RECENT APPROACHES FOR DEVELOPING A NOVEL GENERATION OF BATTERIES USING CEMENT-BASED MATERIALS

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Abstract - In the context of the increasing global demand for sustainable energy development, the solution of using cement-based materials to develop batteries for energy storage has enormous potential, but this topic is still quite new to engineers and scientists in the construction industry. This study aims to systematically provide the basic principles as well as the current approaches and technical challenges in the development of batteries using cement-based materials. First, the paper presents the general principles of conventional batteries and batteries based on cement-based materials. Next, the paper discusses the main factors affecting the performance of cement-based batteries based on experimental results from previous studies. Finally, the paper addresses the challenges and future research directions in this field. The study hopes to help engineers in the construction industry shape the scientific context, thereby providing appropriate directions before developing products related to this novel field.

Key words - Concrete battery; cement-based material; energy storage; electrode; electrolyte

1. Background

In the global context of moving towards sustainable energy sources, the role of energy storage battery solutions is extremely important [1]. The battery was first invented in the 18th century by Alessandro Volta, using copper and zinc electrodes in a salt solution to act as electrolytes [2]. Since then, there have been advances in creating batteries with different combinations of materials for electrodes or electrolytes including both liquid and solid to improve their performance and durability of the battery [3, 4]. Nowadays, these solutions play a key role in increasing the efficiency of energy use, especially for renewable energy sources, thereby contributing to reducing carbon emissions on a global scale [5, 6].

On the other hand, cement-based materials, known by other names such as mortar and concrete, are an extremely popular material in the construction industry. This popularity makes them one of the materials that occupies a huge volume on the earth's surface because they are used in most civil and infrastructure projects. Nowadays, cement-based materials can be more broadly defined as collections of discrete components bonded together by cementitious adhesives. The discrete components used today are very diverse, not only including traditional sand and crushed stone aggregates but can include many other components such as allotropes of carbon, metals or their oxides, air bubbles, or other construction waste materials [7, 8]. The abundance of these components makes them a highly flexible material, creating many different smart functions in addition to its main function of bearing capacity. Recently, cement-based batteries have been applied practically in the field of cathodic protection for steel reinforcement in concrete structures, which helps to prevent corrosion and extend the lifespan of these structures [9]. In the future, it will be a big breakthrough if this material is used in energy storage battery systems. This will pave the way for the development of giant energy storage systems, taking advantage of structures made of cement-based materials in construction projects [10-12].

To develop a cementitious material that acts as an electrolyte for batteries, the key lies in optimizing the mixture composition and microstructure of the material to help create a suitable ion transmission environment. This involves the pore system within the cementitious material, which helps create continuous ion transmission pathways within the material. Besides, recent studies show that fillers have high electrical conductivity and stability such as carbon in different allotropes such as carbon black powder. [13, 14], carbon nanotubes, carbon fibers, graphene [15] or metal-based materials such as steel fibers, iron powder, nickel, zinc, or their oxides [16] are considered as potential fillers and can be used to optimize and adjust the ion conduction, reducing the battery's resistance while still ensuring the inherent mechanical properties of cement-based materials. However, using the right amount and method to help disperse these fillers to create a conductive network inside the material is one of the major technical challenges. In addition, battery performance also depends on the type, size, and structure of the electrodes. However, currently there are still not many documents, especially domestic documents, that systematically overview the general principles, analyze the factors affecting battery performance as well as the technical challenges posed. In the development of batteries using cement-based materials.

With the great significance and potential of this topic, the purpose of this paper is to systematically provide basic principles as well as current approaches and technical challenges in cement-based battery development. Cement-based materials to help engineers shape the context, thereby providing appropriate directions before developing products related to this new field. First, the paper presents the general principles of conventional batteries and batteries based on cement-based materials. Next, the paper presents the main influencing factors on battery performance with cement-based materials based on experimental results from previous studies. Finally, the paper also addresses challenges and future research directions in this field. This study is significant as it systematically addresses the existing knowledge gaps and provides a comprehensive overview of the principles, technical challenges, and recent advancements in cement-based battery development, thereby contributing to the advancement of sustainable energy storage solutions.

2. Basics of batteries and batteries made of cement-based materials

2.1. Principles of batteries

A battery is a device designed to store and provide electrical energy. The basic structure of a battery includes two electrodes: an anode and a cathode immersed in an electrolyte, which can be in liquid, solid, or gel form. The electrolyte acts as a medium for ion exchange between two electrodes. In addition, a separation layer is needed that prevents the flow of electrons and allows only ions to pass through the electrolyte. This helps electrons to only move when the two electrodes are connected to an external circuit, allowing the battery to store energy when not connected to the circuit.

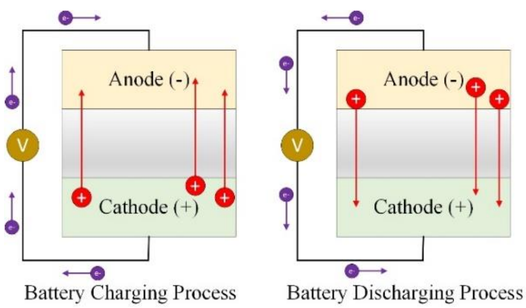


***Figure 1.** Basic operating principle of the battery*

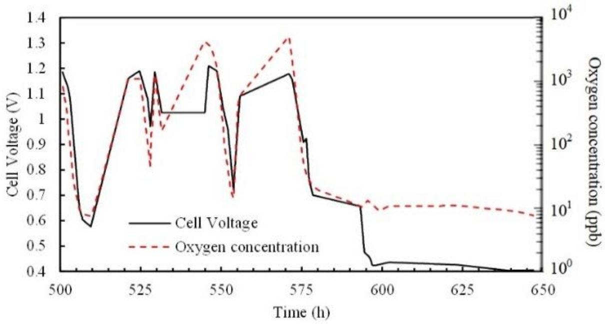
Basically, the operation of a battery is based on the redox (Reduction-Oxidation) reaction at the two electrodes, which creates the flow of ions in the electrolyte and the flow of electrons in the conductor when connected to an external circuit. At the anode, the electrode material reacts with the electrolyte to generate electrons, which accumulate at the anode capable of donating electrons. Meanwhile, another chemical reaction simultaneously occurs at the cathode, making the electrode there capable of receiving electrons. The direction of charge movement (electrons and ions) is opposite in the two processes of charging and discharging, as described in Figure 1. During the charging process, electrons move from the cathode to the anode through the external circuit. Concurrently, positive ions on the cathode material's surface are released and move to the anode through the electrolyte. At the anode, these positive ions meet electrons moving from the external circuit, ensuring the charge-neutral state at the anode. The discharging process is the opposite of charging. When the battery is connected to an external circuit with a stimulating voltage, electrons can move through the external circuit from the anode to the cathode. This also allows the positive ions at the anode to be released and move back to the cathode through the electrolyte. The flow of electrons in the external circuit generates current, and this redox process continuously occurs to achieve charge balance at the anode. The discharging process ends when the stored ions at the anode are depleted, and the electron flow in the external circuit stops.

The materials commonly used to manufacture standard batteries are presented in Table 1. The anode of the battery is typically made of metal or various allotropes of carbon-based materials due to their good electron exchange capability, which facilitates the easy release and acceptance of electrons during electrochemical processes. The cathode of the battery is usually made of metal oxides with stable structures and good ion acceptance capabilities, helping to maintain electrochemical performance during charging and discharging. Additionally, the electrodes need to operate at high voltages with minimal heat generation, reducing energy loss and ensuring safety during battery operation.

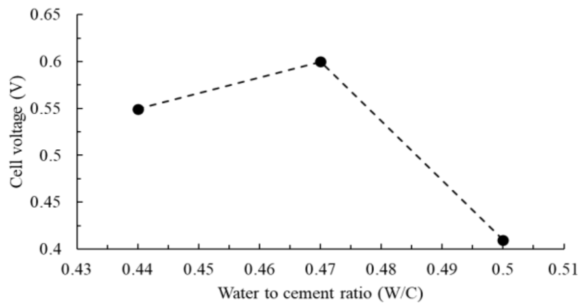
***Table 1.** Constituent materials of some types of batteries*

Classification	Name Battery	Cathot	Anot	Electrolyte
Liquid-state electrolytes	Lead-acid	PbO_2	Pb	Sulfuric acid
	Zinc-carbon	MnO_2	Zn	Chloride salt
	Nickel – metal	NiOOH	Zn or Fe	Alkaline
	Silver oxide	Ag_2O	Zn	
	Alkaline	MnO_2	Zn	
	Mercury	HgO	Zn	
	Lithium-ion	$LiCoO_2$	Graphite	Lithium salt
Solid-state electrolytes	Lithium-Sulfur	Li	S	Sulfide ceramics, oxide ceramics, or ion-conducting polymers
	Lithium-Silicon	Si	$LiCoO_2$	
	Lithium-Graphite	C (Graphite)	$LiFePO_4$	
	Lithium-Cobalt Oxide	Li	$LiCoO_2$	
	Lithium-Iron Phosphate	Graphite	$LiFePO_4$	
	Lithium-Nickel Manganese Cobalt Oxide	Li or C	LiNMC oxide	
	Lithium-Titanate	$Li_4Ti_5O_{12}$	$LiCoO_2$	
	Sodium-Ion	Na	$NaCoO_2$	

On the other hand, the electrolyte of the battery can exist in liquid, solid, or gel form, but it must allow the movement of charged ions. So far, the majority of battery electrolytes exist in liquid form, usually alkaline, salt or acid solutions as shown in Table 1, which have good ion conductivity between cathode and anode. In recent years, batteries using solid electrolytes, also known as solid-state batteries, have received great attention from the scientific community. Common solid electrolyte materials include ceramics such as sulfides, oxides, and phosphates, as well as ion-conducting polymers. These materials need not only to have high ionic conductivity but also to have chemical and temperature stability so as not to react with polar materials and not to decompose during operation. This is especially important in applications such as electric vehicles, where the battery must endure extreme temperature conditions from the environment and the heat generated during operation, to ensure safety and minimize the risk of explosion, a common problem in batteries using liquid electrolyte. In addition, the mechanical strength of the solid electrolyte is an important factor to withstand pressure and dimensional changes during charging and discharging, while maintaining structure and ion transport performance. This is an important key in developing energy storage solutions with high performance and durability.



(a) Ability to maintain voltage and oxygen concentration



(b) Relationship between voltage and water/cement ratio

Figure 2. *Research results from Berstein and Speckert [17]*

2.2. The battery using cement-based materials

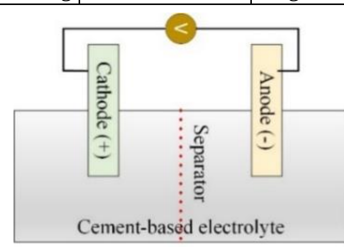
With the general principle presented in Section 2.1, batteries in which cement-based materials are used as electrolytes, or even used for electrode materials are called cement-based materials batteries, or it can be called concrete battery. Wide-scale application of this battery technology has the potential to create a breakthrough in the energy industry, thanks to its ability to self-storage large amounts of energy based on the pore volume of cement-based materials such as concrete and mortar of buildings and construction infrastructure.

The ion transmission capacity of cement-based materials has been investigated by Berstein and Speckert [17] discovered in a research in 2008. The cementitious material is being used for the first time as an electrolyte in a battery system with an anode made from aluminum and a cathode made from iron, leading to the development of batteries made from concrete-encased steel piles to provide power to offshore structures. In this study, the basic principle of the electrolyte is to rely on the pore system of concrete containing seawater to act as an ion transmission environment between two electrodes. The main results of the study are shown in Figure 2. Figure 2(a) shows the relationship between the voltage between the two electrodes after charging the cement mortar battery system as well as the oxygen concentration in the material and the time obtained in the case of using a cement mortar mixture with a water/cement ratio of 0.5 as the electrolyte. The results show that cement mortar has the ability to maintain voltage, but its performance is unstable and is almost proportional to the Oxygen content in the concrete. Besides, Figure 2(b) shows the relationship between the water/cement ratio and the maximum voltage of the battery. The results show that the maximum voltage is not proportional to the water/cement ratio but there exists an optimal value to achieve the highest voltage. This may be related to the loss of charged ions to the surrounding environment when increasing the mortar porosity to an excessively high level. Therefore, the gradation design of the cement mortar mixture is an important key to increasing the performance of this advanced battery system.

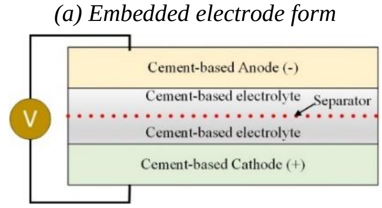
After the above mentioned research, a series of other studies have focused on developing batteries using different cement-based materials. For example, the study by Meng and Chung [18] used cement paste as the matrix, with the pore solution in the cement acting as the electrolyte. Zinc particles dispersed in the matrix served as the anode, manganese dioxide particles as the cathode, and carbon black as the conductive additive in both the anode and cathode regions. The mix composition for each component of the battery is shown in Table 2. The battery achieved an open-circuit voltage of 0.72 V, a current of 120 μA, a power output of up to 1.4 μW/cm², and a capacity of up to 0.2 mAh.

Table 2. *Example of mix design of cement-based battery system [18]*

Anode	Electrolyte	Cathode
Cement: 48g; Zinc: 14.4g; Carbon black: 1.2g; Water: 16.8g; Water reducing agent: 1.0g	Cement: 15g; Water: 6g; Water reducing agent: 0.15g	Cement: 93g; MnO2: 37.2g; Carbon black: 3.7g; Water: 33.6g; Water reducing agent: 1.8g



(a) Embedded electrode form



(b) Multilayer form

Figure 3. *Battery using cement-based materials [23]*

So far, two basic structural types of cementitious battery cells have been mainly studied including (i) embedded electrode form and (ii) multilayer form as shown in Figure 3(a) and 3(b). For multilayer batteries, the electrodes and electrolytes can be made from cement-based materials, in which each layer is fabricated and cured separately and then assembled on top of each other. The degree of contact between the layers and the moisture difference depending on the microstructure of the layers can affect the battery performance. Meanwhile, in batteries using embedded electrode structure, the electrodes are embedded in an electrolyte made of cement-based materials [19-22]. In some studies, alkaline solutions or salts are penetrated into cementitious electrolyte materials to increase ion conductivity within the material [10]. Basically, the operating principles of both types of battery structures are the same as conventional battery systems as described in section 2.1. The detailed influence of factors related to material composition, structure and other factors will be discussed in more detail in part 3 of the paper.

2.3. Basic parameters and methods for evaluating the performance of cement-based batteries

To evaluate the performance of batteries using cement-based materials, the main parameters used by previous studies are as follows:

(i) Voltage: measured across the battery electrodes in the absence of current [24] by connecting the multimeter in DC voltage mode across two electrodes. Some studies evaluate battery performance through the maximum voltage value that the battery can store after charging, or through the relationship between voltage and time to demonstrate the battery's ability to maintain voltage by the time.

(ii) Amperage: While voltage is measured under open circuit conditions, amperage is a measurement of current made across a resistor connected to the battery system. Therefore, the intensity value represents the battery performance under real working conditions. In some studies, the intensity value was measured by connecting low-value resistors of 10 Ω [19, 21], 165 Ω [10] between the two electrodes of the battery. Additionally, this measurement can also be conducted over multiple cycles to evaluate the loss of battery performance over time.

(iii) Lifespan: represents the battery's ability to maintain performance, evaluated through the maximum number of times the battery can be charged and discharged (cycle life) or the maximum period of time (lifespan) that the battery can operate and maintain its ability to work. For cementitious batteries, the reported lifespan is very small compared to conventional batteries. The maximum reported life of 21 days from a study by Byrne et al. [22] when charging and discharging the battery at current level 0.59 mA. Research also shows that charging/discharging at higher current levels can significantly reduce battery life, specifically the life of the same battery configuration is only 4 days for 1mA current. Similar results were also shown in the study of Meng and Chung [18]. This is because battery life depends on factors such as operating temperature, mechanical stress, charging and discharging rates. Increased temperatures and high charging rates tend to reduce battery life [25].

(iv) Capacitance: represents the battery's ability to provide a stable current for a specified period of time, in units of Ampere-Hours (Ah). For example, a battery with a capacity of 10Ah can provide a constant current of 10A for 1 hour continuously, or the same battery can provide a current of 1A for 10 hours. Among the few studies evaluating the capacitance of cement-based materials batteries, Meng and Chung [18] determine the capacitance of a battery made from a mixture of cement mortar and black carbon black filler with a capacity of 0.2 mAh. Similarly, Zhang and Tang [10], fabricated a cement-based material battery combining carbon fiber mesh with active components (Ni and Fe), and reported high capacitance of 62 mAh in the first cycle, then gradually decreased to 55 mAh at the 6th discharge cycle [10].

Density: shown amperage running through a unit of area, the unit is (A/m^{2}). The study by Qiao et al. [26] reported the current density of a battery made from a reinforced concrete structure itself, with the steel reinforcement as the electrode and the concrete as the electrolyte at 35, 21 $\mu A/cm^2$. Additionally, the same value is the energy density, unit W/m^2 also used to evaluate battery performance. Burstein and Speckert [17] reported an energy density of batteries made from foam concrete of 0.1 $\mu W/cm^2$, while Meng and Chung [18] reported an energy density of 1.4 $\mu W/cm^2$ for multilayer battery systems with black carbon black filler.

3. Factors affecting the performance of cement-based batteries

3.1. Porosity

The porosity of cement-based materials affects battery performance by altering the material's ability to conduct ions when used as an electrolyte. High porosity helps create ion pathways, allowing ions to move easily through the electrolyte, helping to maintain electric current. Continuous ion pathways help speed up electrochemical reactions, thereby improving the battery's charging and discharging capabilities. High porosity also increases the surface contact area within the material, providing more reaction sites for ions and electrons, thereby enhancing the overall performance of the battery.

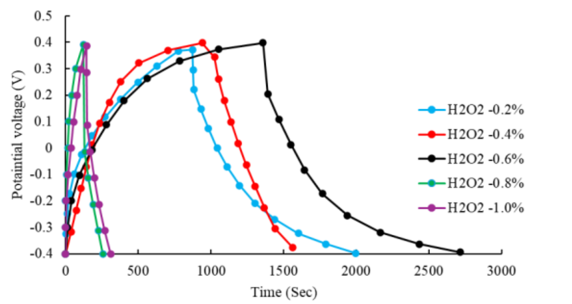


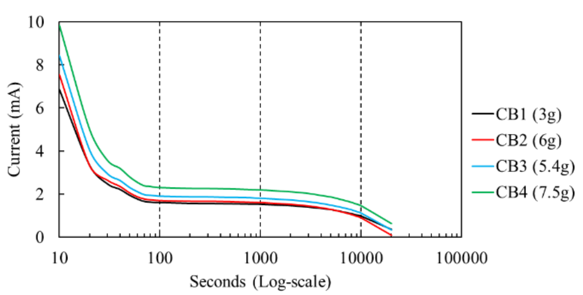
Figure 4. *Effect of H2O2 foaming agent content on the battery's ability to maintain voltage [27]*

The study of Zhou et al. [27] changed the porosity of concrete by changing the content of H_2O_2 foaming agent in the concrete mix, and investigated its effect on storage capacity. battery power. Figure 4 shows the results of the relationship between charging voltage and voltage retention time corresponding to different levels of H_2O_2 content from 0.2 to 1.0%. The results show that with the same charging voltage, the 0.6% content sample is able to maintain the voltage for the longest period of time. This demonstrates that increasing the porosity of concrete to a certain value improves the battery's ability to maintain performance. However, research also shows that excessively increasing the porosity of a material can have the opposite effect, by causing charge loss with the surrounding environment, or by unevenly dispersing the system. The pore system creates discontinuous ion transmission paths within the structure of the cementitious material. Therefore, the samples are as follows 0.8% content or 1.0% content in Figure 4 has a high H_2O_2 content but almost cannot maintain the voltage.

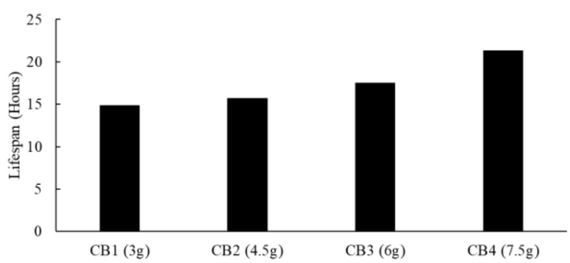
3.2. Conductive filler

In addition to ion conduction, the high conductivity of the electrolyte helps reduce the battery's internal resistance, thereby reducing energy lost as heat and increasing battery performance. Electrolytes with good conductivity also help speed up electrochemical reactions at the electrodes. This increases the battery's ability to generate current and improves overall performance. Ordinary cement-based materials are considered insulating materials. Therefore, adding conductive fillers to the concrete structure helps create effective conductive networks and ion transport inside the material, which is an important solution to enhance storage capacity and reaction speed. electrochemical reactions as well as reduce energy loss during battery operation.

Carbon-based fillers such as carbon black, graphene, or carbon nanotubes (CNTs), or metal-based fillers have been used in some previous studies [14, 28, 29]. Carbon black is known for its high electrical conductivity and low cost. In contrast, graphene has superior electrical conductivity, improving the electrochemical performance of the battery, but is expensive and difficult to distribute evenly within the material [14]. In addition, materials with elongated shapes such as carbon fibers [28] or carbon nanotubes (CNTs) not only help create effective conductive networks thanks to their shape, but also has the ability to improve the mechanical properties of materials [30, 31], thereby increasing the battery's durability and bearing capacity. For metal-based materials, metal nano papers such as silver, copper, or gold have also been used in some previous studies [32]. However, uneven dispersion of nano-sized papers can lead to agglomeration and create areas of uneven conductivity. Besides, metal oxidation over time is also a disadvantage of this type of filler in battery systems using cement-based materials.



(a) Relationship between AC current supply and time



(b) Lifespan

Figure 5. *Effect of carbon black content on battery performance [22]*

The content of fillers is also an important factor affecting the performance of concrete batteries. Low filler content may not be sufficient to create an effective conductive network in the cement, resulting in poor electrical conductivity. Figure 5 shows the effect of black carbon black content on the current intensity and battery life from the results of the study by Byrne et al. [22]. The results show that increasing the black carbon black content helps increase the current intensity, current retention time as well as battery life. However, if the filler content is too high, it can also lead to agglomeration, especially for nanoparticle-sized fillers, creating uneven conductive areas and reducing the overall performance of the battery. Furthermore, too high a filler content can reduce the mechanical strength of the cementitious material, making the battery susceptible to cracking and failure under load.

3.3. Penetration solution

In some studies, highly electrolytic solutions such as alkalis or salts were absorbed into solid cement-based materials [22, 33]. The main task of these solutions is to provide the necessary ions to promote electrochemical reactions occurring at the electrodes, as well as fill the pores in the microstructure of cement-based materials, creating better ion transmission environment, thereby helping to increase battery performance.

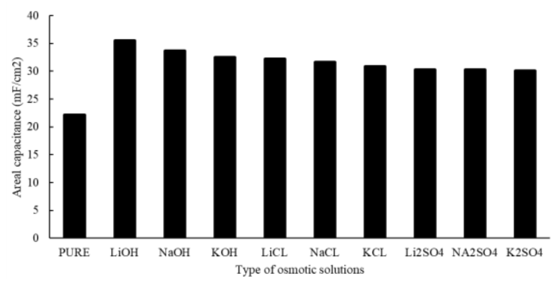


Figure 6. *Effect of osmotic solution on battery capacitance [34]*

Figure 6 shows the results of research by Fang and Zhang [34] on the effectiveness of different penetrating solutions for cement mortar on the capacitance per unit area of the material, converted in mF/cm^2. Penetrating solution was used at 2% volume for all cases, and the red data represents the capacitance of the material when no penetrating solution was used. The results show that using osmotic solution significantly increases the capacitance of the material, in which alkaline solution is more effective than chloride and sulfate-based salt solutions. In addition, the use of electrolytic solutions to improve the ion transmission medium in cement-based materials requires attention to the volatility of the solution, which reduces the effectiveness of this solution over time. Therefore, studying gel electrolyte stimulators [35] maybe a potential future research direction.

3.4. Electrode type and spacing

Electrodes play a key role in optimizing the performance and lifespan of cementitious batteries. The first criterion in choosing electrode materials is the ability to occur oxidation-reduction reactions with the electrolyte to create free ions. In general, a material with good conductivity can enhance the electron exchange capacity and reduce the internal resistance of the battery, thereby improving the energy storage and supply performance. Besides, the surface properties of the electrode determine the contact surface area between the electrode and the electrolyte, which also affects the ion exchangeability, that is, the performance and capacity of the battery. The high porosity of the electrode material also facilitates the retention of more ions. However, it should be noted that high surface porosity can also create the opposite effect because it is easy to form impurity layers that form insulating films, thereby reducing the interaction between the electrode and the electrolyte. At the same time, corrosion resistance when interacting with cement-based materials is also an important characteristic to consider because it helps prolong the life of the battery.

Table 3. *The standard electrode potential of materials against the hydrogen comparison electrode [36]*

Materials	Electrode	Standard electrode potential (V)
Magnesium		-2.363
Aluminium	↑ Anot	-1.662
Zinc		-0.763
Iron		-0.440
Nickel		-0.250
Copper	Cathot ↓	+0.345
Platinum		+1.200
Gold		+1.498

Table 3 presents the values Standard voltage according to the galvanic series of some materials, used to predict the ability of a material to donate and accept electrons from redox reactions [36]. A higher positive standard electrode potential indicates a stronger ability to be reduced, meaning the substance more easily accepts electrons. Conversely, a lower negative standard electrode potential indicates a stronger ability to be oxidized, meaning the substance more easily donates electrons. Based on this principle, it can be explained why materials such as magnesium, aluminum or zinc are often used for the anode, while copper is mainly used for the cathode because it is cheaper than gold or platinum. Additionally, Figure 7 shows the battery current delivered over time for cementitious batteries with different electrode materials [22]. Figure 7 shows the highest battery performance when using magnesium for the anode and copper for the cathode, following the principles in Table 2.

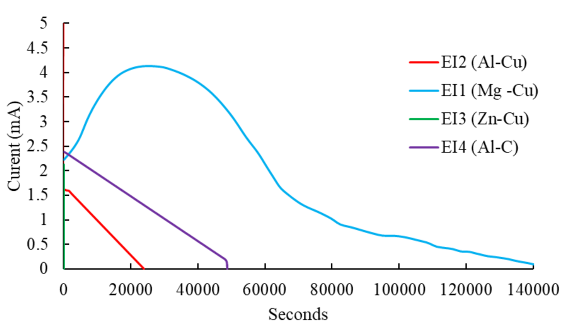


Figure 7. *Effect of electrode material on the current supplied by the battery [22]*

In addition, Figure 8 shows the effect of electrode distance on current intensity and battery life from the study of Byrne et al. [22]. With the distance between the aluminum anode and copper cathode varied in the range of 5-80mm, there was no obvious change in the battery's intensity-time relationship. This proves that with the same type of electrode material and electrolyte, the distance between the electrodes does not significantly affect the performance of the cement-based battery.

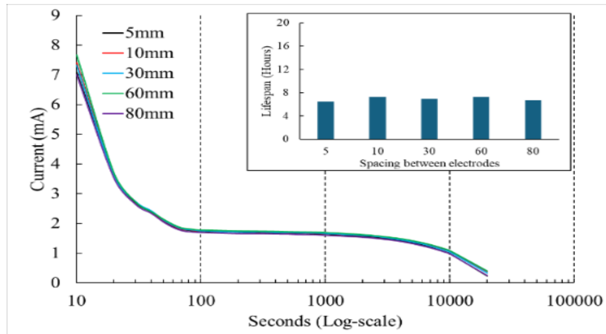
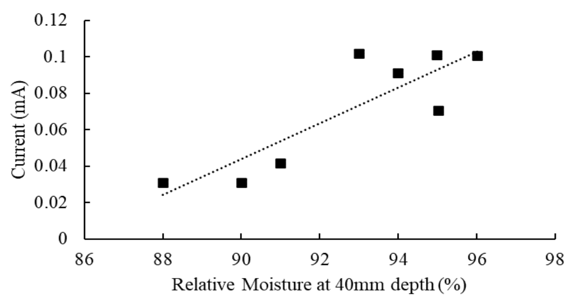


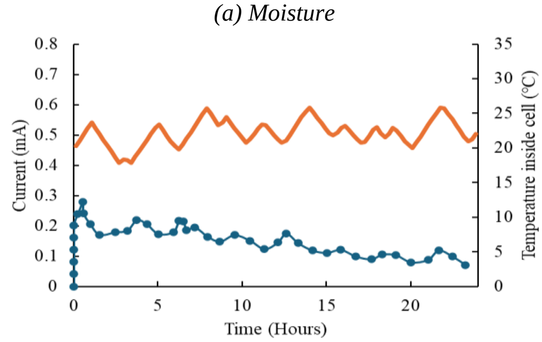
Figure 8. *Effect of electrode distance on battery performance and life [22]*

3.5. Environmental factors

Environmental factors including temperature and humidity can also affect the performance of cementitious batteries. Basically, increasing humidity helps create a better ion transmission environment and increase the electrical conductivity of the material [28], especially for highly porous materials. Figure 9(a) shows the relationship between the moisture content of cement mortar at a depth of 40mm from the surface and the supplied current intensity from the study of Byrne et al. [20]. The results show a high correlation between humidity values and current intensity. However, maintaining humidity at a stable level and not causing electricity to leak into the surrounding environment is one of the scientific challenges that needs to be researched. Additionally, increasing amperage through humidity can reduce battery life, due to negative effects on corrosion of cement as well as metal electrodes.



(a) Moisture



(b) Temperature

Figure 9. *The influence of the environment on the intensity of current supplied by the battery [20]*

Meanwhile, high temperatures enhance electronic oscillations in the material, thereby increasing the speed and current delivered by the battery. Figure 9(b) shows the results of Byrne et al. [17], showing that the oscillating current intensity increases and decreases in response to the increase or decrease in temperature measured inside the cementitious material. However, it should be noted that increasing the battery's supply capacity can reduce battery life through increasing mechanical stresses and breaking the inherent microstructure of the material over repeated use.

4. Research challenges and prospects

With the above analysis, it can be said that batteries using cement-based materials are attracting interest in the field of energy storage thanks to its extremely large potential. However, to put this technology into practice, there are still many technical challenges that need to be resolved.

First, one of the biggest challenges is to optimize stable ion transmission properties while ensuring the inherent mechanical properties such as strength, permeability, and durability of cement-based materials when used as an electrolyte in batteries but also as a structural component in construction. Previous studies have shown that increasing porosity, as well as adding conductive materials such as metal, activated carbon, and graphene in different shapes and sizes from micro to nano within the microstructure can be effective. potential solution. For example, the addition of metal-based or carbon-based powder fillers with large surface contact areas is effective in creating a conductive network within the cementitious material. However, these fillers tend to agglomerate, creating uneven dispersion within the microstructure, making the conductive network they create unstable. In addition, agglomeration also creates an uneven pore system, affecting other mechanical properties of the original cementitious material. Therefore, research on aggregate composition, construction methods as well as optimization of filler size needs to be continued in the future.

Second, despite creating a suitable cementitious electrolytic material, catalytic alkaline solutions are still being used in combination to create an electrolytic environment. However, this is only a temporary solution because this solution can evaporate or lose significantly during battery operation under the influence of the environment. To solve this problem, further research is needed on the development of solid or gel electrolytes that can maintain stability in harsh environments. These electrolytes need to have good ionic conductivity and be compatible with cement while being unaffected by changes in temperature and humidity. In addition, designing protective structures for concrete batteries to prevent evaporation and loss of alkaline solution is also an important research direction.

Third, the maximum voltage, voltage maintenance time as well as lifespan are important parameters to evaluate the performance of cement-based material batteries. However, these values are still too low compared to the current battery system, meaning the energy loss is still too high for the cement-based battery system. Therefore, before finding solutions to reduce this energy loss, basic research is needed to clarify in more detail the energy loss mechanism in cement-based materials, thereby proposing solutions. Suitable approaches include both material and structural methods.

Finally, one of the exciting prospects of concrete batteries is their ability to absorb and self-convert renewable energy, particularly solar energy. Integrating photovoltaic materials into the cement structure could enable concrete batteries to generate energy from sunlight and store it for later use. This could open up many new applications in the fields of construction and renewable energy. For example, photovoltaic nanoparticles such as titanium oxide or perovskite can be embedded into cement to create efficient light-absorbing surfaces [37, 38]. When exposed to light, these particles can convert solar energy into electrical energy and store it within the battery structure. However, integrating photovoltaic materials into cement also presents many chemical and mechanical compatibility challenges. It is essential to ensure that the photovoltaic particles do not degrade the cement's strength and can operate stably under harsh environmental conditions.

5. Conclusion

This study has presented general principles, analyzed factors affecting battery performance as well as the potential and challenges of batteries using cement-based materials towards the development of sustainable energy solutions. Sustainability, an extremely important but still new topic to engineers and scientists in the construction industry. In general, initial research in this field has come to conclusions about the feasibility of using cement-based materials to develop new-generation batteries. The basic principle of these solutions is to optimize the ion transmission environment inside the cementitious material so that it can be used as an electrolyte in solid-state batteries. Experimental results show that there are many factors that significantly affect the performance of cement-based materials batteries including porosity, functional filler composition, osmotic solution, electrode material as well as effects temperature and humidity.

Although current research demonstrates the potential of cementitious batteries, the overall performance of these batteries is still significantly lower than that of current conventional batteries. Therefore, to advance towards commercialization and large-scale implementation of this solution, significant research efforts from the scientific community are still required. Research directions aimed at optimizing ion conductivity properties while balancing the inherent mechanical properties of cement-based materials, extending energy storage duration, and integrating renewable energy sources into the material are crucial in the near future.

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