CONCRETE BATTERIES FOR ENERGY STORAGE: MECHANISMS, POTENTIALITY, AND PROSPECTS FOR NANO-GRAPHENE INTEGRATION

Pin bê tông lưu trữ năng lượng: Cơ chế, tiềm năng và triển vọng tích hợp nano-graphene

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Tóm tắt: Pin bê tông đang là một hướng tiếp cận mới trong phát triển vật liệu xây dựng đa chức năng, cho phép tích hợp khả năng lưu trữ năng lượng trực tiếp vào các cấu kiện công trình. Nghiên cứu này tổng hợp và phân tích nguyên lý hoạt động của hệ pin bê tông dựa trên sự kết hợp giữa cơ chế điện hóa và tích điện bề mặt, đồng thời làm rõ vai trò của các yếu tố vật liệu và cấu trúc đến hiệu suất lưu trữ. Kết quả cho thấy việc sử dụng các vật liệu dẫn điện có thể cải thiện đáng kể tính dẫn điện của bê tông, đồng thời nâng cao khả năng tích trữ năng lượng ở mức phù hợp cho các ứng dụng phân tán. Trong đó, graphene thể hiện ưu thế nhờ khả năng hình thành mạng dẫn điện hiệu quả với hàm lượng thấp và góp phần cải thiện đặc tính cơ học của vật liệu. Ngoài ra, nghiên cứu cũng thảo luận khả năng ứng dụng trong hạ tầng đô thị và những thách thức cần giải quyết để triển khai thực tế.

Từ khóa: Pin bê tông; Lưu trữ năng lượng; Bê tông dẫn điện; Nano graphene; Hạ tầng đô thị thông minh

Abstract: Concrete batteries have recently emerged as a promising approach in the development of multifunctional construction materials, enabling energy storage to be integrated directly into structural components. This study reviews and analyzes the working principles of concrete-based energy storage systems, which combine electrochemical reactions with surface charge storage mechanisms. It also highlights the influence of material composition and microstructural characteristics on overall performance. The findings indicate that incorporating conductive materials can significantly enhance the electrical properties of concrete and improve its energy storage capability for distributed applications. Among these materials, graphene demonstrates notable advantages due to its ability to form efficient conductive networks at low dosage while also contributing to improved mechanical performance. In addition, the study discusses potential applications in smart urban infrastructure and outlines key challenges that must be addressed for practical implementation.

Key words: Concrete battery; Energy storage; Conductive concrete; Nano graphene; Smart infrastructure.

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1. INTRODUCTION

The increasing pressure on urban energy systems, together with the widespread adoption of renewable energy technologies such as solar and wind power, has intensified the demand for alternative energy storage approaches [1]. Conventional storage technologies, particularly lithium-ion batteries, provide relatively high energy density; however, their application is still constrained by high production costs, safety concerns, limited durability, and difficulties associated with integration into building structures.

As a result, recent studies have focused on multifunctional construction materials capable of performing both structural and non-structural functions. Among these approaches, conductive concrete has attracted attention due to its potential to combine load-bearing performance with sensing, self-repair, and energy storage capabilities [2]. In this context, the concept of a "concrete battery" has emerged as a novel strategy for embedding energy storage functions directly into structural components, including walls, slabs, foundations, and transportation infrastructure [3], [4].

Previous research has shown that the incorporation of conductive fillers such as carbon black, carbon fibers, and graphene can significantly improve the electrical behavior of concrete and enable energy storage functionality [5], [6]. This development creates opportunities for distributed energy storage systems embedded within urban infrastructure.

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Potential applications include low-power urban systems such as smart lighting, traffic monitoring sensors, IoT networks, and structural health monitoring devices. By integrating storage capability into construction materials, concrete batteries may reduce dependence on external power supplies while improving the autonomy and sustainability of urban infrastructure systems.

For developing cities facing increasing energy demand and sustainability challenges, concrete batteries could support the development of integrated urban energy networks. When combined with renewable energy systems, this technology may contribute to future smart infrastructure in which buildings function not only as energy consumers but also as energy storage and distribution components (Figure 1).

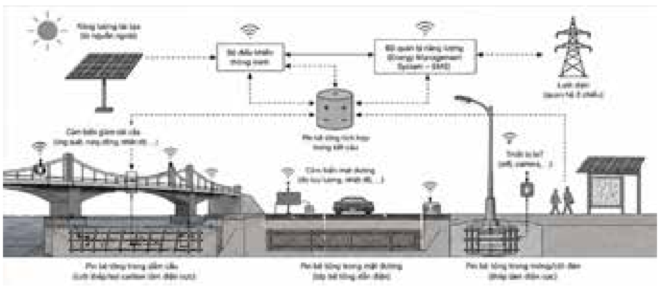

Figure 1. Concrete battery-based energy system for smart infrastructure

Despite the promising potential of concrete batteries, several challenges remain before this technology can be widely implemented in real construction applications. Key issues include storage efficiency, long-term durability, material cost, and the development of appropriate design standards. In this context, the incorporation of advanced nanomaterials, particularly graphene, has attracted growing attention due to its potential to enhance the electrical performance and overall functionality of cement-based energy storage systems. This approach may provide a new pathway for the development of construction materials capable of simultaneously serving structural and energy-related functions [7], [8].

2. RESEARCH METHODOLOGY

The study was conducted using a document-based review approach to investigate previous studies related to concrete batteries and electrically conductive cementitious materials. Scientific publications from recent years in the areas of construction materials, nanotechnology, and energy storage were collected and analyzed. Through comparative evaluation of these studies, the research identified major parameters affecting the storage capability of concrete-based systems, including conductive materials, internal microstructure, and mixture composition. Based on the analyzed findings, the study further discusses the potential application of graphene nanomaterials for enhancing the performance of concrete energy storage systems.

3. WORKING PRINCIPLES OF CONCRETE BATTERIES

3.1. Energy Storage Mechanism

Concrete batteries can be considered a hybrid material system in which energy storage capability is incorporated directly into structural components (Figure 2). Unlike conventional battery systems that rely on separated electrolytes, concrete-based systems utilize the pore solution within the cement matrix as an ion transport medium, while conductive phases dispersed throughout the material facilitate electron transfer [9].

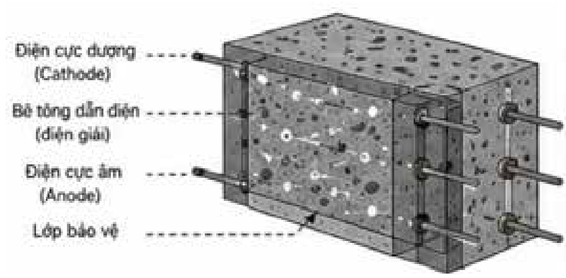

Figure 2. Schematic configuration of a concrete battery system

When the system operates, the potential difference between the two electrodes drives electron flow through the external circuit, while ions within the pore solution migrate to maintain charge balance. Depending on the material configuration, energy may be stored through electrochemical reactions or surface charge accumulation. In general, energy storage in concrete batteries can occur through two primary mechanisms.

The first mechanism is electrochemical storage ("battery-type storage"), in which oxidation–reduction reactions take place at the electrode surfaces. During operation, electron transport occurs through the conductive network, while ionic movement within the cement pore solution maintains electrical neutrality. This mechanism enables the storage and release of energy through reversible electrochemical processes.

The second mechanism is "capacitive storage", which is commonly associated with super-capacitor systems. In this case, energy is stored in the form of electrical charges accumulated on the surface of conductive materials. Owing to the large specific surface area of carbon-based materials, particularly graphene (Figure 3), this mechanism provides rapid charge–discharge capability and high cycling stability, making it suitable for applications in smart urban infrastructure [10].

In practice, many concrete battery systems operate through a hybrid mechanism that combines both electrochemical and capacitive storage in order to improve overall performance.

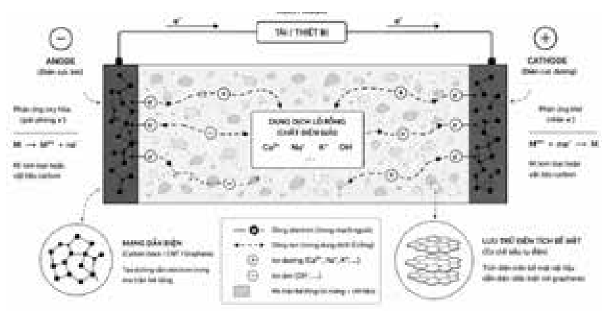

Figure 3. Energy storage mechanism of a concrete battery

3.2. Structural Components and Material Functions

A typical concrete battery system consists of several main components, as illustrated in Figure 4:

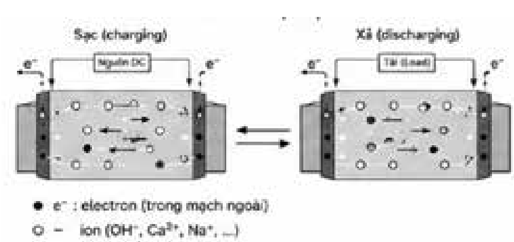

Figure 4. Working principle of a concrete battery system

- Concrete matrix: consisting of cement, water, and aggregates, which provides both structural support and an electrolyte medium through the pore solution containing ions such as Ca^{2+}, OH^-, and Na^+.

- Conductive materials: including carbon black, carbon fibers, carbon nanotubes (CNTs), and graphene, which are responsible for forming conductive pathways for electron transport within the material.

- Electrodes: typically made of metals such as zinc, aluminum, or steel, or carbon-based materials, where electrochemical reactions occur.

- External circuit: enabling electron flow between the two electrodes (Figure 4).

The performance of the system strongly depends on the formation of a continuous conductive network, commonly referred to as a "percolation network," within the concrete matrix [2]. Once the conductive material content reaches a critical threshold, conductive particles become interconnected, creating pathways for electron transport and significantly improving the electrical conductivity of the material [11], [12].

4. RESULTS AND DISCUSSION

4.1. Factors Affecting Performance

A review of recent studies indicates that the performance of concrete batteries is primarily governed by the electrical conductivity and energy density of the material system, in which the type and dosage of conductive additives play a critical role [3], [13]. Representative experimental results are summarized in Table 1.

The results presented in Table 1 demonstrate significant differences in performance among conductive materials, particularly between conventional carbon-based materials and nanomaterials. Specifically, the electrical conductivity of concrete can increase from approximately 10^{-6} S/m to 10^3 S/m, representing an improvement of nearly nine orders of magnitude when advanced conductive materials are incorporated. At the same time, energy density can increase from nearly zero to approximately 2–10 Wh/m^3 in systems containing graphene-based nanomaterials.

Notably, conventional conductive fillers such as carbon black generally require relatively high dosages (5–10%) to achieve the percolation threshold [13], whereas graphene-based materials may achieve comparable conductive performance at much lower contents of approximately 0.05–0.5% [6], [16]. These findings suggest that graphene not only improves the energy storage capability of concrete batteries but may also contribute to enhanced mechanical performance of cementitious materials [18].

Table 1. Comparison of conductive materials, performance, and mixture compositions used in concrete batteries

Conductive Material	Electrical Conductivity (S/m)	Energy Density (Wh/m³)	Mixture Composition (% by cement weight)	Characteristics	Research Source
Carbon black	$10^{-3} – 10^{-1}$	0,1 – 1	5 – 10%	Low cost, but requires high dosage to achieve percolation	[13], [14]
Carbon fibers	$10^{-2} – 1$	0,5 – 2	0,5 – 2%	Improves both mechanical properties and electrical conductivity	[15]
Carbon nanotube	$10^{0} – 10^{2}$	1 – 5	0,1 – 1%	High performance, but associated with relatively high cost	[2]
Graphene	$10^{1} – 10^{3}$	2 – 10	0,05 – 0,5%	Excellent electrical conductivity and effective at low dosage	[16]
Conventional concrete	$10^{-6} – 10^{-9}$	≈ 0	0%	No energy storage capability	[9]

These findings indicate that optimizing conductive materials, particularly graphene-based nanomaterials, represents an effective approach for improving the performance of concrete batteries. In addition, recent application-oriented studies have demonstrated the practical potential of implementing such materials in real construction systems [17].

4.2. Discussion on the Potential Application of Graphene in Concrete Batteries

Based on the performance analysis presented in Section 4.1, it can be observed that improving the efficiency of concrete batteries depends not only on increasing the amount of conductive additives but also on the formation and connectivity of conductive networks within the cement matrix. Owing to its nanoscale sheet-like structure, graphene enables the development of highly efficient conductive pathways with extensive contact areas between material phases [6]. This characteristic enhances electron transport while simultaneously facilitating surface charge accumulation, thereby improving the overall energy storage performance of the system.

Experimental studies have further shown that graphene incorporation not only improves the electrical properties of cement-based materials [19] but may also enhance mechanical durability by limiting microcrack propagation within the cement matrix [18]. This provides a significant advantage over conventional conductive materials, which often reduce compressive strength when used at high contents.

Nevertheless, several challenges remain for the practical application of graphene in concrete batteries, particularly regarding material dispersion within the cementitious environment and the relatively high material cost. Consequently, current research efforts mainly focus on improving dispersion techniques and combining graphene with other conductive materials to achieve better performance and economic feasibility [18], [19].

From a broader perspective, the incorporation of graphene-based nanomaterials not only improves the mechanical properties of cementitious materials but also contributes to the optimization of conductive pathways within the concrete matrix. This creates significant potential for the development of high-performance concrete battery systems. Such an approach suggests a shift in concrete battery design strategies, moving from simply increasing the amount of conductive additives toward optimizing the microstructural organization of the material system.

5. CONCLUSIONS

Concrete batteries represent an emerging research direction in the field of multifunctional construction materials, with the capability of integrating energy storage functions directly into structural components. Based on the analysis of operating mechanisms and performance-related factors, it can be observed that the electrical conductivity and energy storage capacity of the system are strongly dependent on the type and structural characteristics of the conductive materials employed [3].

The reviewed studies indicate that conventional carbon-based materials such as carbon black offer advantages in terms of cost but are limited by the high dosage required to achieve conductive performance, which may negatively affect mechanical properties. In contrast, graphene-based nanomaterials have demonstrated significant potential due to their ability to establish efficient conductive networks at relatively low contents while simultaneously improving the microstructure and durability of concrete. This enables enhanced energy storage performance without compromising structural requirements [14], [18].

Nevertheless, the application of graphene in concrete batteries still faces several challenges, particularly regarding material cost and dispersion techniques within cementitious environments. Therefore, current research trends focus on combining graphene with conventional conductive materials to improve both performance and practical feasibility. In recent years, graphene-based nanomaterials have also been produced in Vietnam from recycled resources [20], [21], providing more competitive production costs compared with conventional manufacturing methods and creating opportunities for future applications in concrete battery systems.

In the future, concrete batteries may find potential applications in small-scale distributed energy systems, especially within smart urban infrastructure such as sensors, public lighting, and structural health monitoring systems. Further studies on mixture optimization, material technology, and design standards will play a critical role in advancing this technology from laboratory-scale research toward practical implementation [5], [22]. With the support of graphene-based nanomaterials, concrete batteries may contribute to redefining the role of construction materials in urban energy systems, transforming them from passive energy consumers into active energy storage and distribution components.

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