Development of Rechargeable Cement-based Batteries with Carbon Fiber Mesh for Energy Storage Solutions

Liqiang Yin[ab], Shihui Liu[a*], Dandan Yin[a], Kang Du[a], Jing Yan[a], Catherine K. Armwood-Gordon [a], Lin Li[a]

ABSTRACT

This paper presents the development of novel rechargeable cement-based batteries with carbon fiber mesh for energy storage applications. With the increasing demand for sustainable energy storage solutions, there is a growing interest in exploring unconventional materials and technologies. The batteries featured the carbon fiber mesh, which coated with nickel oxide and iron materials as electrodes and immersed in a cement-based electrolyte, offering a unique approach to energy storage. Experimental investigations, including electrochemical impedance spectroscopy, cyclic voltammetry, charge-discharge cycling, and rate performance assessments, were conducted to evaluate the batteries' performance. Results indicated that the batteries have promising features such as high ionic conductivity of the cement-based electrolyte and stable charge-discharge behaviors over 100 cycles. Cyclic voltammetry curves demonstrated quasi-reversible redox peaks, indicative of battery-type electrochemistry. The rechargeable cement-based batteries exhibited stability in discharge capacity, efficiency, and energy density, surpassing existing literatures on cement batteries, with a maximum energy density of 7.6 Wh/m^2. Despite challenges related to efficiency and energy density, this paper envisions the practical applications for the batteries, from powering light sensors to supporting 5G base stations and meeting daily electricity needs. Integration of rechargeable cement-based batteries and clean energy sources holds significant promise for global energy storage solutions. In conclusion, this research provides valuable insights into developing rechargeable cement-based batteries, highlights their potential as sustainable energy storage solutions with opportunities for further optimization and future advancements.

Keywords: rechargeable cement-based batteries; carbon fiber mesh; cement electrolyte; sustainable energy storage

1. Introduction

The global transition towards sustainable energy practices necessitates innovative solutions to address challenges associated with the intermittency of clean energy sources [1],[2]. As solar and wind energy become integral components of the energy mix, the need for efficient energy storage systems grows [3]-[6]. Battery technology, particularly solid-state batteries, plays a pivotal role in

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ensuring grid stability, facilitating renewable energy integration, and advancing transportation [7]-[10]. Among various materials explored for solid-state batteries, cement-based materials emerge as promising candidates due to its inherent alkaline and porous characteristics [11]-[16].

Cement, as the world's most widely used building material, possesses an alkaline and porous internal structure, making it an ideal candidate for integration into energy storage systems. The synergy between cement and energy storage introduces the concept of rechargeable solid-state cement-based batteries. These batteries not only function as energy storage units but also serve as structural components in buildings and infrastructures, aligning with the emerging paradigm of "Smart Concrete Structures" contributing to energy efficiency [17][18].

Pioneering study by Burstein and Speckert [19] explored the use of setting concrete as a unique electrolyte and aluminum and zinc as anodes. Functioning as an alkaline aluminum/water cell, their battery system showed versatility by operating efficiently at a low current density. Meng and Chung's [20] study established the feasibility of a cement-based battery using cement pore solution as electrolyte, with zinc as anode and manganese dioxide as cathode. Their innovative monolithic slab-shaped batteries demonstrated superior current capability and power density compared to prior technologies. While achieving an open-circuit voltage of 0.72 V and a current density of 3.8 A/cm^2, their performance falls short of commercial alkaline batteries. The research underscored the complex interplay of resistivity, electronic and ionic contacts, indicated the prevalence of ionic conduction in cement-based electrolytes, and highlighted the achievements and challenges in advancing this battery technology. Byrne et al. [21] optimized cement-based batteries for sustainable electricity generation. Their study explored various electrolyte formulations by emphasizing crucial parameters like water/cement ratio, anode-to-cathode surface area, and additives. Magnesium anode and copper cathode prove most effective, delivering an open-circuit voltage of 1.55 V, peak current over 4 mA, 4 days' sustained of 1 mA, and a quasi-steady current of 0.59 mA with an impressive 21-day lifespan. This research marked a substantial advance in cement-based battery design, by focusing on higher electrical outputs and extended lifespans, and promising avenues like photovoltaic recharging. Chen et al.'s [22] exploration of geopolymer-based batteries presented a promising alternative with rapid ionic conduction. Magotra et al. [23] introduced an innovative concept of white cement brick fuel cells by utilizing rice husk ash, and offering an eco-friendly solution for power generation.

Zhang and Tang [24] presented a breakthrough in sustainable energy storage through their rechargeable cement-based battery. They utilized Fe and Zn as anodes, Ni oxides as cathodes, and enhanced the conductivity of cement with short carbon fiber (CF). Comparative tests highlighted Ni–Fe's superior performance, especially with metal coatings, which reduced the electronic resistivity and improved the rechargeability. Despite Zn's unsuitability as a concrete battery anode, the initial battery shows a viable energy density of 7 Wh/m^2 or 0.8 Wh/L. This indicated the potential for large-scale implementation in buildings by emphasizing the ongoing prospects for advancements in rechargeable cement-based batteries within the construction sector. Diversified studies, including those by Arjun et al. [25] , Hire et al. [26] , Holmes et al. [27], Byrne et al. [28], and Nadzri et al. [29] , contributed to the continuous development of cement-based batteries by emphasizing their multifunctional applications ranging from sustainable power generation to cathodic protection.

The nickel-iron (Ni-Fe) battery, a century-old technology, is experiencing a resurgence due to its robustness and longevity. Its performance makes it suitable for niche applications like off-grid energy storage [30],[31]. The integration of carbon fiber as crucial electrode material further enhanced the properties of various batteries, positioning them as promising alternatives in the realm of energy storage [32],[33].

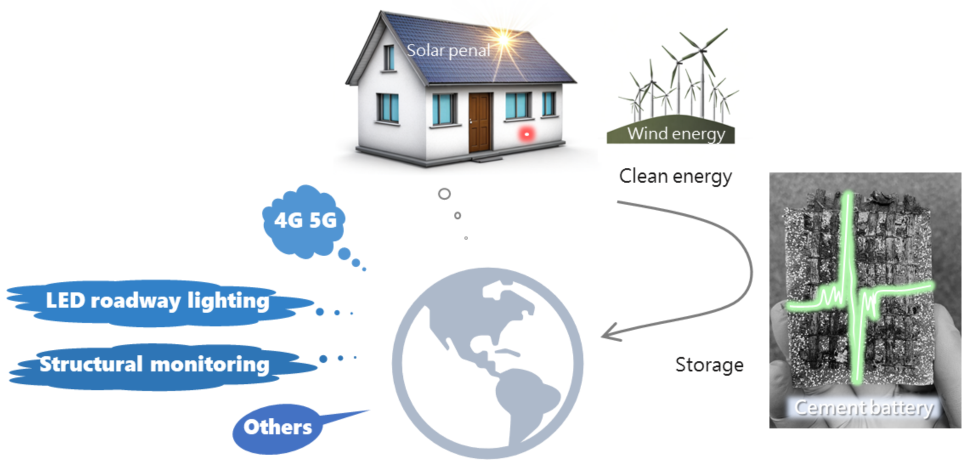

Fig. 1. Idea for developing cement battery to address energy storage challenges.

As illustrated in Fig. 1, the concept of developing rechargeable cement-based batteries to address energy storage challenges is introduced in this paper. Within this framework, the paper delves into the development of rechargeable cement-based batteries with nickel-iron electroplated carbon fiber mesh, by combining the principles of traditional Ni-Fe batteries with the advantages of carbon fiber and cement electrolytes. The synergy of these materials aims to tackle existing challenges and unlock new possibilities, thus contributing to the envisioned future of sustainable energy globally.

2. Materials and Method

2.1 Materials

This study utilizes a carbon fiber mesh as the electrode substrate, featuring a grid space size of 5mm×5mm. The longitudinal fiber bundles consist of 12K filaments (with each fiber bundle comprising 12,000 filaments), while the vertical weft fiber bundles are 6K. The thickness direction of the mesh cloth is maintained at less than 1mm. The electrodepositing solution for nickel oxide coating comprises 250g/L $NiSO_4 \cdot 7H_2O$, 20g/L $NiCl_2 \cdot 6H_2O$, 25g/L H_3BO_3, and water. For iron oxide coating, the solution consists of 180g/L $FeSO_4 \cdot 7H_2O$ and water. The electrodeposition process was conducted with a current of 1.0 A over a duration of 6 hours. The negative carbon fiber mesh carries 5.4g of iron oxide active material. The positive carbon fiber mesh is loaded with 6.2g of nickel oxide active material. The cement-based electrolyte is a mixture of cement, fine sand, ion exchange resin, and alkali solution, with the detailed proportions shown in Table 1. Specifically, the cement used in this paper is type I/II Portland cement commercially from Quikrete in the United States. The fine sand employed is Ottawa silica sand with a D50 of 0.46 mm, sourced from AGSCO Corporation in the United States. The ion exchange resin used is Amberlyst™ A-21. Additionally, the mixing ratio of the alkaline solution is specified in Table 2.

Table 1 Cement-based electrolyte composition and mass mixing ratio.

Cement	Fine sand	Ion exchange resin	Alkaline solution
1.0	0.5	0.3	0.6

Table 2 Alkaline solution composition and mass mixing ratio.

KOH	$LiOH \cdot H_2O$	Deionized water
0.2	0.02	0.78

2.2 Battery Preparation Method

2.2.1 Design of Rechargeable Cement-based Batteries

Drawing inspiration from the operational principles of nickel-iron batteries [34] and leveraging the inherent alkaline characteristics and porous internal structure of cement concrete, this article introduces and outlines the design of a novel rechargeable cement-based battery model with carbon fiber mesh, as illustrated in Fig. 2. The battery model features two layers of carbon fiber mesh, with the positive electrode mesh hosting nickel oxide as the active material, the negative electrode composed of iron, and the electrolyte comprising hardened cement slurry infused with additives facilitating ion exchange.

During the discharging process, the oxide on the positive electrode undergoes reduction to form nickel hydroxide or nickel oxide, while iron on the negative electrode dissolves in the electrolyte, producing Fe^{2+} ions. This electrochemical reaction motivates the generation of batteries' electrical energy. Conversely, during the charging process, the positive electrode experiences oxidation of nickel hydroxide or nickel oxide into oxide, and the iron ions in the negative electrode are reduced to iron, which facilitates the storage of electrical energy. The combined action of charging and discharging process makes the cement-based batteries with electroplated carbon fiber mesh rechargeable.

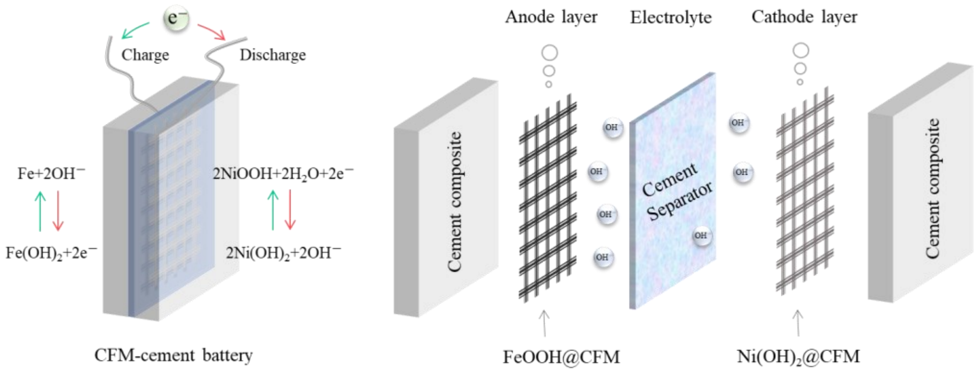

Fig. 2. Details of the rechargeable cement-based battery model with electroplated carbon fiber mesh.

2.2.2 Battery Preparation

As illustrated in Fig. 3, the schematic diagram delineates the preparation process of the rechargeable cement-based battery with carbon fiber mesh. Initially, the surface of carbon fiber mesh was treated to remove bearing oil stains from production to ensure its purity. Subsequently, the carbon fiber mesh was immersed in nickel-based and iron-based solution separately to undergo electrodeposition treatment to yield metal-plated carbon fiber mesh for positive and negative electrodes. Simultaneously, meticulous material weighing took place, the alkali solution was prepared, and the cement-based electrolyte slurry was meticulously mixed. Ultimately, the positive and negative electrodes of the metal-coated carbon fiber mesh were arranged in layers and embedded within the cement-based slurry to create a cement battery. The spacing between the positive and negative electrode meshes was precisely controlled at a thickness of 2.0 ± 0.5mm.

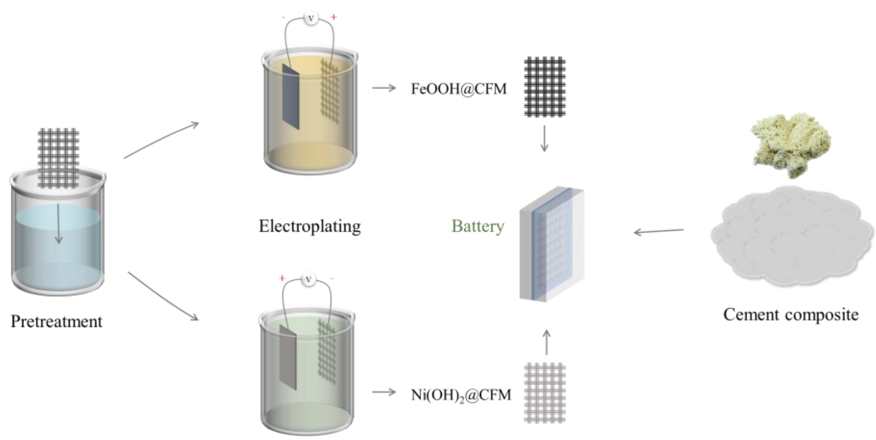

Fig. 3. Preparation process of carbon fiber mesh-cement battery.

2.3 Battery Testing Methods

2.3.1 Electrochemical Test

The electrochemical impedance spectrum of the cement-based electrolyte material was assessed using the SP-150 electrochemical workstation from BioLogic. The scanning frequency ranged from 1 mHz to 1 MHz, and the current amplitude was set at 100 microamps. The schematic diagram of sample for ion conductivity test is depicted in Fig. 4, where stainless steel sheets function as blocking electrodes at both ends, serving as the counter electrode and working as electrode in the two-electrode system. The ionic conductivity of the cement-based electrolyte is determined by Formula (1) [35]:

$$\sigma = d/(s \times R_b) \quad (1)$$

where, σ represents the ionic conductivity, d is the thickness of the cement-based electrolyte, s denotes the contact area between the cement-based electrolyte and the blocking electrode, and R_b signifies the bulk resistance of the cement-based electrolyte, which is ascertained through the results of the electrochemical impedance spectroscopy (EIS) test.

Furthermore, this equipment was employed to conduct the positive and negative cyclic voltammetry (CV) curves for the batteries. The scanning frequency for these curves ranged from 0.5 mV/s to 8 mV/s.

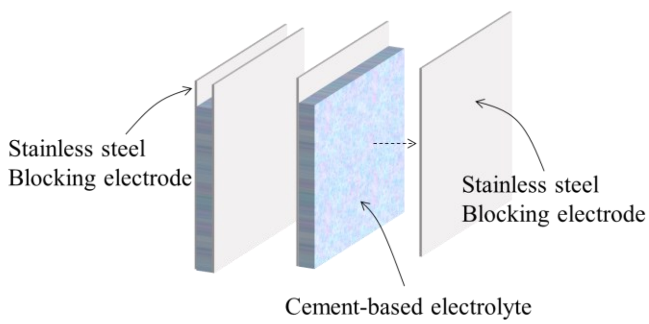

Fig. 4. Overview of battery sample for electrolyte ion conductivity test.

2.3.2 SEM-EDS Analysis

Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analyses of the positive and negative electrodes were conducted at the Vanderbilt Institute of Nanoscale Science and Engineering, utilizing the Oxford X-max 50 SDD EDS system for testing.

2.3.3 Charge and Discharge Test

The charge and discharge tests for the rechargeable cement-based batteries were conducted using the 8 Channel Battery Analyzer (0.02 -10 mA, up to 5 V) from MTI Corporation. Fig. 5 illustrates both the experimental setup and an overview of battery samples. The Galvanostatic charge/discharge control method was applied, where 6 or 8 hours' charging with a 10mA constant current was involved and discharging with a 3mA constant current was followed. The discharge cut-off voltage was set as 0.5 V. The average charging and discharging cycle extended for approximately 10 hours. Throughout the charge and discharge tests, the cement-based batteries maintained a saturated state.

Fig. 5. Details of battery samples and overview of charge and discharge experiments.

3. Results and Analysis

3.1 Electrochemical Impedance Spectroscopy of Cement-based Electrolyte

Fig. 6(a) is the electrochemical impedance spectrum (EIS) of the cement-based electrolyte sample shown in Fig. 4 which was tested by the two-electrode method at the 21-day curing age. The body resistance of cement-based electrolyte is around 50 ohms. The ionic conductivity of the hardened cement-based electrolyte can be calculated from formula (1), which is approximately 3.7×10^{-3} S/cm. Compared with the oxide solid electrolyte 10^{-6}~10^{-3} S/cm, the sulfide solid electrolyte 10^{-7}~10^{-2} S/cm and the polymer solid electrolyte 10^{-7}~10^{-5} S/cm [36]-[39], the cement-base electrolytes prepared in this study have relatively good ionic conductivity.

3.2 Microscopic Analysis of Carbon Fiber Mesh Electrodes

As shown in Fig. 6(b)-(c), they are the microscopic analysis results of metal-coated carbon fiber mesh electrodes, including SEM and EDS. Fig. 6(b) reveals nickel's uniform adhesion to the carbon fiber surface, indicating high coating quality; EDS data confirms carbon as the base material, with nickel and oxygen constituting the coating, and nickel oxide acts as the positive electrode activity Material. In Fig. 6(c), iron is also evenly distributed on the carbon fiber surface. Compared to nickel, the iron coating appears rougher yet thicker. EDS analysis identifies carbon as the electrode base material, with the coating composed of iron and oxygen, iron oxide acts as the negative active material.

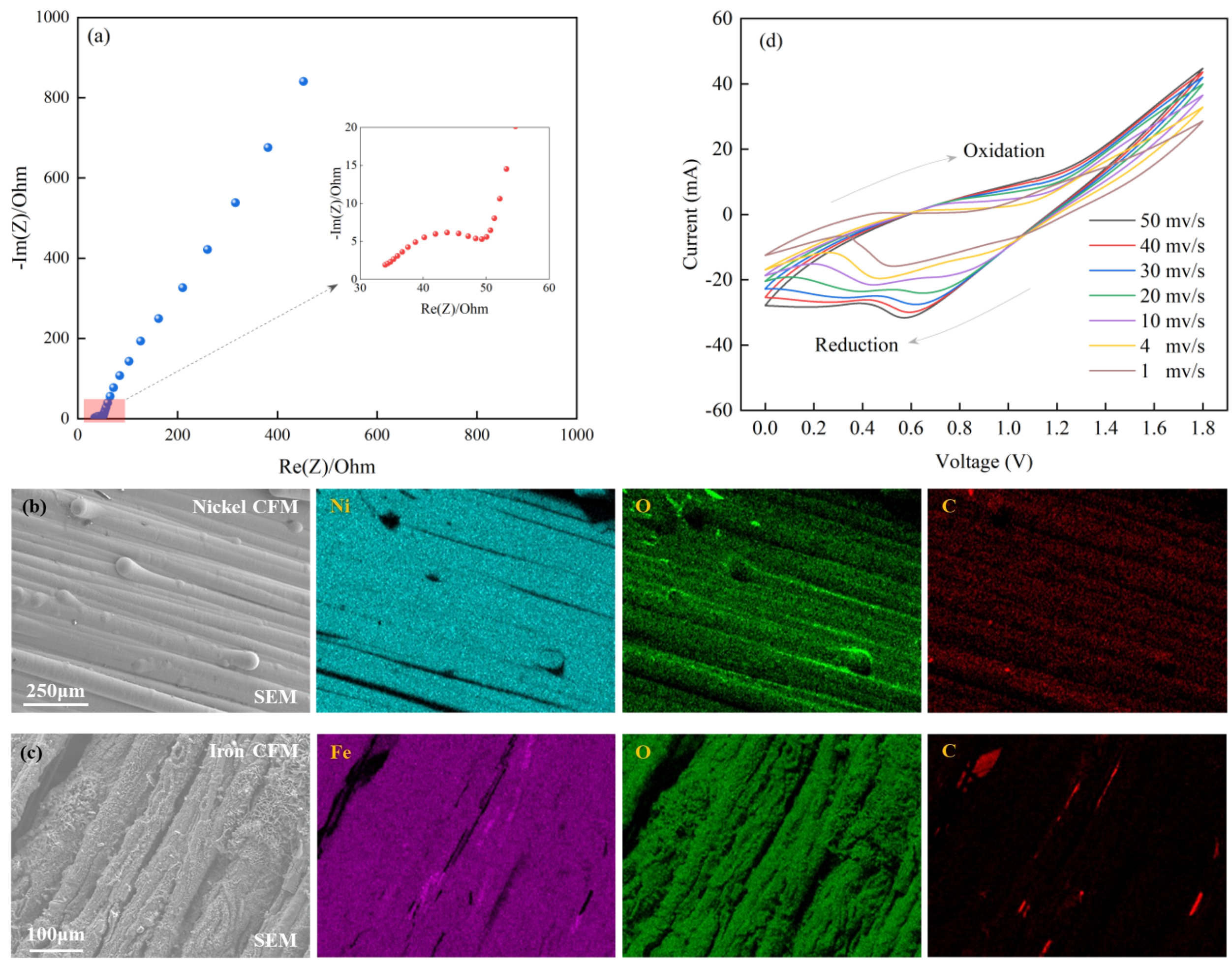

Fig. 6. Electrochemistry and microscopic analysis: (a) EIS of cement-based electrolyte; (b) SEM and EDS of nickel electroplated CFM; (c) SEM and EDS of nickel electroplated CFM; (d) CV curves.

3.3 Cyclic Voltammetry Curve of Rechargeable Cement-based batteries

As shown in Fig. 6(d), the cyclic voltammetry curves (CV curves) illustrate the performance of rechargeable cement-based batteries with the nickel-iron coated carbon fiber mesh within a voltage spanning from -2.0 V to +2.0 V. The scan rates in this study varied of 0.5 mV/s, 1.0 mV/s, 2.0 mV/s, 4.0 mV/s, and 8.0 mV/s. All the corresponding CV curves distinctly exhibit quasi-reversible redox peaks, which indicate the characteristic of battery-type electrochemistry for cement-based batteries. Upon closer examination of the figure, it becomes obvious that the oxidation peak in the cyclic voltammogram moves to the right gradually with increasing scan rates. Remarkably, the peak intensity undergoes minimal alteration. Conversely, the reduction peak gradually moves to the left, accompanied by a tendency towards significantly enhanced peak intensity. This observation underscores the imperfect reversibility of the batteries and indicates the room for enhancement. Furthermore, there is a positive correlation between scan rate and current amplitude range. As the scan rate increases from 1.0 mV/s to 50.0mV/s, the current amplitude expands from the initial range of -15.8 mA to +28.6 mA to a wider range of -31.6 mA to +44.8 mA. This result emphasizes the sensitivity of the batteries' electrochemical response to variations in scan rate and highlights the potential for optimizing its performance characteristics.

3.3 Charging and Discharging Stability of Rechargeable Cement-based Batteries

The stability and performance of the novel rechargeable cement-based battery during charging and discharging are crucial factors that directly impact the reliability, longevity, and overall efficiency of the battery system. In Fig. 7(a), the voltage and current data curves for 100 galvanostatic charge/discharge (GCD) cycles over 975 hours demonstrate the highly stable charge and discharge voltage paths. The charging peak voltage hovers around 2.0 V consistently, while the charge and discharge current paths remine stable at 3.0 mA with excellent stability.

Fig. 7(b) shows the capacity and energy data curves of the rechargeable cement-based batteries across 100 GCD cycles. The curves, including the capacitance change curve, peak charging capacity, peak discharge capacity, energy change curve, peak charging energy, and peak discharge energy, demonstrate overall stability.

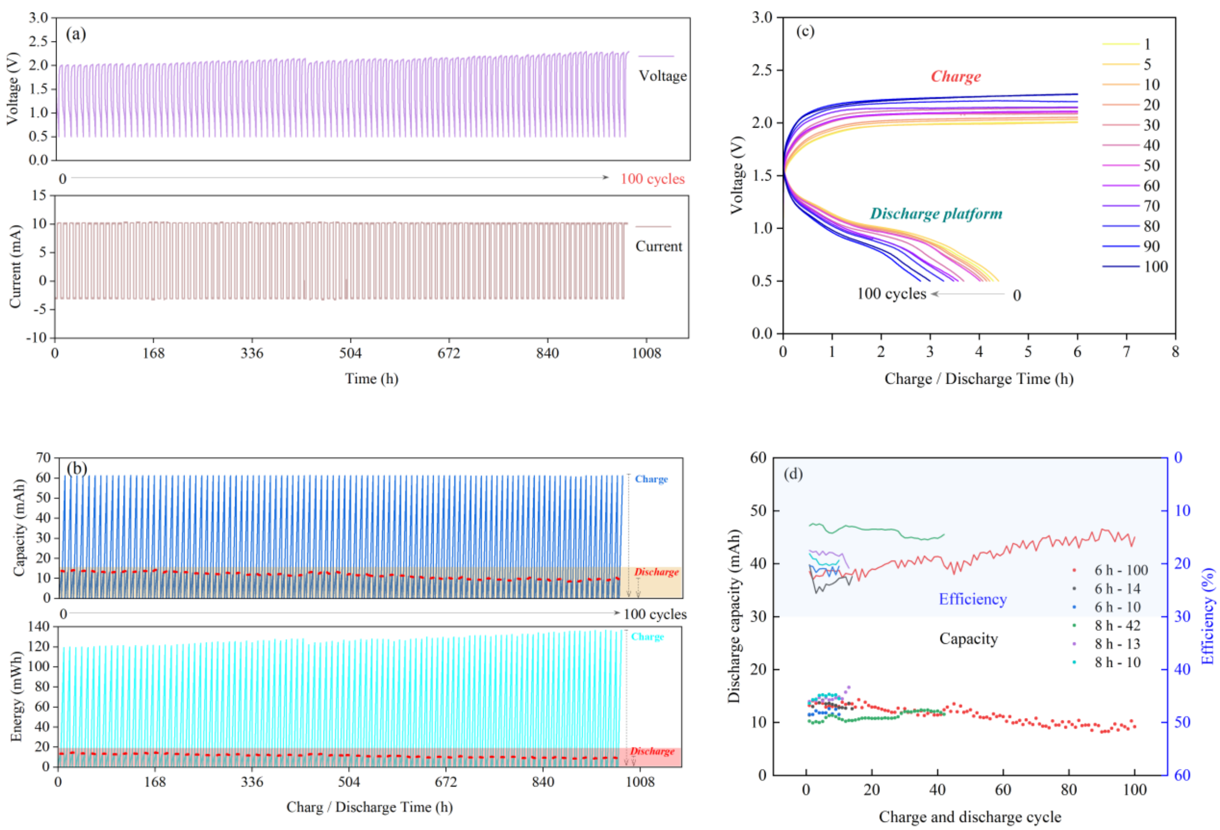

Fig. 7. Charging and discharging stability of rechargeable cement-based batteries: (a) voltage and current curves; (b) capacity and energy curves; (c) voltage platform curves; (d) discharge capacity and efficiency.

In particular, the charging voltage platform curve and discharge voltage platform curve of the rechargeable cement-based batteries, as illustrated in Fig. 7(c), display smooth and stable characteristics over 100 cycles. The paths of each charging and discharging platform are highly consistent. Notably, the discharge platform exhibits two distinct steps, aligning with the two-platform discharge characteristics observed in traditional nickel-iron batteries.

Upon analyzing the curves, it becomes evident that as the number of charge and discharge cycles increases, the peak charge voltage experiences a slight upward trend, with the amplitude limited to about 10% after 100 cycles. Concurrently, the discharge curve shifts to the left, indicating that the discharge time decreases from approximately 4.4 hours to approximately 2.8 hours after 100 cycles.

These comprehensive observations affirm that the rechargeable cement-based battery, as prepared in this article, possesses a high degree of stability in its charge and discharge behavior, emphasizing its reliability and performance efficiency.

3.4 Cyclic Discharge Capacity and Efficiency of Rechargeable Cement-based Battery

The author team of this article continued to refine the detailed design of the overall battery model, adjust the preparation and molding technology, optimize the preparation process of positive and negative electrodes, and explore various cement-based electrolyte ratios. Following experimental research on over a hundred sample groups, a rechargeable cement-based battery with the highest performance to date was developed successfully, as well as its design parameters and preparation methods.

As shown in Fig. 7(d), the discharge capacity and efficiency of six groups of rechargeable cement-based batteries are presented, along with their evolutionary characteristics during charge and discharge cycles. Notably, the figure shows that the average discharge capacity of a single battery concentrates in the range of 10 mAh to 15 mAh. As the number of charge and discharge cycles increases, the overall discharge capacity can be maintained in a relatively stable state, and no attenuation trend within 42 cycles. Although the discharge capacity shows a visible downward trend as the number of cycles reaches 100, the capacity retention rate can still remain at more than 70% of the discharge energy in the first cycle.

Comparative analysis with existing literature [15],[16],[19],[29] shows that the rechargeable cement-based battery proposed in this article surpasses previous research results related to cement concrete batteries in terms of discharge capacity retention rate and the number of charge and discharge cycles.

Fig. 7(d) also reveals the efficiency of rechargeable cement-based batteries, which is calculated based on the ratio of discharge capacity to charge capacity— a detail that has not been mentioned in previous studies related to cement-concrete batteries. Notably, the figure shows that the efficiency of rechargeable cement-based batteries tends to be relatively low, which centered around 20%. This may be attributed to the significant loss of capacity during the final charging process due to the large internal resistance of the battery and self-discharge which is also the focus of our subsequent research work.

3.5 Cyclic Discharge Energy and Energy Density Rechargeable Cement-based Battery

The evaluation of discharge energy and energy density in rechargeable cement-based batteries is crucial for assessing their overall performance and practical applicability. Batteries with optimal discharge characteristics and high energy density are more likely to meet the diverse demands of technology and energy storage needs.

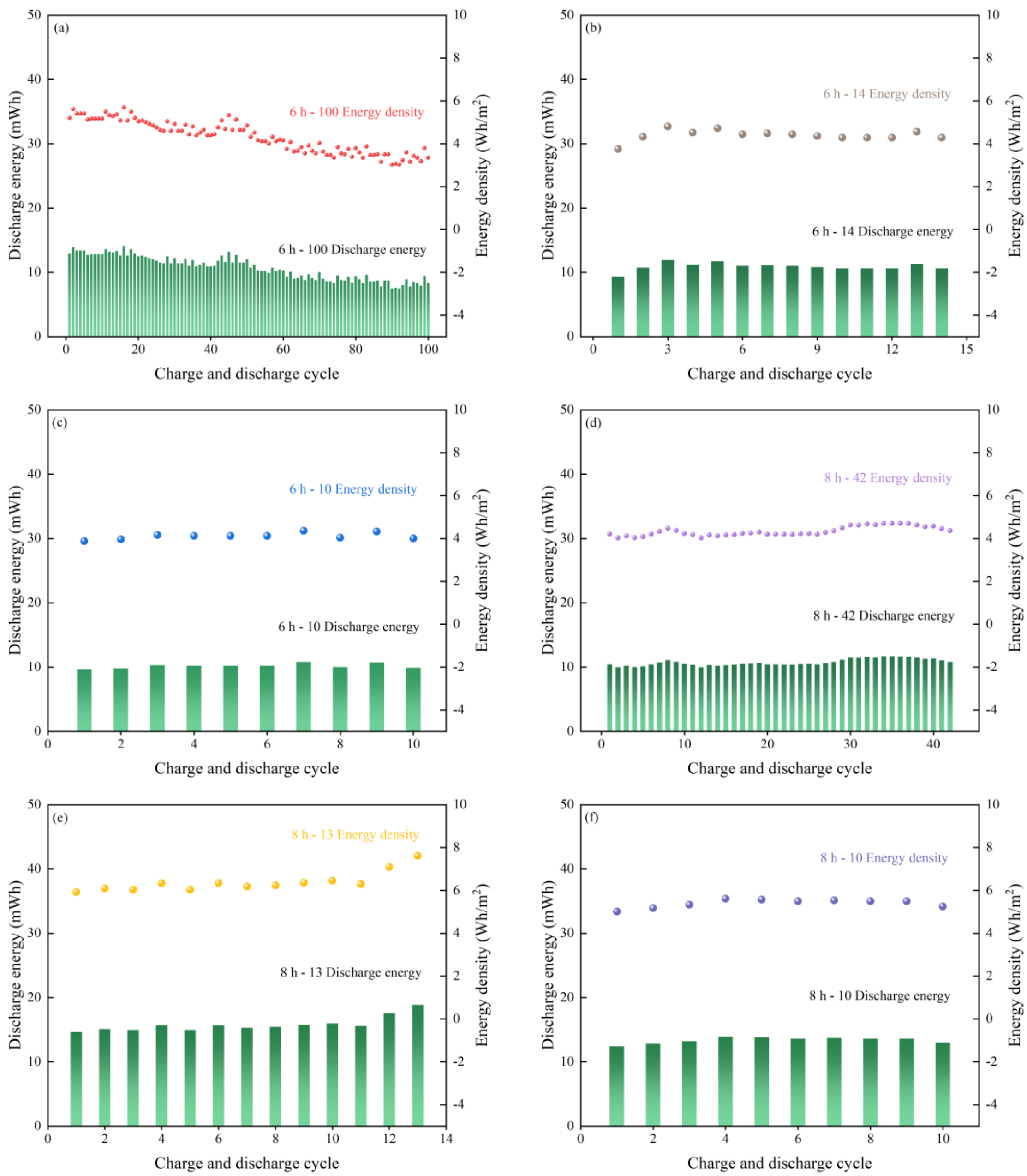

Fig. 8. Discharge energy and energy density of rechargeable cement-based batteries.

In Fig. 8, the discharge energy and energy density of six groups of rechargeable cement-based battery samples are presented, along with their evolutionary characteristics during charge and discharge cycles. Discharge energy is automatically calculated by the battery charge and discharge test system, and energy density is measured as the discharge energy value per unit area of a single-layer cement battery, calculated using the formula (2):

$$W = E/S \tag{2}$$

where, W represents the energy density of the rechargeable cement-based battery in Wh/m^2; E is the discharge energy of the cement battery in Wh; S is the area of the single-layer cement battery, which is calculated as 2.475×10^{-3} m^2. It's noteworthy that all batteries prepared in this article are single layered.

Observing Fig. 8(a)~(f), it is apparent that the discharge energy of the six groups of rechargeable cement-based battery samples concentrates around 10 mW. Overall, the battery discharge energy remains relatively stable. Notably, in Fig. 8(a) with a high number of charge and discharge cycles, a gradual downward trend becomes evident after 50 cycles. However, even after 100 charge and discharge cycles, the discharge energy can still be maintained at more than 64% of the first cycle.

Comparative analysis of Fig. 8(a)~(c) and Fig. 8(d)~(f) indicates that the discharge energy of the battery with an 8-hour charging time is slightly higher than that of the battery with a 6-hour charging time. This suggests that the charging time significantly impacts the cement battery, a phenomenon worthy of further investigation.

Regarding the energy density, a critical concern, the figure illustrates that the energy density of the rechargeable cement batteries developed in this article generally remains stable above 4 Wh/m^2, with a maximum of 7.6 Wh/m^2. This marks a significant breakthrough and sets a new record for the energy density of cement batteries.

3.6 Charging Time Response of Rechargeable Cement-based Batteries

Studying the impact of charging time on rechargeable cement-based batteries is crucial for fine-tuning their performance, ensuring the energy efficiency, extending the battery life, implementing the effective thermal management, and meeting the specific requirements of various applications and industries. This article explores a total of nine different charging time lengths: 0.5 h, 1.0 h, 2.0 h, 4.0 h, 6.0 h, 8.0 h, 10.0 h, 12.0 h, and 16.0 h.

As depicted in Fig. 9(a), stable charge and discharge voltage and current stroke curves are presented, covering a charge and discharge duration of nearly 100 hours. Fig. 9(b)-(e) illustrates the discharge capacity, efficiency, charging capacity, energy density, discharge energy, and their evolution characteristics with charging time for rechargeable cement-based batteries.

As the charging time increases, the charging capacity of the cement battery increases linearly. The discharge capacity also increased almost linearly within 6-8 hours, then stabilized and reached a slight increase of around 13% within 16 hours. However, this is achieved by consuming 2.6 times the charging capacity. Efficiency, on the other hand, gradually decreases as the charging time increases. It's noteworthy that while the maximum efficiency can reach an astonishing 76%, it occurs with a relatively short charging time, resulting in a releasable capacity of only 3.6 mAh.

As for the discharge energy, its evolution characteristics are consistent with the discharge capacity, initially increasing and then stabilizing until 16 hours. The corresponding energy density increases from 6-8 hours to 16 hours, a modest increase of 12.5%. This analysis underscores the importance of finding a balance between charge capacity, discharge capacity, efficiency, discharge energy, and energy density, which is a critical and meaningful research topic.

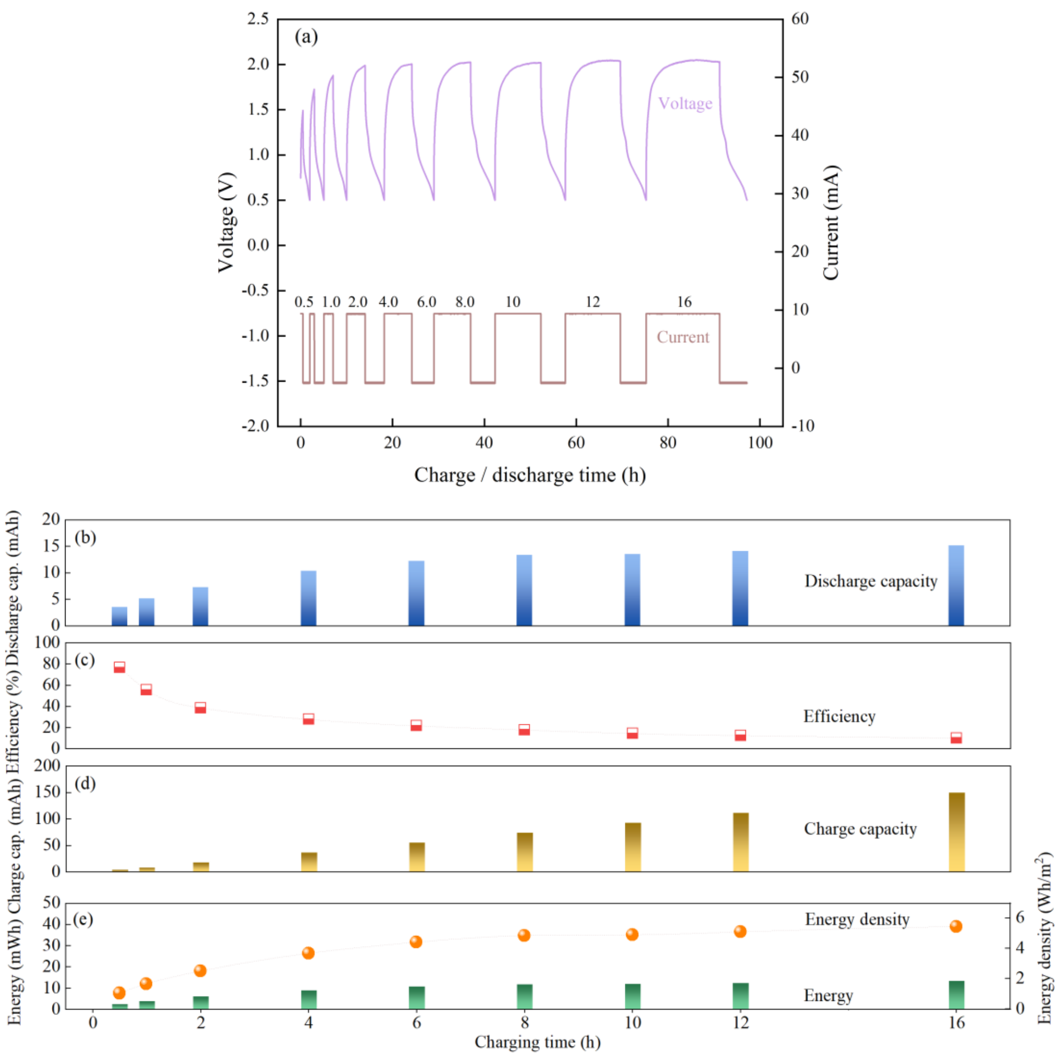

Fig. 9. Evolution characteristics of battery performance with charging time: (a) voltage and current stroke curves; (b) discharge capacity; (c) efficiency; (d) charging capacity; (e) energy and energy density.

3.7 Rate Performance of Rechargeable Cement-based Batteries

This article examines four distinct discharge rates, quantified by the discharge current sizes of 3.0 mA, 6.0 mA, 9.0 mA, and 12.0 mA, respectively. As shown in Fig. 10(a), stable charge-discharge voltage and current stroke curves are presented, spanning over 200 hours.

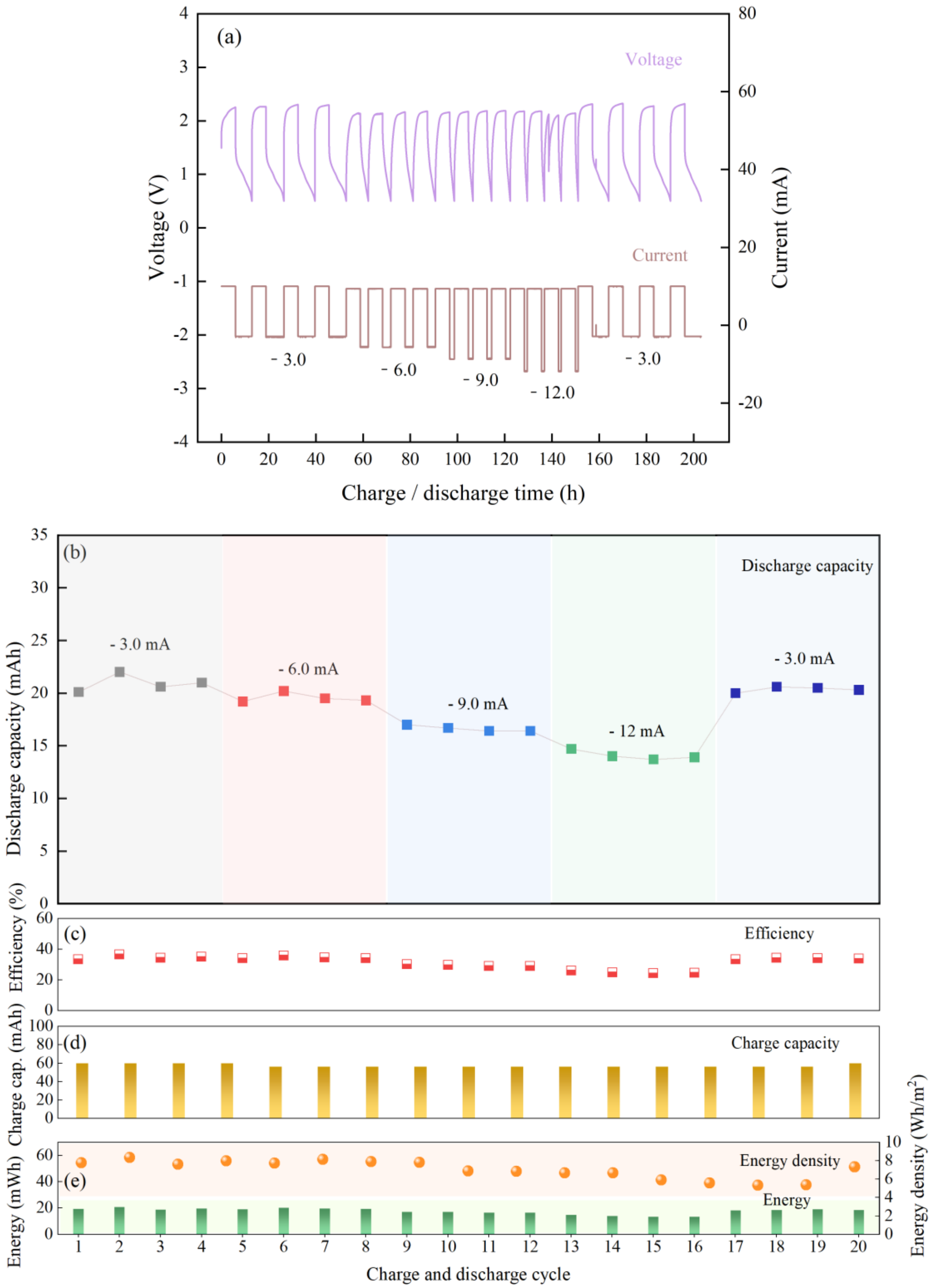

Fig. 10. Evolution characteristics of battery performance with discharge rates: (a) voltage and current stroke curves; (b) discharge capacity; (c) efficiency; (d) charging capacity; (e) energy and energy density.

In Fig. 10(b)-(e), the discharge capacity, efficiency, charging capacity, energy density, discharge energy, and their evolution characteristics with discharge rate are depicted for the carbon fiber mesh-cement battery. Observing Fig. 10(b), the discharge capacity gradually decreases in a stepwise manner as the discharge current increases from 3.0 mA to 6. 0 mA, 9.0 mA, and 12.0 mA. Upon returning from 12.0 mA to the initial 3.0 mA, the discharge capacity also returns to near the initial value, with an average loss of no more than 3%. Correspondingly, in Fig. 10(c), after charging and discharging at rates from 3.0 mA to 12.0 mA, the battery efficiency perfectly returns to near the initial value, with the average reduction also not exceeding 3%. In Fig. 10(e), the battery's discharge energy and energy density are reduced by no more than 6% on average, showing excellent recovery capabilities under rate discharge conditions. In conclusion, the rate performance of the rechargeable cement-based battery is evidently stable.

3.8 Energy Storage Evaluation of Rechargeable Cement-based Batteries

3.8.1 Laboratory sample demonstration

As depicted in Fig. 11(a), our laboratory demonstration illustrates the illumination of a 2.0 V ~ 2.2 V LED bulb powered by two series-connected rechargeable cement-based batteries. Combining innovation with practical application, our research paper showcases compelling visuals capturing the radiant glow of LED bulbs powered by our rechargeable cement batteries – a powerful proof of the tangible possibilities of sustainable energy storage in real-world scenarios.

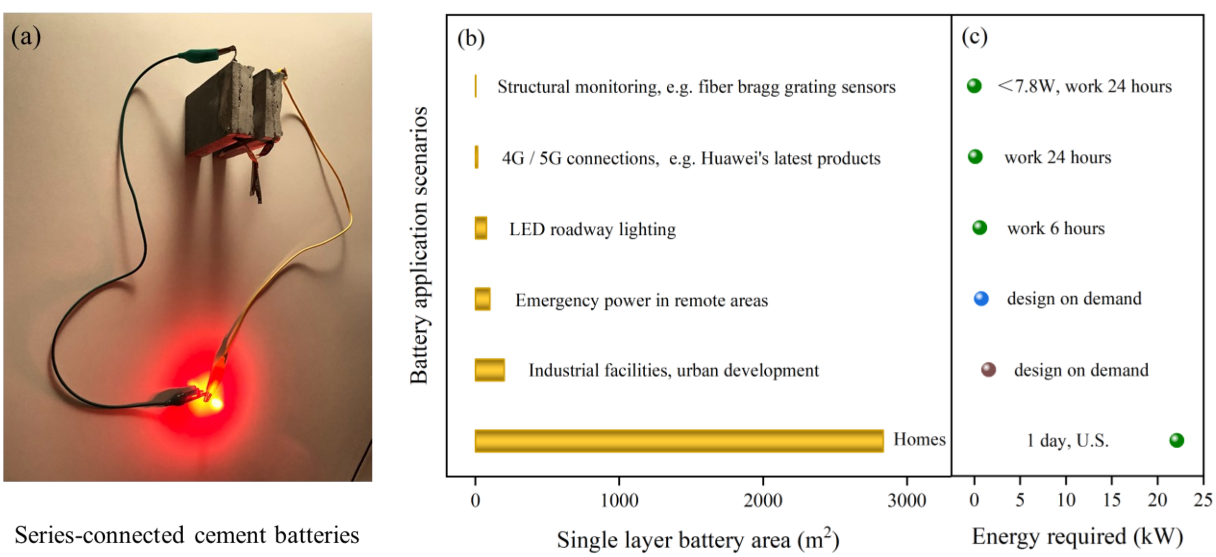

Fig. 11. Energy storage evaluation: (a) powering LED; (b) envisioned practical applications.

3.8.2 Analysis of the Potential Applications of Rechargeable Cement-based Batteries

This article presents the development of a rechargeable cement-based battery, with a comprehensive evaluation of its electrochemical performance, charge and discharge cycle stability, and battery performance indicators. The laboratory demonstration results are also provided.

In this section, we delve into the future of the application of rechargeable cement-based batteries in the field of energy storage. As illustrated in Fig. 11(b), we offer approximate data on the potential analysis for different energy storage scenarios, including energy requirements and corresponding cement batteries' volume. The battery energy density, reaching a maximum value of 7.8 Wh/m^2, is a key factor. To power a light sensor for structural health monitoring for 24 hours, a single-layer cement battery of just 1 m^2 proves sufficient. For continuous 24-hour operation of Huawei's latest low-energy consumption 5G base station (consuming less than 5 W) in remote areas, a single-layer cement battery covering approximately 15m^2 is adequate. Additionally, based on the average electricity consumption of single-family homes in the Northeastern United States in 2020, a 2,835 m^2 single-layer cement battery can fulfill a day's electricity demand [40].

Despite the current low energy density of the developed rechargeable cement batteries, future advancements hold significant promise. If energy density reaches higher levels, combined with cement concrete – the world's most used building material – and its integration with clean energy sources such as solar and wind, the prospects become immense. This synergy could provide substantial support for global energy storage solutions.

4. Conclusion

In this study, we have focused on highlighting the distinguished and innovative aspects of our work in developing and characterizing a novel rechargeable cement-based battery for energy storage applications. Our findings reveal several key advancements:

1. High Ionic Conductivity: The cement-based electrolyte displayed remarkable ionic conductivity, facilitating efficient charge-discharge cycling.
2. Stable Charge-Discharge Behavior: Over 100 cycles, our battery exhibited consistent and stable charge-discharge behaviors, demonstrating its reliability for prolonged usage.
3. Quasi-Reversible Redox Peaks: Analysis of cyclic voltammetry curves revealed quasi-reversible redox peaks, confirming the battery's electrochemistry and validating the efficacy of our battery design.
4. Stability in Discharge Capacity, Efficiency, and Energy Density: Our rechargeable cement-based battery showcased stability in discharge capacity, efficiency, and energy density, surpassing existing literature on cement batteries and achieving a record-breaking maximum energy density of 7.6 Wh/m^2.

Despite challenges related to efficiency and energy density, our research envisions practical applications for the rechargeable cement-based battery. From powering light sensors to supporting 5G base stations and meeting daily electricity demands, the integration of these batteries with clean energy sources holds significant promise for global energy storage solutions.

Credit Author Statement

Liqiang Yin: Writing - Original Draft**; Shihui Liu:** Conceptualization, Supervision, Resources, Funding acquisition; **Dandan Yin:** Investigation, Methodology; **Kand Du:** Writing – review & editing; **Jing Yan:** Formal Analysis; **Catherine K. Armwood-Gordon:** Resources; **Lin Li:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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