-world conditions remain critical areas for further research. These challenges highlight the need for advanced material systems, such as carbon fiber–reinforced geopolymer composites, which can effectively balance mechanical robustness with electrochemical performance for next-generation sustainable infrastructure.

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3- Carbon Fiber Reinforcement in Cement-Based Systems:

Carbon fibers have gained considerable attention as an effective reinforcement material for cementitious composites due to their exceptional mechanical strength, durability, and electrical conductivity. Their high tensile strength and modulus significantly improve the crack resistance and flexural performance of cement-based materials, making them suitable for advanced structural applications. In addition to mechanical benefits, carbon fibers introduce electrical conductivity into otherwise insulating cement matrices, enabling the development of smart and multifunctional materials. Previous studies have demonstrated that carbon fiber–reinforced cement composites exhibit enhanced fracture toughness, reduced microcracking, and improved durability under mechanical and environmental loading conditions [7]. The incorporation of carbon fibers also facilitates the formation of percolated conductive networks within the matrix. These networks enable efficient electron transport, which is essential for applications such as structural health monitoring, electromagnetic shielding, and energy storage systems. As a result, carbon fibers have emerged as a promising reinforcement material for the development of cement-based supercapacitors and energy-integrated infrastructure systems. A comparative analysis of different conductive reinforcement materials used in cementitious composites is presented in Table 3, highlighting the advantages of carbon fibers over alternative materials.

Table 3: Comparison of Conductive Reinforcement Materials in Cement-Based Composites.

Reinforcement Material	Electrical Conductivity	Mechanical Strength	Dispersion Ability	Cost	Suitability for Large-Scale Use
Carbon Fibers	High	Very High	Good	Moderate	High
Carbon Nanotubes (CNTs)	Very High	High	Poor	Very High	Limited
Graphene	Very High	High	Moderate	Very High	Limited
Carbon Black	Moderate	Low	Good	Low	Moderate
Steel Fibers	Moderate	High	Good	Moderate	High

Carbon fibers provide an optimal balance between electrical conductivity, mechanical performance, and scalability. While nanomaterials such as carbon nanotubes and graphene offer superior conductivity, their high cost and dispersion challenges limit their practical application in large-scale civil infrastructure. In contrast, carbon fibers exhibit better compatibility with cementitious matrices and are easier to process, making them more suitable for real-world engineering applications. The effectiveness of carbon fiber reinforcement in cement-based systems is strongly influenced by factors such as fiber content, orientation, length, and distribution, as illustrated in Figure 2.

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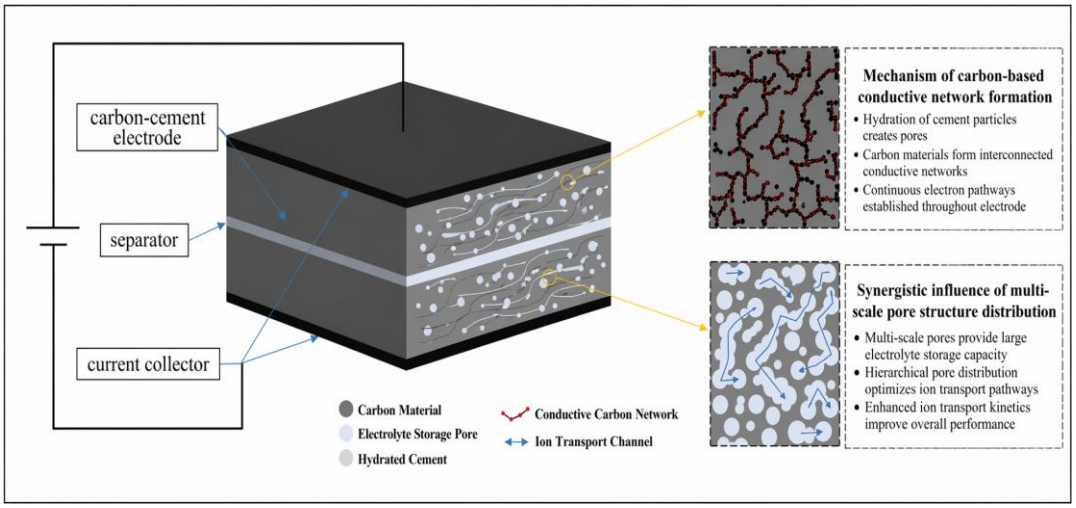


Figure 2: Carbon Fiber Distribution and Conductive Network Formation in Cement Matrix

Randomly distributed carbon fibers form interconnected conductive pathways within the cement matrix once a critical percolation threshold is reached. Below this threshold, the fibers remain isolated, resulting in low conductivity. However, beyond the threshold, a continuous conductive network is established, significantly enhancing electrical performance. At the same time, fiber orientation and distribution influence stress transfer mechanisms, affecting the overall mechanical strength and durability of the composite. Uniform dispersion and optimal fiber alignment are therefore essential to achieve balanced multifunctional performance [8]. Carbon fiber reinforcement provides a highly promising pathway for enhancing both the mechanical and electrical properties of cement-based materials, enabling their use in multifunctional applications such as structural supercapacitors. The ability of carbon fibers to form conductive networks while maintaining structural integrity makes them particularly suitable for large-scale infrastructure systems. However, achieving an optimal balance between mechanical strength and electrochemical performance requires careful control of fiber parameters and material composition. This highlights the importance of further research into carbon fiber–reinforced geopolymer systems for the development of next-generation energy-integrated civil infrastructure.

4- Methodology:

This section outlines the systematic approach adopted for the design, fabrication, and evaluation of the proposed carbon fiber–reinforced geopolymer cement (CFGPC) structural supercapacitor. The methodology integrates material engineering, composite fabrication, and electrochemical analysis to develop a multifunctional system capable of both mechanical load-bearing and energy storage. A combination of experimental procedures and analytical modeling is employed to investigate the influence of material composition and processing conditions on the overall performance of the composite. Key stages include raw material selection, mix design optimization, specimen fabrication, curing, and comprehensive mechanical and electrochemical characterization. The objective is to establish a reliable framework for achieving an

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optimal balance between structural integrity and energy storage efficiency in geopolymer-based composites.

4.1- Materials Selection and Preparation:

The development of the CFGPC composite begins with the careful selection of constituent materials to ensure sustainability, durability, and multifunctional performance. The primary binder consists of geopolymer cement synthesized from industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS). An alkaline activating solution, typically composed of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), is used to initiate the geopolymerization process and form a stable aluminosilicate network. Carbon fibers are incorporated as conductive reinforcement to enhance both mechanical strength and electrical conductivity. Short, randomly distributed fibers are selected due to their ease of dispersion and ability to form conductive pathways within the matrix [9]. Additionally, an electrolyte medium, such as sodium sulfate (Na_2SO_4) or potassium hydroxide (KOH), is introduced to facilitate ionic transport for supercapacitor functionality. Geopolymer matrix forms the structural backbone of the composite, while carbon fibers are uniformly dispersed to create conductive pathways. The electrolyte phase facilitates ionic movement, enabling electrochemical activity within the material. Proper mixing and dispersion are essential to ensure homogeneity and to avoid agglomeration, which can negatively affect both mechanical and electrical properties.

4.2- Mix Design and Composite Fabrication:

The mix design of the carbon fiber–reinforced geopolymer cement (CFGPC) composite is carefully developed to achieve an optimal balance between mechanical strength and electrochemical performance. The primary objective is to establish a composition that ensures adequate structural integrity while enabling efficient electrical conductivity and charge storage. In this study, the carbon fiber content is systematically varied to investigate its influence on both mechanical and electrochemical properties [10]. Typical fiber volume fractions range from 0.5% to 3% by weight of the binder, which is considered sufficient to achieve the percolation threshold required for conductive network formation. The geopolymer binder is formulated using a combination of fly ash and ground granulated blast furnace slag (GGBFS), activated by an alkaline solution consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The ratio of activator to binder, as well as the Na_2SiO_3/NaOH ratio, is carefully controlled to ensure proper geopolymerization and mechanical performance. Carbon fibers are introduced as a reinforcing and conductive phase, and their uniform dispersion within the matrix is critical to achieving consistent composite behavior [11]. A representative mix design used in this study is summarized in Table 4, which outlines the proportions of key components.

Table 4: Representative Mix Design of CFGPC Composite

Component	Proportion (by weight %)	Function
Fly Ash	50–60%	Primary geopolymer precursor

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GGBFS	40–50%	Enhances reactivity and strength
NaOH Solution	8–12%	Activator for geopolymerization
Na_2SiO_3 Solution	20–25%	Improves polymer network formation
Carbon Fibers	0.5–3%	Reinforcement and conductivity
Water (if required)	5–10%	Adjusts workability

The mix proportions are selected to ensure proper workability, uniform fiber dispersion, and optimal geopolymerization. The variation in carbon fiber content allows for the evaluation of its impact on conductivity and mechanical strength, enabling identification of the optimal composition for multifunctional performance [12]. The fabrication process of the CFGPC composite involves a sequence of controlled steps to ensure homogeneity and structural integrity. The overall fabrication procedure is illustrated in Figure 3, which provides a schematic overview of the mixing and casting process.

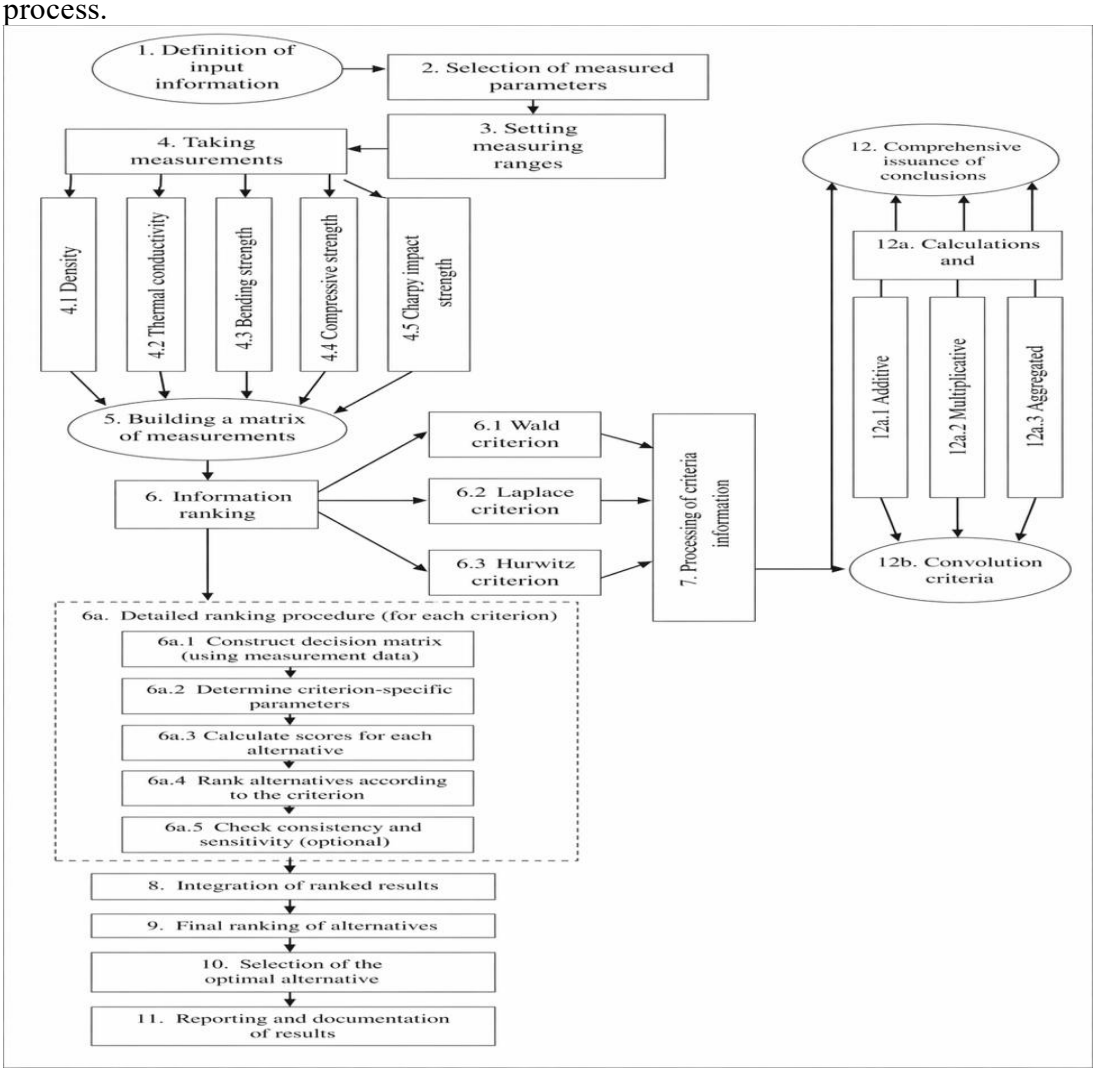


Figure 3: Fabrication Process of Carbon Fiber–Reinforced Geopolymer Composite

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The fabrication process begins with the dry mixing of geopolymer precursors (fly ash and GGBFS) to ensure uniform distribution of the base materials. Carbon fibers are then gradually added using mechanical or manual dispersion techniques to prevent agglomeration and to achieve uniform within the matrix. Following this, the alkaline activator solution is slowly incorporated into the mixture while continuous mixing is maintained to promote proper geopolymerization [13]. Overall, the mix design and fabrication process play a crucial role in determining the final performance of the CFGPC composite. The controlled variation of carbon fiber content, along with optimized mixing and casting procedures, ensures the development of a uniform and high-performance multifunctional material suitable for structural supercapacitor applications.

4.3- Controlled Thermal–Ambient Curing Regime for Enhanced Geopolymerization:

The curing process plays a critical role in determining the mechanical strength, durability, and electrochemical performance of the carbon fiber–reinforced geopolymer cement (CFGPC) composite. Proper curing ensures the completion of geopolymerization reactions, leading to the formation of a stable and dense aluminosilicate network. In this study, a controlled thermal–ambient curing regime is adopted to optimize the microstructure and performance of the composite material. After casting, the specimens are initially subjected to elevated temperature curing to accelerate the geopolymerization process [14]. Typically, samples are cured at temperatures ranging from 60°C to 80°C for a duration of 24 to 48 hours. This thermal curing phase enhances the dissolution of aluminosilicate precursors and promotes rapid polymer network formation. Following this stage, the specimens are allowed to undergo ambient curing at room temperature for an extended period to ensure gradual strength development and structural stabilization [15]. The curing parameters, including temperature, duration, and humidity conditions, are carefully controlled to avoid undesirable effects such as microcracking, shrinkage, and uniform material properties. A summary of the curing conditions employed in this study is presented in Table 5.

Table 5: Curing Conditions for CFGPC Composite.

Curing Stage	Temperature Range	Duration	Purpose
Initial Thermal Cure	60–80°C	24–48 hours	Accelerates geopolymerization
Intermediate Stage	40–50°C (optional)	12–24 hours	Reduces thermal gradients
Ambient Curing	25–30°C	7–28 days	Enhances long-term strength and stability
Humidity Control	60–80% RH	Throughout	Prevents moisture loss and shrinkage

The curing conditions are designed to ensure optimal development of both mechanical and electrochemical properties. The combination of thermal and ambient curing provides a balance between rapid strength gain and long-term durability, which is

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Volume 4, Issue 4 (2026)

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http://amresearchreview.com/index.php/Journal/about

essential for multifunctional structural applications. The overall curing process and its effect on the microstructural development of the composite are illustrated in Figure 4, which presents a schematic representation of the curing stages.

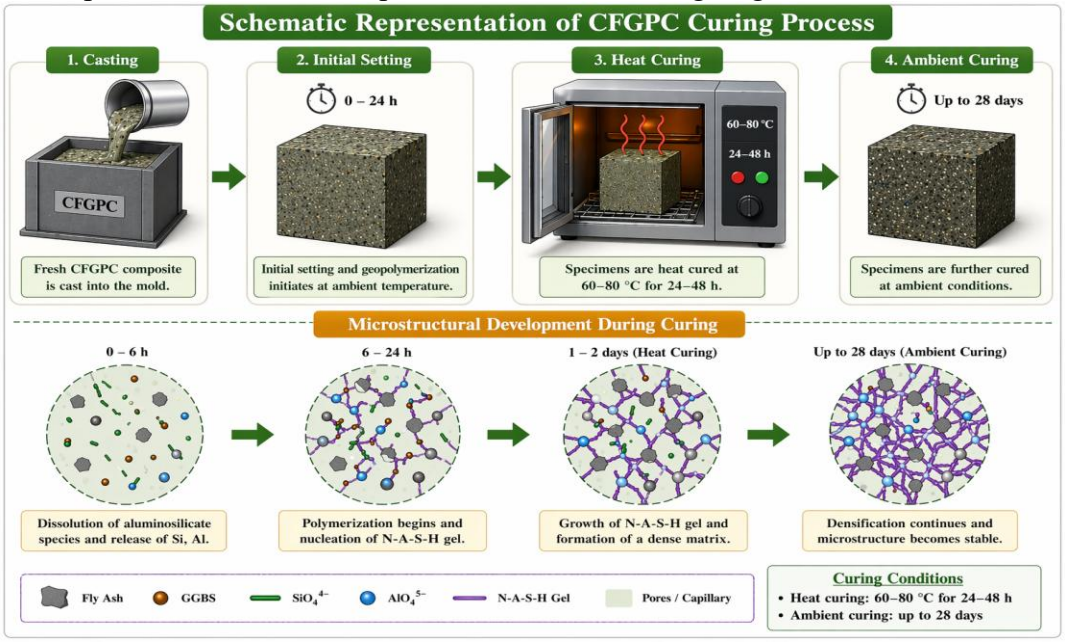


Figure 4: Schematic Representation of CFGPC Curing Process.

The curing process begins with an initial thermal stage that promotes rapid geopolymerization and early strength development. This is followed by a gradual transition to ambient curing, where the composite undergoes further structural refinement and densification. The controlled curing environment minimizes stresses and ensures uniform distribution of carbon fibers within the matrix. Additionally, proper humidity control prevents excessive moisture loss, which could otherwise lead to shrinkage cracks and reduced [16]. Overall, the controlled curing regime significantly influences the final properties of the CFGPC composite. By carefully optimizing temperature and curing duration, it is possible to enhance both the mechanical integrity and electrochemical performance of the material. This optimized curing strategy ensures the development of a stable, durable, and high-performance composite suitable for structural supercapacitor applications in energy-integrated civil infrastructure.

4.4- Structural and Electrochemical Configuration:

To enable supercapacitor functionality within the carbon fiber–reinforced geopolymer cement (CFGPC) composite, the material is engineered as an integrated structural electrode system that simultaneously supports mechanical loads and facilitates electrochemical energy storage. In this configuration, the carbon fiber–reinforced geopolymer matrix serves as the electrode material, while the incorporated electrolyte phase enables efficient ionic transport. This dual-function design transforms conventional construction materials into active storing components, suitable for next-generation smart infrastructure [17]. The structural supercapacitor system is typically

Annual Methodological Archive Research Review
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Volume 4, Issue 4 (2026)

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http://amresearchreview.com/index.php/Journal/about

composed of two conductive electrode layers separated by an ion-permeable separator. The carbon fibers embedded within the geopolymer matrix form a continuous conductive network that allows electron transport, while the electrolyte provides a medium for ion migration during charge–discharge cycles. Depending on the design requirements, the system can be configured as either a solid-state or quasi-solid-state supercapacitor, where the electrolyte is retained within the porous structure of the geopolymer matrix. The components work synergistically to achieve both structural and electrochemical functionality [18]. The integration of these elements within a single composite system eliminates the need for separate energy storage devices, thereby enhancing overall system efficiency and reducing. A schematic representation of the integrated structural supercapacitor configuration is presented in Figure 5, illustrating the layered architecture and charge transport mechanism.

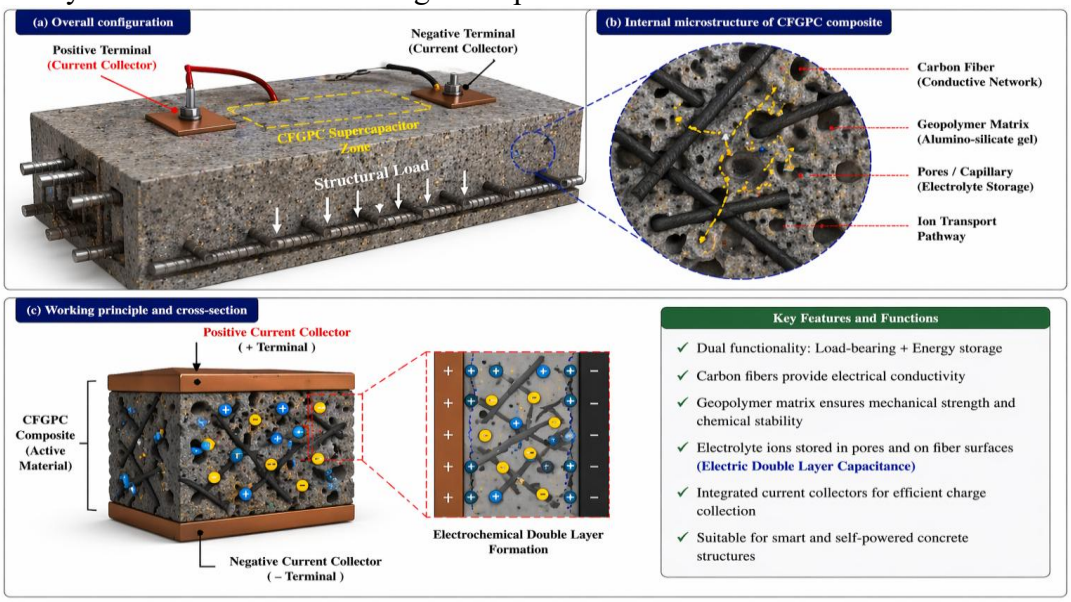


Figure 5: Integrated Structural Supercapacitor Configuration of CFGPC Composite

The CFGPC composite is arranged in a layered configuration consisting of two conductive electrode regions separated by an rich intermediate layer. During operation, electrons flow through the external circuit, while ions migrate through the electrolyte within the composite structure. The carbon fiber network ensures efficient electron conduction, while the geopolymer matrix provides mechanical stability and environmental resistance. The separator layer, when used, prevents electrical short-circuiting while maintaining ionic continuity [19]. The electrochemical behavior of the system is governed by electric double-layer capacitance and, in some cases, pseudocapacitive effects depending on the composition. The porous nature of the geopolymer matrix enhances electrolyte penetration, thereby increasing the effective surface area available for charge storage. Furthermore, the integration of structural and electrochemical functionalities enables distributed energy storage across the entire infrastructure element, improving energy efficiency and system reliability. The integrated structural–electrochemical configuration of the CFGPC composite represents a significant advancement in multifunctional material design. By combining

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http://amresearchreview.com/index.php/Journal/about

load-bearing capability with energy storage functionality, the proposed system offers a highly efficient and space-saving solution for modern infrastructure applications [20]. However, challenges related to interface optimization, electrolyte stability, and long-term performance under mechanical loading conditions remain critical areas for future research. Addressing these challenges will further enhance the feasibility of deploying structural supercapacitors in large-scale civil engineering systems.

4.5- Mechanical Characterization and Structural Performance Evaluation:

The mechanical characterization of the carbon fiber–reinforced geopolymer cement (CFGPC) composite is essential to assess its suitability for load-bearing structural applications. Since the proposed material is intended to function as both a structural component and an energy storage system, it is critical to ensure that the incorporation of carbon fibers and electrochemical functionality does not compromise its mechanical integrity. Therefore, a series of standardized mechanical tests are conducted to evaluate the strength, stiffness, and durability of the developed composite. The primary mechanical properties investigated in this study include compressive strength, flexural strength, and durability characteristics. Compressive strength tests are performed in accordance with standard testing procedures (e.g., ASTM standards) to determine the load-bearing capacity of the composite [21]. Flexural strength tests are conducted to evaluate the material against bending and cracking, which is particularly important for structural applications such as beams and slabs. In addition, durability assessments, including water absorption and resistance to chemical exposure, are carried out to examine the long-term performance of the composite under environmental conditions. A summary of the mechanical testing methods and their corresponding objectives is presented in Table 6.

Table 6: Mechanical Testing Methods and Evaluation Parameters.

Test Type	Standard/Method	Measured Parameter	Purpose
Compressive Strength	ASTM C109 / C39	Compressive strength (MPa)	Evaluate load-bearing capacity
Flexural Strength	ASTM C348	Flexural strength (MPa)	Assess to bending and cracking
Density Measurement	ASTM C642	Bulk density (kg/m³)	Determine material compactness
Water Absorption	ASTM C642	Absorption (%)	Evaluate porosity and durability
Durability Test	Chemical exposure test	Strength retention (%)	Assess long-term environmental stability

The testing methods provide a comprehensive evaluation of the structural performance of the CFGPC composite. These tests are essential to verify that the material maintains sufficient mechanical strength while incorporating conductive reinforcement and electrochemical functionality. The experimental setup and loading conditions for mechanical testing are illustrated in Figure 6, which presents the schematic

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representation of compressive and flexural testing procedures.

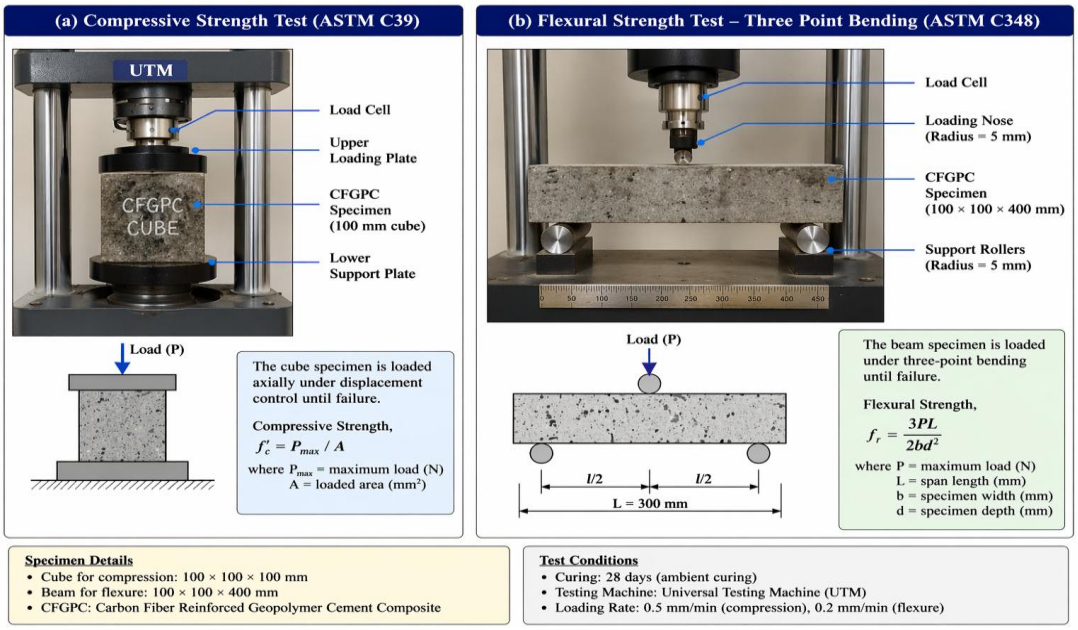


Figure 6: Mechanical Testing Setup for CFGPC Composite

Compressive strength tests are conducted using a universal testing machine (UTM), where the specimen is subjected to axial loading until failure. The maximum load at failure is used to calculate the compressive strength. For flexural testing, a three-point bending setup is employed, where the specimen is loaded at the while supported at both ends. The resulting stress–strain behavior provides insight into the fracture resistance and toughness of the composite. The incorporation of carbon fibers plays a significant role in enhancing the mechanical performance of the CFGPC composite [22]. The fibers act as crack-bridging, preventing the propagation of microcracks and improving the overall toughness of the material. However, excessive fiber content may lead to poor dispersion and reduced workability, which can negatively affect compressive strength. Therefore, an optimal fiber content must be identified to achieve a balance between strength enhancement and material workability. The mechanical characterization of the CFGPC composite demonstrates its capability to maintain adequate structural performance while integrating energy storage functionality [23]. The results obtained from compressive, flexural, and durability tests provide critical insights into the of carbon fiber reinforcement on the mechanical behavior of the composite. This comprehensive evaluation ensures that the proposed material meets the requirements for practical implementation in structural supercapacitor applications within energy-integrated civil infrastructure.

5- Results and Discussion:

The performance of the carbon fiber–reinforced geopolymer cement (CFGPC) composite was evaluated through a comprehensive set of mechanical and electrochemical tests to assess its suitability for multifunctional structural supercapacitor applications. The experimental results reveal that the incorporation of

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carbon fibers significantly influences both structural integrity and energy storage capability, demonstrating the feasibility of integrating these two functionalities within a single composite system. The mechanical behavior of the composite shows a clear dependence on carbon fiber content. At lower concentrations (0.5–1.0%), the addition of carbon fibers enhances crack resistance and flexural performance due to effective crack-bridging mechanisms. This results in improved toughness and resistance to microcrack propagation. However, at higher fiber contents (>2.0%), a slight reduction in compressive strength is observed, which can be attributed to fiber agglomeration and the formation of microvoids within the matrix. Despite this reduction, the composite maintains sufficient strength for structural applications. A quantitative comparison of compressive strength across different fiber contents is presented in Table 7.

Table 7: Effect of Carbon Fiber Content on Mechanical Properties.

Carbon Fiber Content (%)	Compressive Strength (MPa)	Flexural Strength (MPa)
0 (Control Sample)	42.5	5.8
0.5	45.8	6.7
1.0	48.3	7.5
2.0	46.7	7.2
3.0	43.9	6.9

The data in Table 7 indicate that the optimal mechanical performance is achieved at approximately 1.0% carbon fiber content, where both compressive and flexural strengths reach their peak values. This behavior highlights the importance of uniform fiber dispersion and controlled mix design in achieving enhanced structural performance. The variation in mechanical response under loading conditions is further illustrated in Figure 7, which shows the typical stress–strain behavior of the composite for different fiber contents.

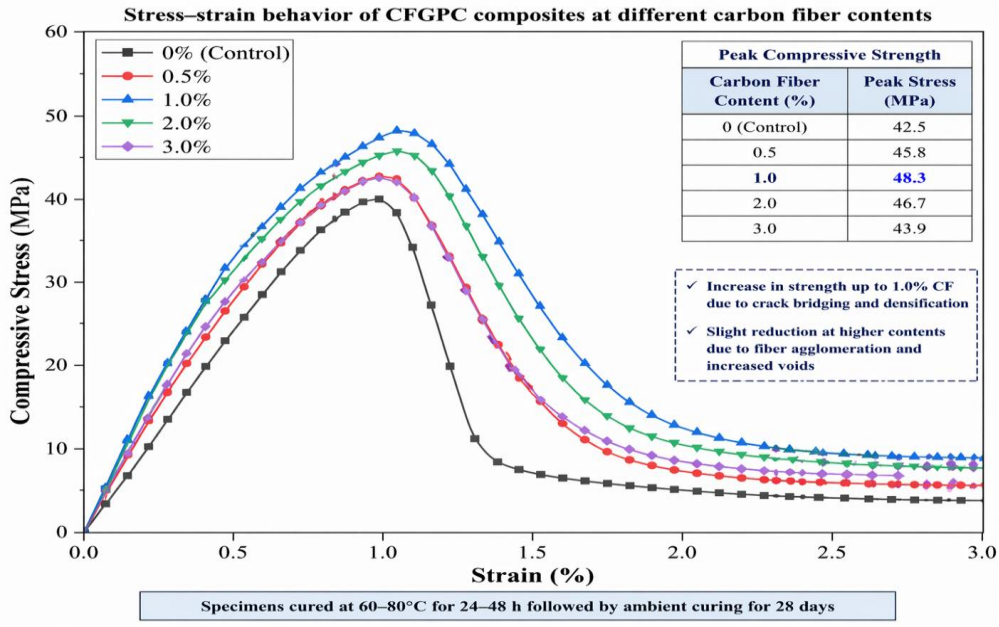


Figure 7: Stress–strain behavior of CFGPC composites at different carbon fiber

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contents.

The CFGPC composite exhibits improved ductility and higher strain capacity with increasing fiber content, indicating enhanced energy absorption capability. The presence of carbon fibers delays crack propagation and contributes to a more gradual failure mechanism compared to brittle behavior observed in conventional geopolymer systems. In addition to mechanical performance, the electrochemical characteristics of the composite demonstrate significant improvement with increasing carbon fiber content [24]. The electrical conductivity of the composite increases sharply once the percolation threshold is reached, typically around 1.0–1.5% fiber content. This results in improved charge transport and enhanced supercapacitor behavior. The electrochemical performance parameters, including specific capacitance, energy density, and power density, are summarized in Table 8.

Table 8: Electrochemical Performance of CFGPC Composite.

Carbon Fiber Content (%)	**Specific Capacitance (F/g)**	**Energy Density (Wh/kg)**	**Power Density (W/kg)**
0.5	12.5	1.8	220
1.0	18.7	2.6	310
2.0	22.4	3.1	360
3.0	23.2	3.3	370

The results presented in Table 8 demonstrate that the electrochemical performance improves with increasing carbon fiber content due to the formation of conductive networks and increased effective surface area for charge storage. However, beyond 2.0% fiber content, the rate of improvement becomes marginal, indicating a saturation effect in conductivity enhancement. The electrochemical behavior of the composite is further illustrated in Figure 8, which presents representative charge–discharge characteristics of the CFGPC supercapacitor system.

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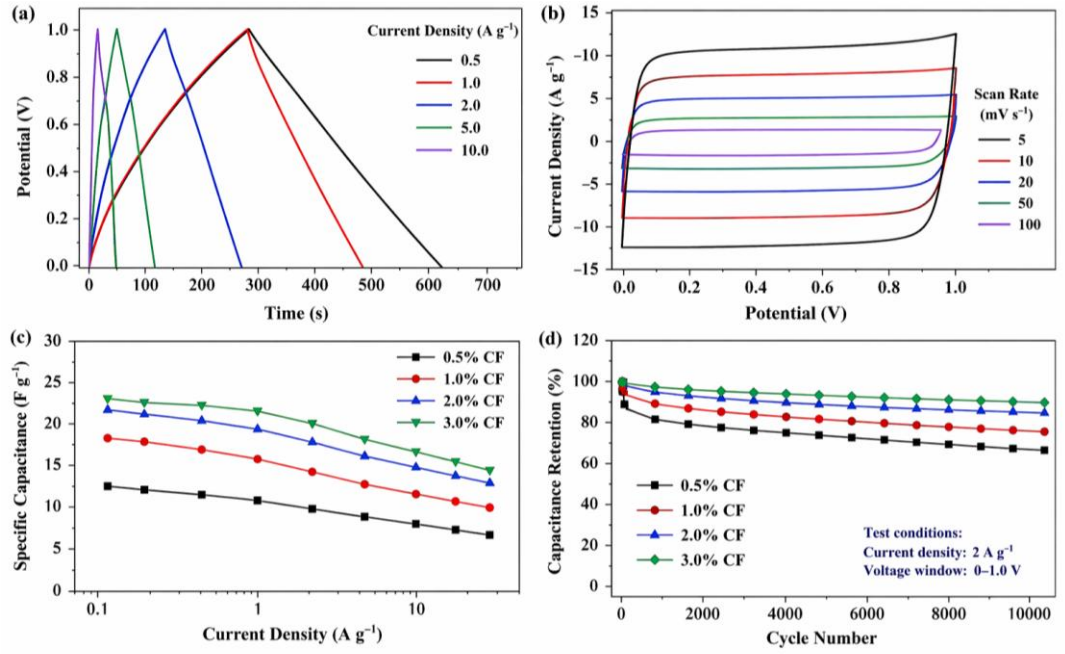


Figure 8: Charge–discharge performance of CFGPC supercapacitor.

The charge–discharge curves exhibit nearly linear and symmetric profiles, indicating good capacitive behavior and high coulombic efficiency. The stable cycling performance and minimal voltage drop further confirm the suitability of the composite for energy storage applications. The cyclic voltammetry characteristics also indicate the dominance of electric double-layer capacitance, with minor contributions from pseudocapacitive effects depending on material composition. A critical observation from the results is the inherent trade-off between mechanical strength and electrochemical performance. While increasing carbon fiber content enhances conductivity and capacitance, it may adversely affect compressive strength due to reduced matrix cohesion and increased porosity. Therefore, an optimal fiber content of approximately 1.5–2.0% is identified as the best compromise for achieving balanced multifunctional performance. Overall, the experimental results confirm that the CFGPC composite successfully integrates structural and energy storage functionalities within a single material system [25]. The combination of improved mechanical strength, enhanced electrical conductivity, and stable electrochemical performance demonstrates its potential for application in smart and energy-integrated civil infrastructure, such as self-powered buildings, intelligent transportation systems, and energy-storing pavements.

6- Future Work:

Although the developed carbon fiber–reinforced geopolymer cement (CFGPC) composite demonstrates promising multifunctional performance, several research directions remain open for further investigation to enhance its practical applicability. Future work should focus on optimizing the material composition through advanced modeling and experimental techniques to achieve a more precise balance between

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mechanical strength and electrochemical efficiency. In particular, the incorporation of nanostructured additives, such as graphene or carbon nanotubes, may significantly improve electrical conductivity and energy density while maintaining structural integrity [26]. In addition, long-term durability studies under realistic environmental conditions, including temperature variations, moisture exposure, and mechanical loading cycles, are essential to evaluate the reliability of the material for real-world infrastructure applications. The development of advanced electrolyte systems, including solid-state and gel-based electrolytes, can further improve the stability, safety, and performance of the structural supercapacitor system. Another important direction involves the integration of the proposed material into large-scale structural elements, such as beams, slabs, and pavements, to assess scalability and practical feasibility. The use of numerical modeling and simulation tools can also provide deeper insights into the coupled mechanical–electrochemical behavior of the system. Furthermore, the integration of smart sensing and monitoring technologies within the composite can enable real-time performance evaluation and predictive maintenance [27]. Future research should aim to bridge the gap between laboratory-scale development and real-world implementation, enabling the deployment of energy-storing construction materials in smart and sustainable infrastructure systems.

Conclusion:

This study presented the design and development of a carbon fiber–reinforced geopolymer cement (CFGPC) composite as a multifunctional structural supercapacitor for energy-integrated civil infrastructure. The proposed material successfully combines mechanical load-bearing capability with electrochemical energy storage, offering a sustainable and efficient alternative to conventional construction materials and external energy storage systems. The experimental results demonstrated that the incorporation of carbon fibers significantly enhances both the mechanical and electrical properties of the geopolymer matrix. Improved crack resistance, flexural strength, and electrical conductivity were observed due to the formation of interconnected conductive networks within the composite. The electrochemical analysis confirmed that the developed material exhibits stable capacitive behavior with promising specific capacitance, energy density, and power density characteristics. A key finding of this study is the identification of an optimal carbon fiber content range of approximately 1.5–2.0%, which provides a balanced trade-off between structural integrity and electrochemical performance. While higher fiber content improves conductivity and energy storage capability, excessive amounts may reduce compressive strength due to agglomeration and increased porosity. Therefore, careful optimization of material composition is essential for achieving reliable multifunctional performance. The integration of structural and energy storage functionalities within a single material system represents a significant advancement in the field of smart and sustainable infrastructure. The proposed CFGPC composite has the potential to enable the development of self-powered buildings, intelligent transportation systems, and energy-storing construction elements.

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