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Invited Review Article

Energy storage potential of cementitious materials: Advances, challenges and future Directions

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ABSTRACT

This review paper investigates the use of cementitious materials for energy storage, emphasizing their role in advancing sustainable development. It starts with a comprehensive overview of energy storage technologies and explores the key properties of cementitious materials that make them suitable for energy storage, alongside the challenges and opportunities they present. The review covers different energy storage mechanisms, including chemical, thermal, and electrical methods, highlighting the efficiency and capacity of each approach. Performance evaluation is addressed through specific criteria, experimental techniques, and case studies, with numerical outcomes provided to illustrate the effectiveness of these materials in energy storage. The paper also discusses potential applications in energy infrastructure and construction, identifying emerging technological advancements and trends. Environmental and economic considerations, such as sustainability benefits and cost analysis, are evaluated in detail. Finally, the review summarizes key insights, outlines the implications for sustainable energy systems, and offers specific recommendations for future research and development to optimize the use of cementitious materials in energy storage.

1. Introduction

Energy storage technologies serve as the backbone of modern energy systems, essential for bridging the gap between intermittent renewable energy generation and consistent energy demand. Among the various storage methods, electrochemical storage stands out for its versatility and widespread applications. Lithium-ion batteries, renowned for their high energy density and efficiency, power everything from smartphones to electric vehicles, enabling mobility and electrification while reducing carbon emissions [33,107,145,167]. Additionally, emerging battery technologies like solid-state batteries promise even greater energy density and safety, poised to revolutionize energy storage further [190,173,64].

The growing interest in energy-efficient buildings has spurred research into the latent heat storage capacity of cementitious materials. This involves incorporating phase change materials (PCMs) within the matrix, allowing the materials to absorb, store, and release thermal energy, thereby moderating temperature fluctuations in buildings [183,76,155,164]. Moreover, advancements in material science have led to the development of smart cementitious composites that can store electrical energy through mechanisms such as electrochemical reactions. These innovations contribute to a dual functionality of cement in structures, enabling them to act as both load-bearing elements and energy storage systems [146,14,57]. As the global push towards renewable energy sources intensifies, the integration of energy storage capabilities into traditional building materials like cement is pivotal. It not only enhances the energy efficiency of buildings but also contributes to reducing carbon emissions, aligning with broader sustainability goals. The potential for cementitious materials to function as effective energy storage systems represents a significant advancement in construction technology and sustainability practices.

Supercapacitors complement batteries with their ability to rapidly charge and discharge, making them ideal for applications requiring quick bursts of power, such as regenerative braking in electric vehicles or grid stabilization. Furthermore, advancements in supercapacitor technology, including increased energy density and improved cycling stability, hold promise for expanding their role in energy storage solutions [171,62,158,185,50]. Mechanical energy storage methods offer scalable and cost-effective solutions. Pumped hydroelectric storage, leveraging gravitational potential energy by pumping water uphill

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during periods of low demand and releasing it downhill during peak hours, remains one of the most established and efficient energy storage technologies globally. Compressed air energy storage (CAES) similarly capitalizes on surplus electricity by compressing air and storing it in underground caverns or tanks for later use in power generation, offering flexibility and grid stability [43,83,18,105].

Thermal energy storage systems harness the inherent properties of materials like molten salts or phase change materials to store and release heat or cold. These systems find applications in various sectors, from heating and cooling buildings to optimising energy production in concentrated solar power plants [104,120,63,118,186]. By capturing excess energy during periods of low demand and releasing it when needed, thermal energy storage enhances energy efficiency and reduces reliance on fossil fuels. The collective impact of these energy storage technologies extends far beyond mere energy storage; they are catalysts for a more sustainable, reliable, and resilient energy future. Through their continued advancement and integration into energy systems worldwide, they pave the way for a greener, more efficient, and decentralized energy landscape.

Energy storage plays a critical role in advancing sustainable development, serving as a linchpin for achieving multifaceted objectives such as energy security, economic prosperity, and environmental stewardship. Its significance lies in its ability to address the inherent intermittency of renewable energy sources like solar and wind. By capturing surplus energy generated during periods of high production and releasing it strategically during times of peak demand or low renewable energy availability, energy storage systems effectively mitigate the variability and intermittency associated with renewables. This ensures a reliable and stable energy supply, enabling the seamless integration of renewable energy into the grid and fostering a sustainable energy future.

Furthermore, energy storage plays a pivotal role in enhancing grid flexibility and resilience. It enables the integration of distributed energy resources, such as rooftop solar panels and community microgrids, into the existing energy infrastructure, thereby decentralizing power generation and reducing dependence on centralized fossil fuel-based power plants [55,74,39,3]. This decentralized approach not only enhances energy security but also promotes local economic development and empowers communities to take control of their energy future. Moreover, energy storage technologies contribute to reducing greenhouse gas emissions by enabling the displacement of fossil fuel-based power generation with clean, renewable energy sources [154,128,121,67]. By facilitating the transition to a low-carbon energy system, energy storage accelerates progress towards mitigating climate change and achieving sustainability goals. In essence, energy storage is a cornerstone of sustainable development, offering solutions to address energy access challenges, combat climate change, and foster economic growth while ensuring environmental protection and social equity. Its integration into energy systems worldwide is essential for building a resilient and sustainable future for generations to come.

The aim of this paper is to comprehensively investigate the utilisation of cementitious materials for energy storage, emphasising their pivotal role in sustainable development. By providing an overarching view of energy storage technologies, the paper seeks to delve into the specific properties of cementitious materials relevant to energy storage applications. It aims to explore various energy storage mechanisms within cementitious materials, spanning chemical, thermal, and electrical methods. Through rigorous assessment criteria, experimental techniques, and case studies, the paper aims to evaluate the performance of cementitious materials for energy storage. Ultimately, it aims to synthesise key findings, discuss implications for sustainable energy development, and suggest future research pathways.

This paper's novelty lies in its focus on cementitious materials as a novel avenue for energy storage, addressing a gap in existing literature. Unlike conventional studies that concentrate on established storage technologies, this paper explores the unique properties and potential of cementitious materials across chemical, thermal, and electrical storage methods. By integrating experimental results and case studies, it aims to provide a comprehensive evaluation of these materials' performance and their implications for sustainable energy solutions. This novel approach promises to broaden the scope of energy storage technologies and offers new insights into enhancing sustainability and efficiency in energy systems.

2. Cementitious materials and energy storage

2.1. Properties of cementitious materials relevant to energy storage

Cementitious energy storage refers to the use of cement-based materials, such as concrete, to store and manage energy. This involves incorporating energy storage capabilities into concrete structures or composites, either by leveraging the thermal mass of concrete for sensible heat storage or integrating phase change materials (PCMs) to absorb and release thermal energy. Unlike other energy storage methods, such as batteries or pumped hydro, cementitious storage utilizes the inherent properties of cementitious materials to enhance energy management. This approach is particularly suitable for large-scale, durable applications, offering benefits in terms of thermal stability, scalability, and integration into existing infrastructure.

Cementitious materials exhibit a range of properties that render them highly relevant for energy storage applications, encompassing thermal, chemical, and structural considerations. Firstly, their inherent porosity provides an extensive surface area conducive to accommodating various energy storage mediums [92,42,76,96]. This porous structure allows for efficient diffusion and adsorption of gases, liquids, or solid-state materials, enabling effective energy storage and release within the material matrix. By optimising pore size and distribution, cementitious materials can enhance their energy storage capacity and efficiency. Secondly, the thermal conductivity of cementitious materials can be tailored to suit specific energy storage requirements [132,94,127,98]. This property is crucial for thermal energy storage applications, where efficient heat transfer is essential. By adjusting the composition and microstructure, cementitious materials can exhibit desired levels of thermal conductivity, enabling effective heat storage and exchange during thermal energy storage processes.

Cementitious materials possess excellent chemical stability, ensuring long-term durability and reliability in energy storage applications [95,168,141,181,135]. They can withstand exposure to high temperatures, aggressive chemical environments, and cyclic loading without significant degradation, ensuring sustained performance over extended periods. In terms of structural integrity, cementitious materials boast robust mechanical properties, including high compressive strength and durability. These properties are essential for supporting energy storage systems and withstanding mechanical stresses during operation. Additionally, their compatibility with reinforcing materials allows for the construction of durable and stable energy storage structures capable of withstanding various environmental conditions.

Ettringite, a common hydrate present in cement-based materials, possesses a distinctive ability to store energy at high density but operates at relatively low temperatures, typically around 60 °C [28,29,30,31]. This property has sparked interest in utilising ettringite for thermal energy storage (TES) systems, particularly in applications where moderate temperature differentials are encountered. In TES systems, ettringite's reversible dehydration and rehydration process serve as the mechanism for storing and releasing thermal energy. At elevated temperatures, ettringite undergoes dehydration, effectively storing thermal energy within its crystal lattice [15,81,17,100,86,161]. Conversely, when the temperature decreases, it readily rehydrates, releasing the stored energy in a controlled manner. This characteristic makes ettringite-based TES systems promising for efficiently harnessing and utilising thermal energy from renewable or waste heat sources, such as solar thermal energy or industrial processes. Such systems could find applications in various sectors, including residential and commercial heating and cooling, industrial process heat, and electricity generation through concentrated solar power systems. By leveraging the energy storage capabilities of ettringite, researchers aim to enhance the efficiency and sustainability of energy-intensive processes, contributing to the global transition towards cleaner and more sustainable energy technologies.

In a standalone house, employing ettringite-based thermal energy storage can significantly enhance energy efficiency, particularly during the summer months when ample solar energy is available. This approach involves utilising evacuated tube solar air collectors installed on the roof to capture solar radiation. These collectors generate high-temperature hot air, often exceeding 120 °C. This hot air is then directed into the thermal energy storage system, where ettringite, known for its low dehydration reaction temperature of approximately 60 °C, undergoes dehydration. This process allows the storage system to effectively absorb and store the thermal energy in the form of chemical energy within the ettringite. Importantly, the performance of this system is directly influenced by the temperature of the hot air, with higher temperatures resulting in greater heat storage capacity. Therefore, by harnessing solar energy to generate high-temperature hot air and leveraging the unique properties of ettringite, homeowners can optimise their energy usage, reduce reliance on traditional heating methods, and contribute to sustainability efforts. Fig. 1 illustrates this concept, showcasing the integration of solar air collectors and the thermal energy storage system within the house's infrastructure.

Environmental compatibility is another key advantage of cementitious materials. They are produced using abundant raw materials such as limestone and clay, and can incorporate supplementary cementitious materials like fly ash or slag, further enhancing their eco-friendliness. This sustainable production process aligns with the principles of environmental stewardship and resource conservation, making cementitious materials an attractive option for sustainable energy storage solutions. Furthermore, cementitious materials offer flexibility in formulation, allowing for the incorporation of additives or functional fillers to enhance specific energy storage properties [36,7,179,9]. This versatility enables customisation of cementitious composites to meet the diverse requirements of different energy storage applications, further extending their utility and applicability. The unique combination of porosity, thermal conductivity, chemical stability, structural integrity, environmental compatibility, and formulation flexibility makes cementitious materials highly relevant and promising for a wide range of energy storage applications. Their utilisation holds significant potential for advancing sustainable energy storage technologies and addressing the evolving energy needs of society.

Baquerizo et al. [17] conducted a modelling study on the practical stability of ettringite under varying conditions (see Fig. 2), leveraging experimental data and extending theoretical insights through the Van't Hoff equation. While the overall trends and zones aligned with previous models, discrepancies emerged particularly below 60 °C, notably regarding reformation. Additionally, theoretical thermodynamic stability curves for ettringite and *meta*-ettringite were plotted without hysteresis. It was estimated that at 25 °C, ettringite would reform from *meta*-ettringite when relative humidity (RH) exceeds 62 %, while at 70 °C, ettringite is deemed unstable at RH levels below 15 %. Specific formulations, labelled as Ett30-32 for ettringite and Met13 for *meta*-ettringite, were positioned on the reformation and decomposition curves, respectively. These findings, derived from a limited quantity of ettringite powder, suggest a consistent water removal process under constant conditions, without significant localized variations in partial conditions within the samples.

Cementitious materials are emerging as promising candidates for energy storage applications due to their unique properties and widespread availability. Table 1 provides a comparative Analysis of Cementitious Materials for Energy Storage Portland cement, being the most traditional and widely used, provides moderate energy density and is effective for thermal and chemical energy storage. However, its energy density (0.5–1.0 Wh/kg) and efficiency (80–90 %) are relatively modest compared to newer materials. Despite its limitations, its established use and low cost make it a practical choice. Geopolymer cement, with its higher energy density (1.0–2.0 Wh/kg) and efficiency (85–95 %), demonstrates superior performance in storing energy. Its chemical composition, which includes silicon and aluminium oxides, enhances its energy storage capabilities and cycling stability. However, the higher cost may restrict its application in certain scenarios. Calcium sulphoaluminate cement provides a balance between performance and cost. It offers decent energy density (0.8–1.5 Wh/kg) and good cycling stability, though its efficiency (75–85 %) is lower compared to geopolymers. This balance makes it suitable for applications where cost and performance are both crucial considerations.

Magnesium-based cement supports both thermal and electrical energy storage with an energy density range of 0.6–1.2 Wh/kg and moderate efficiency. While its higher cost may be a drawback, its ability to handle different types of energy storage can be advantageous for specific applications. Overall, while traditional Portland cement remains cost-effective, materials like geopolymer and calcium sulphoaluminate cements offer better energy storage performance and stability. Magnesium-based cement provides versatility but at a higher price. The choice of material depends on the specific energy storage requirements,

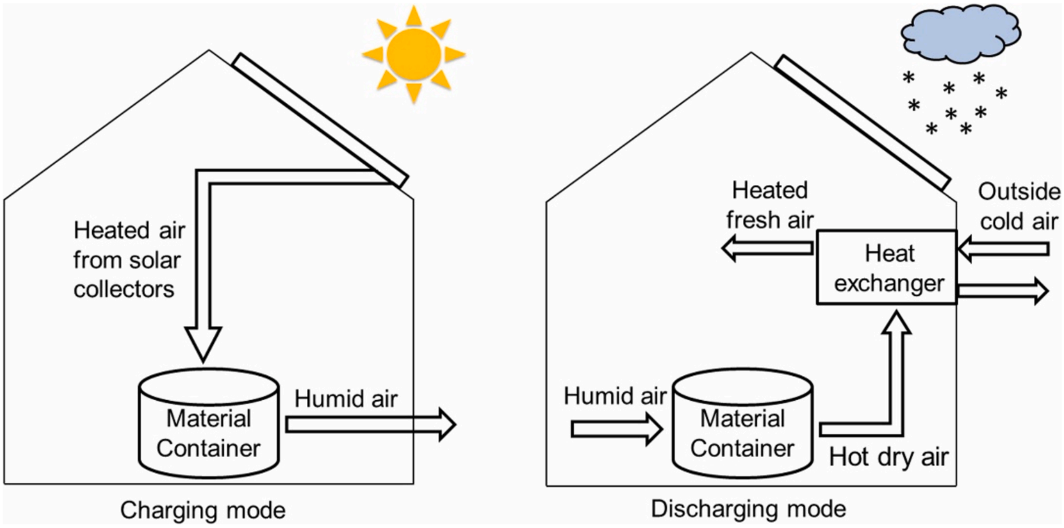

Fig. 1. A possible concept of charging mode (left) and discharging mode (right) of solar thermal energy storage by ettringite materials for a single-family house [69].

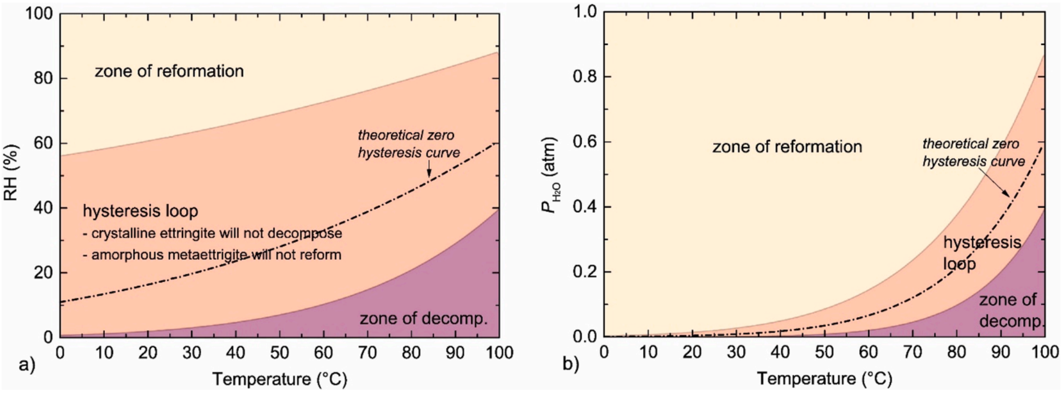

Fig. 2. Curves of reformation (left, equation of best fit: $RH = 56.608 + 0.186\ T + 0.001T^2$) and decomposition (right, equation of best fit: $RH = 0.327 + 0.108\ T - 0.002T^2 + 4.8E\text{-}5T^3$) as function of RH in (a) or P_{H2O} in (b) and temperature showing the separated zones. Dashed line represents the theoretical stability limit of ettringite [17].

Table 1
Comparative Analysis of Cementitious Materials for Energy Storage: Chemical Compositions and Performance Metrics.

Material	Chemical Composition	Energy Storage Mechanism	Energy Density (Wh/kg)	Charge/ Discharge Efficiency	Cycling Stability	Reference
Portland Cement	CaO, SiO_2, Al_2O_3, Fe_2O_3	Thermal, Chemical	0.5–1.0	80–90 %	Moderate	[49]
Geopolymer Cement	SiO_2, Al_2O_3, Na_2O, K_2O	Chemical	1.0–2.0	85–95 %	High	[175]
Calcium Sulphoaluminate	CaO, Al_2O_3, SO_3	Chemical	0.8–1.5	75–85 %	High	[10]
Magnesium-based Cement	MgO, SiO_2, CaO	Thermal, Electrical	0.6–1.2	70–80 %	Moderate	[108]

including performance, cost, and the type of energy storage needed.

2.2. *Factors affecting energy storage properties of various cementitious materials*

Energy storage in cementitious materials is influenced by several key factors. The chemical composition of the material plays a significant role, as the inclusion of supplementary cementitious materials (SCMs) like fly ash, slag, or silica fume can enhance energy storage. These SCMs improve the material's thermal and electrical properties due to their fine particles and high reactivity, which increase surface area and porosity, contributing to better energy absorption and retention. Porosity and density are also crucial factors. Materials with higher porosity have more voids, allowing them to store more energy, particularly thermal energy, by trapping air or water. However, excessive porosity can reduce structural strength. Conversely, materials with higher density generally have fewer pores, which can limit energy storage but provide increased strength. Achieving the right balance between porosity and density is important for optimizing energy storage while maintaining material integrity.

The internal microstructure of cementitious materials, including the size, shape, and distribution of pores, affects their energy storage capabilities. A well-developed microstructure with interconnected pores allows for better thermal and electrical conductivity, which enhances energy storage and transfer. Moisture content also influences energy storage. Water within the pores can enhance thermal mass, improving the material's ability to absorb and store heat. However, improper moisture management can lead to degradation issues, such as freeze–thaw damage. Finally, curing conditions impact the hydration process, which affects the material's microstructure and overall properties. Proper curing ensures the development of a strong, stable structure that supports effective energy storage. Inadequate curing can result in incomplete hydration and a weaker material with reduced energy storage capabilities. Balancing these factors—chemical composition, porosity, microstructure, moisture content, and curing—helps optimize the energy storage properties of cementitious materials for various applications. Table 2 provides a comparative overview of different energy-storage materials, considering their type, capacity, advantages, and disadvantages. Each material has its own specific use cases and suitability depending on the application and requirements.

2.3. *Current challenges and opportunities in energy storage using cementitious materials*

Energy storage using cementitious materials presents both challenges and opportunities as researchers and engineers navigate the complexities of developing efficient and reliable systems. One significant challenge is optimising the energy storage capacity and efficiency of cementitious materials. While their inherent porosity provides a foundation for energy storage, enhancing their capacity and improving the kinetics of energy storage and release processes remain areas of active research. Strategies such as tailoring the pore structure, modifying the chemical composition, and incorporating nano-scale additives show promise in enhancing energy storage performance.

Addressing the long-term durability and stability of cementitious energy storage systems is another critical challenge. Cementitious materials must withstand harsh environmental conditions, including temperature variations, moisture exposure, and chemical attack, without compromising their structural integrity or energy storage capabilities. Research efforts focus on developing durable and resilient cementitious composites through advanced material characterisation, modelling, and testing methodologies [187,153,32,40,170]. Moreover, ensuring cost-effectiveness is essential for the widespread adoption of cementitious energy storage technologies. While cementitious materials themselves are relatively low-cost and abundant, optimising production processes, scaling up manufacturing, and minimising lifecycle costs pose economic challenges. Innovations in materials synthesis, manufacturing techniques, and system integration are essential to reducing costs and improving the economic viability of cementitious energy storage systems.

Despite these challenges, numerous opportunities exist for advancing energy storage using cementitious materials. Integrating cementitious energy storage systems with renewable energy sources, such as solar and wind, presents opportunities for enhancing grid stability, promoting

Table 2
Comparative Overview of Various Energy Storage Materials.

Material	Energy Storage Type	Energy Storage Capacity	Advantages	Disadvantages
Cementitious Materials	Thermal and some electrical energy storage	Moderate (varies with composition)	Good thermal mass, durability, and structural benefits	Lower energy storage capacity compared to specialized materials
Phase Change Materials (PCMs)	Thermal energy storage	High (depending on PCM type)	High energy density, effective for temperature regulation	Can be expensive, phase change may affect material stability
Lithium-Ion Batteries	Electrical energy storage	High (150–200 Wh/kg)	High energy density, long cycle life, high efficiency	Expensive, potential safety issues, limited thermal storage
Supercapacitors	Electrical energy storage	Moderate (5–10 Wh/kg)	High power density, fast charge/discharge cycles	Lower energy density, high cost per unit of energy stored
Flywheel Energy Storage	Mechanical energy storage	High (varies with design)	High efficiency, fast response time, long life cycle	Expensive, requires maintenance, space-intensive
Thermal Energy Storage Systems (e.g., molten salt)	Thermal energy storage	Very high (up to 2000 Wh/kg)	Effective for large-scale storage, high capacity	Expensive, complex to manage, potential safety issues
Hydrogen Storage	Chemical energy storage	High (varies with storage method)	High energy density, versatile use (fuel cells, combustion)	Expensive, storage and transport challenges, safety concerns

renewable energy integration, and reducing carbon emissions. Additionally, leveraging the widespread availability of cementitious materials and existing infrastructure offers opportunities for deploying energy storage solutions at various scales, from residential to industrial applications. Collaborative efforts among researchers, industry stakeholders, and policymakers are critical for overcoming these challenges and unlocking the full potential of energy storage using cementitious materials. By addressing technical, economic, and regulatory barriers, cementitious energy storage technologies can play a pivotal role in transitioning towards a sustainable and resilient energy future.

2.4. Previous research and developments

Previous research and developments have highlighted the promising energy storage potential of cementitious materials, shedding light on their multifaceted role beyond conventional construction applications. Cementitious materials, primarily composed of cement, sand, and aggregates, have garnered attention due to their ability to store and release energy through various mechanisms.

One notable avenue of exploration involves the integration of phase change materials (PCMs) within cementitious matrices. PCMs possess the ability to store and release large amounts of thermal energy during phase transitions, thus enhancing the thermal properties of cementitious composites. Research has focused on optimising the composition and distribution of PCMs within cementitious materials to maximise energy storage capacity while maintaining structural integrity. Furthermore, advancements in nanotechnology have enabled the development of cement-based nanocomposites with enhanced energy storage capabilities. Nano-sized additives, such as carbon nanotubes and graphene, have been incorporated to improve electrical conductivity and capacitance, facilitating the storage of electrical energy within the cementitious matrix. Moreover, researchers have explored the feasibility of utilising waste materials, such as fly ash and slag, as supplementary cementitious materials for energy storage applications. These waste materials not only contribute to sustainable development but also exhibit unique properties conducive to energy storage, such as high surface area and chemical reactivity.

The energy storage potential of cementitious materials has been extensively explored and validated through various studies, as evidenced by the references provided. These studies collectively highlight the versatility and efficacy of cement-based composites for storing and releasing thermal, electrical, and even mechanical energy. Xu & Li [168] investigated the performance of novel thermal energy storage engineered cementitious composites incorporating a paraffin/diatomite composite phase change material. Their findings demonstrated the feasibility of utilising phase change materials within cementitious matrices to enhance thermal energy storage capabilities. [113,114,115] conducted modelling and experimental studies on low-temperature energy storage reactors using innovative cementitious materials. Their research emphasized the potential of these materials for thermal energy storage applications, paving the way for practical implementations. Lavagna et al. [91] provided a preliminary characterisation and theoretical analysis of cementitious composite materials for thermal energy storage applications, further validating the suitability of such materials for energy storage purposes.

Saafi et al. [134] explored the multifunctionality of geopolymeric cementitious composites, demonstrating their capability for both electrical energy storage and self-sensing structural applications, showcasing the diverse functionalities of cement-based materials beyond traditional roles. Brooks et al. [23] and Halder et al. [65] investigated the incorporation of phase change materials encapsulated within fly ash cenospheres, offering insights into enhancing thermal energy storage capacities while maintaining the mechanical stability of cementitious materials. Almotlaq et al. [9] proposed enhancing self-sensing and energy storage capabilities of cementitious composites through marine sand doping, showcasing innovative approaches to improving the multifunctionality of cement-based materials. Yousefi et al. [178] developed novel form-stable phase change material composites using recycled expanded glass for thermal energy storage in cementitious composites, contributing to sustainable energy storage solutions. Sam et al. [135] conducted thermo-physical and mechanical investigations of cementitious composites enhanced with microencapsulated phase change materials, further validating the potential of such materials for thermal energy storage applications.

While the referenced studies underscore the promising energy storage potential of cementitious materials, a critical evaluation reveals several considerations. Many studies focus on specific aspects like thermal or electrical energy storage, lacking holistic assessments. Additionally, scalability and practical implementation remain understudied, with limited real-world applications. Furthermore, long-term durability and environmental impacts of incorporating additives like phase change materials warrant further investigation. Overall, while cementitious materials show promise for energy storage, future research should prioritize comprehensive evaluations, scalability, and sustainability to bridge the gap between laboratory findings and practical applications. Table 3 summarizes recent advancements in cementitious materials focused on energy storage, highlighting various research areas such as phase change materials, electrical energy storage, and the use of waste materials.

Recent advancements in cementitious materials have expanded their applications beyond traditional construction, with notable progress in energy storage technologies. These materials, historically used for their

Table 3
Cementitious Materials as Multifunctional Energy Storage Systems: A Review.

Research Focus	Materials Used	Key Findings	References
Integration of Phase Change Materials (PCMs)	Paraffin/ diatomite composites	Enhanced thermal energy storage capabilities in cementitious composites.	Xu & Li [168], Brooks et al. [23]
Electrical Energy Storage	Graphene and carbon nanotubes	Improved electrical conductivity and capacitance for energy storage applications.	Xu et al. [169], Saafi et al. [134]
Waste Material Utilization	Fly ash and slag	Sustainable energy storage solutions with unique properties for enhancing performance.	[113,114,115]; Yousefi et al. [178]
Multifunctional Applications	Geopolymeric composites and piezoelectric materials	Capability for both electrical energy storage and self-sensing applications.	Halder et al. [65],Wang et al. [159]
Hybrid Systems	Cement composites with embedded PCMs	Improved thermal and mechanical properties for energy efficiency in buildings.	Lavagna et al. [91],Yu et al. [181]
Form-Stable PCMs	Recycled expanded glass	Development of novel composites for thermal energy storage, promoting sustainability.	Yousefi et al. [178],Sam et al. [135]
Self-Sensing Materials	Smart cementitious composites	Enhanced monitoring of structural integrity while providing energy storage capabilities.	Saafi et al. [134],Almotlaq et al. [9]
Environmental Impact Studies	Cementitious materials with natural additives	Evaluated sustainability and long-term durability of energy storage solutions.	[114,115]; Brooks et al. [23]
Energy Harvesting from Mechanical Stress	Piezoelectric cement composites	Ability to convert mechanical stress into electrical energy from environmental vibrations.	Wang et al. [159],Xu et al. [169]
Thermal Energy Storage Applications	Cementitious composites with encapsulated PCMs	Significantly boosts thermal storage capacity for solar energy applications.	Yang et al. [174],Halder et al. [65]

structural properties, are now being adapted to meet the growing demands for efficient and sustainable energy storage solutions. In the realm of electrochemical energy storage, researchers have explored incorporating conductive additives, such as graphene and carbon nanotubes, into cementitious matrices. These additives enhance the electrical conductivity of the materials, making them suitable for use in supercapacitors and batteries. For instance, Xu et al. [169] demonstrated that graphene-enhanced cement composites exhibit high specific capacitance and excellent cycling stability, offering a promising alternative to conventional electrochemical storage materials.

Thermal energy storage has also seen innovations with the integration of phase change materials (PCMs) into cementitious matrices. This approach improves the material's ability to store and release thermal energy while maintaining its structural integrity. Research by Yang et al. [174], Brooks et al. [23] and Yu, et al. [181] have shown that encapsulating PCMs within cementitious materials significantly boosts their thermal storage capacity. Such materials are particularly useful for building applications where they can store excess solar energy and release it when needed, contributing to energy efficiency in structures. Piezoelectric cementitious materials represent another exciting development. By embedding piezoelectric fibres or particles into cement matrices, these materials can convert mechanical stress into electrical energy. Wang et al. [159] have reported promising results in harnessing energy from environmental vibrations, providing a novel approach to energy harvesting.

3. Types of energy storage in cementitious materials

Cementitious materials exhibit various energy storage mechanisms, encompassing chemical, thermal, and electrical storage. Chemical energy storage involves incorporating phase change materials within cement matrices, allowing reversible chemical reactions to store and release energy. Thermal storage utilises the high heat capacity of cementitious composites, enabling them to absorb and release thermal energy efficiently. Electrical storage leverages nanotechnology to enhance conductivity, enabling the storage of electrical energy within the cementitious matrix. Each mechanism offers distinct advantages, highlighting the multifunctional potential of cementitious materials in energy storage applications.

3.1. Chemical energy storage

Chemical energy storage in cementitious materials involves two primary processes: carbonation and hydration/dehydration reactions. Carbonation entails the absorption of carbon dioxide from the atmosphere by cementitious materials, leading to the formation of carbonates, which store chemical energy. Hydration and dehydration reactions involve the absorption and release of water molecules during the curing and drying phases of cement, respectively, storing and releasing energy in the process. These mechanisms enable cementitious materials to store and release energy through chemical transformations, providing a versatile approach to energy storage within construction materials.

3.1.1. Carbonation of cementitious materials

Carbonation of cementitious materials involves the chemical reaction between carbon dioxide (CO_2) from the atmosphere and calcium hydroxide ($Ca(OH)_2$) present in cement-based matrices, forming calcium carbonate ($CaCO_3$) and water. This process offers a unique avenue for energy storage within cementitious materials. During carbonation, the exothermic reaction releases heat energy, which can be stored within the material [45,124,75]. This stored energy can later be utilised for various purposes, such as space heating or process heat in buildings, thereby reducing the reliance on external energy sources. Additionally, the carbonation process is reversible, allowing the stored energy to be released when needed. Furthermore, the carbonation reaction helps in enhancing the durability and mechanical properties of cementitious materials. The formation of calcium carbonate within the pore structure of the cement matrix can improve its density and strength, contributing to the overall performance and longevity of structures [106,79,140,54].

Carbonation of cementitious materials serves as a sustainable approach to energy storage, utilising readily available atmospheric CO_2 to store and release heat energy. It offers a promising avenue for improving the energy efficiency and resilience of buildings and infrastructure while reducing carbon emissions associated with conventional heating systems. Additionally, it aligns with the principles of circular economy by utilising waste CO_2 as a valuable resource for energy storage.

3.1.2. Hydration and dehydration reactions

Hydration and dehydration reactions are fundamental processes within cementitious materials, integral to their setting, hardening, and energy storage capabilities. Hydration initiates when water is introduced to cement particles, prompting a series of exothermic chemical reactions. During hydration, compounds like tricalcium silicate react with water to form calcium silicate hydrates (C-S-H) and calcium hydroxide ($Ca(OH)_2$) [27;125,188;102;25;166]. This process releases heat known as the heat of hydration, crucial for the initial curing and strength development of concrete.

The heat generated during hydration presents a valuable opportunity for energy storage. By capturing and storing this thermal energy within the material, concrete can serve as a thermal reservoir. This stored heat can be utilised for space heating, particularly beneficial in colder climates or during periods of high energy demand. Additionally, it can supplement industrial processes requiring thermal energy, enhancing energy efficiency and reducing reliance on external energy sources. Furthermore, dehydration occurs as the hydrated cementitious matrix loses water, typically during the drying phase of concrete curing. Although dehydration releases less heat compared to hydration, it still contributes to the overall thermal dynamics of the material. Capturing and utilising the heat released during dehydration can further enhance energy storage capabilities, providing additional opportunities for energy-efficient design and construction practices [11,13,101].

The synergy between hydration and dehydration reactions not only influences the mechanical properties and durability of concrete but also offers pathways for sustainable energy storage. By harnessing these processes, cementitious materials become effective thermal reservoirs, contributing to energy efficiency and resilience in the built environment. Leveraging the heat of hydration and dehydration represents a promising avenue for sustainable construction practices, aligning with efforts to mitigate climate change and promote resource efficiency. Ultimately, integrating energy storage capabilities into cementitious materials advances the transition towards a more sustainable and resilient infrastructure.

3.2. Thermal energy storage

Thermal energy storage in cementitious materials is facilitated through two main methods: utilising phase change materials (PCMs) and thermochemical energy storage. Heat storage using PCMs involves embedding materials capable of undergoing phase transitions within cement matrices, enabling the absorption and release of thermal energy during solid–liquid phase changes. Thermochemical energy storage utilises chemical reactions within the cementitious materials to absorb and release heat, providing a means of storing thermal energy through reversible chemical processes. Both approaches offer effective means of thermal energy storage, enhancing the versatility and sustainability of cement-based composites in various applications.

3.2.1. Heat storage using phase change materials (PCMs)

Heat storage using phase change materials (PCMs) represents a cutting-edge approach to thermal energy management, offering significant potential for enhancing energy efficiency and sustainability in various applications. PCMs are substances capable of undergoing phase transitions, such as melting or solidification, at specific temperature ranges while storing or releasing large amounts of latent heat in the process. This unique property makes them ideal candidates for thermal energy storage. In the context of cementitious materials, integrating PCMs offers several advantages. By embedding PCM capsules or fibres within the cement matrix, the material gains the ability to store and release thermal energy efficiently. During the phase transition from solid to liquid (melting) or liquid to solid (solidification), PCMs absorb or release latent heat without a significant change in temperature, enabling the storage or release of thermal energy at a constant temperature. Fig. 3 illustrates the heating and cooling behaviour of a Phase Change Material (PCM). Leveraging the substantial latent heat capacity of PCM renders it a viable supplement or even alternative to conventional cooling systems.

One of the key benefits of using PCMs in cementitious materials is their ability to stabilize indoor temperatures. During hot periods, PCMs absorb excess heat from the surrounding environment, preventing overheating and reducing the need for air conditioning. Conversely, during colder periods, PCMs release stored heat, helping to maintain comfortable indoor temperatures without excessive reliance on heating systems. Moreover, PCM-enhanced cementitious materials contribute to energy efficiency in buildings by reducing peak energy demand and enhancing thermal comfort for occupants. By moderating temperature fluctuations, they can also extend the lifespan of building components,

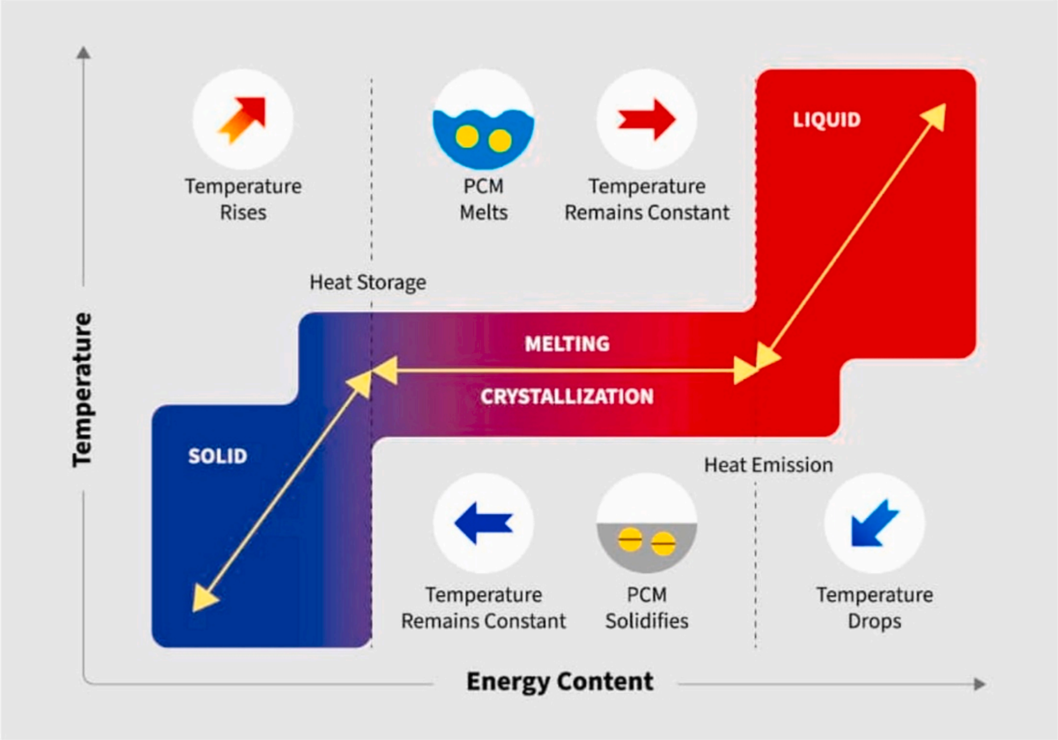

Fig. 3. Schematic drawing representing a PCM during absorption and release of heat [176].

such as HVAC systems, by minimising thermal stress and fatigue. Furthermore, PCM integration aligns with sustainable construction practices by reducing energy consumption, lowering greenhouse gas emissions, and promoting resource efficiency. As the demand for energy-efficient buildings grows, PCM-enhanced cementitious materials offer a viable solution for achieving sustainability goals while enhancing occupant comfort and reducing operational costs.

D'Alessandro et al. [36] conducted multi-physics thermomechanical research on novel concretes with paraffin-based PCM for structural-thermal multifunctional applications in high-energy-efficiency building envelopes. Their study, illustrated in Fig. 4, introduced a composite incorporating both traditional Microencapsulated Phase Change Materials (MPCMs) and innovative Macro-encapsulated PCMs with an 18 °C phase transition temperature. Results confirmed the thermal benefits of PCM and indicated that integrating PCM into concrete reduced mass density by nearly double the PCM's weight. While PCM addition generally decreased average compressive strength, it had a minimal impact on the coefficient of variation, suggesting promising structural reliability of the material.

PCM integration into building materials like concrete and mortar is effective for thermal energy storage due to their appropriate heat transfer rates. Studies by Entrop et al. [47] and Faraji [51] demonstrated PCM's impact on concrete floors and walls, showing temperature decreases and increases during specific periods. While PCM integration with burned clay bricks is challenging due to production temperatures, it's feasible with cement-based bricks, though leakage concerns exist. Various studies, including those by Sarı et al. [136],Hekimoğlu et al. [70],Hekimoğlu et al. [71], explored different PCM-cement composites, showing promising melting temperatures, latent heats, and mechanical strengths. Gencel et al. [58] and Gencel et al. [59] examined PCM incorporation into cement using bottom ash and blast furnace slag, indicating reduced CO_2 emissions compared to coal. Additionally, PCM integration into foam concrete and gypsum-based materials shows potential for temperature reduction, despite some loss in mechanical strength. Other approaches involve adding PCM layers between concrete blocks or within cement plaster, as demonstrated by Arivazhagan et al. [12] and Sarı et al. [137], respectively, showing significant indoor temperature reductions. Overall, PCM-infused building materials offer promising solutions for energy-efficient construction, despite some trade-offs in mechanical properties.

3.2.2. *Thermochemical energy storage*

Thermochemical energy storage (TES) in cementitious materials represents a cutting-edge approach to storing and releasing thermal energy through reversible chemical reactions. Unlike conventional methods, which rely on physical storage mechanisms such as phase change materials or capacitive energy storage, thermochemical storage harnesses the heat generated or absorbed during chemical reactions within the material itself. In cementitious materials, thermochemical energy storage can be achieved by incorporating certain compounds capable of undergoing reversible reactions that absorb or release heat. For example, the hydration and dehydration reactions of certain salts or hydrates can store and release thermal energy as they transition between different chemical states.

The TES method involves storing heat through a reversible thermochemical process, as outlined by Abedin & Rosen [2]. This approach boasts a higher storage density compared to other Thermal Energy Storage (TES) methods, thus minimising both mass and space requirements for storage facilities. In the literature, discussions typically revolve around two types of Thermochemical Energy Storage systems: sorption-based and reaction-based. Definitions of these systems vary from one author to another, as noted in references [117,41]. Fig. 5 illustrates the charging, storage, and discharging processes of sorption-based Thermal Chemical Energy Storage. Charging involves an endothermic process where external heat is supplied, leading to the dissociation of the sorbent and sorbate. These dissociated components can then be stored separately at ambient temperature. During discharging, the sorbent and sorbate are recombined to form the original substrate, resulting in the generation of heat. This exothermic reaction releases heat that can be utilised for various purposes.

Fig. 6 depicts the cycle of reaction-based Thermochemical Energy Storage, which comprises three key stages: charging, storage, and discharging. Charging initiates with an endothermic reaction, wherein solar thermal collectors supply the reaction heat (ΔH) to the thermochemical material (TCM). This reaction leads to the dissociation of the TCM into products A and B. Charging can be further subdivided into three sequential steps [54]. Firstly, the TCM is preheated to its dissociation temperature. Then, in the second step, the actual reaction occurs, elevating the energy of the TCM by the enthalpy of the reaction. Finally, in the third step of charging, the TCM is cooled to the storage temperature. Following the recovery of sensible heat, the resulting products (A and B) are stored separately, with no change in their chemical potential during storage. During discharging, the stored energy is released through an exothermic reaction by recombining the products A and B to regenerate AB.

One of the key advantages of thermochemical energy storage in cementitious materials is its high energy density and long-term storage capabilities. Chemical reactions can store a significant amount of energy per unit mass compared to physical storage methods, allowing for compact and efficient energy storage solutions. Additionally, thermochemical storage can maintain stored energy for extended periods without significant degradation, making it suitable for applications requiring long-term energy storage, such as seasonal heat storage for buildings or renewable energy systems. Furthermore, thermochemical energy storage offers flexibility in terms of operating temperature and energy release profiles. By selecting appropriate chemical compounds

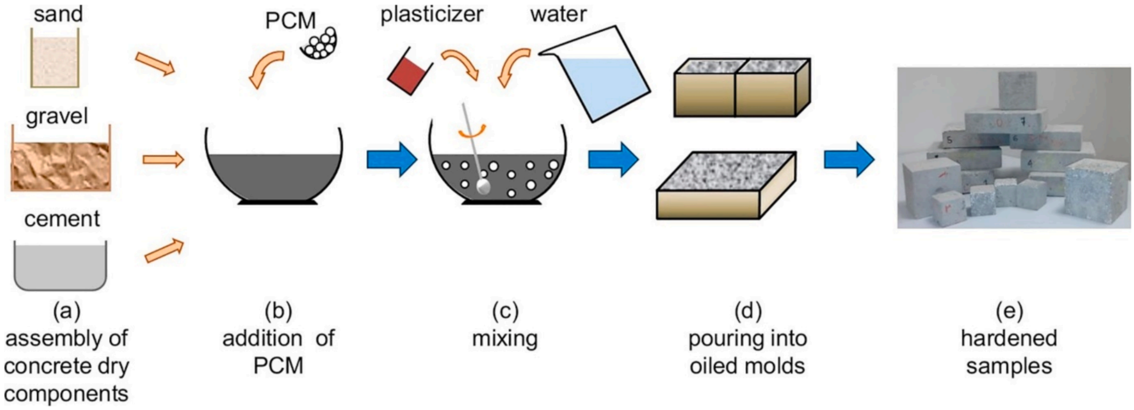

Fig. 4. Preparation procedures of concrete samples with microPCM and macroPCM [36]

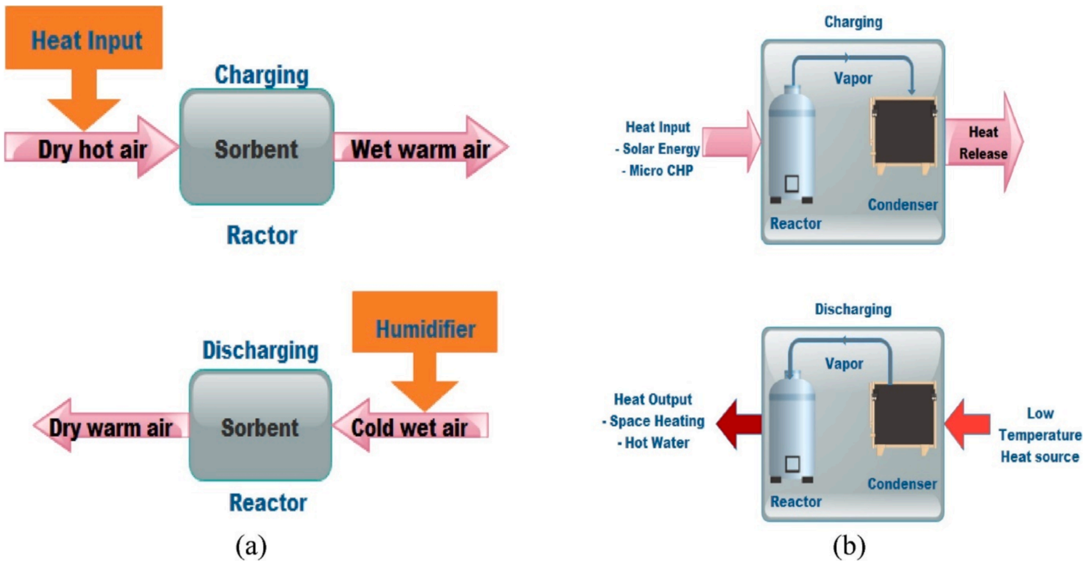

Fig. 5. Working principle of sorption energy storage: (a) open system, and (b) closed system [180].

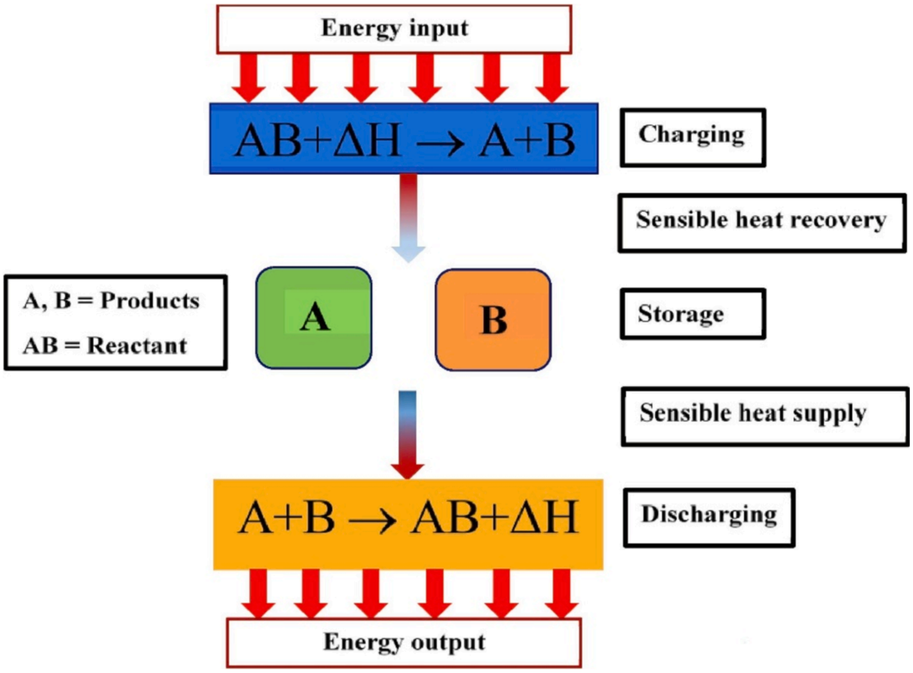

Fig. 6. TCES cycle: charging, storage and discharging [37].

and reaction conditions, engineers can tailor the storage system to meet specific energy storage requirements, such as temperature range, energy capacity, and response time. This versatility makes thermochemical storage suitable for a wide range of applications, from residential heating and cooling to industrial process heat and energy grid management. Moreover, thermochemical energy storage in cementitious materials aligns with the growing demand for sustainable and resilient infrastructure solutions. By leveraging the inherent properties of concrete and integrating advanced materials technology, thermochemical storage can contribute to energy-efficient buildings, smart infrastructure networks, and sustainable urban development.

3.2.3. *Sensible heat storage*

Sensible heat storage systems using cement water tanks, such as the Ecovat system from the Netherlands, offer a practical approach to thermal energy storage. The Ecovat system utilizes a large, underground tank constructed from durable cementitious materials to store heated water. This setup allows for the efficient retention of thermal energy over extended periods. In this system, water is heated to a high temperature when excess thermal energy is available, such as from renewable sources like solar thermal collectors or from industrial waste heat. The cement tank's substantial thermal mass enables it to store a significant amount of heat, making it possible to manage energy supply and demand effectively. This stored heat can be used during times of high demand or when energy supply is low, providing a stable and reliable heat source.

One of the main benefits of this approach is the tank's durability and low maintenance requirements, as cement-based tanks are built to last. They can be scaled to meet various energy needs, from residential heating to industrial applications. However, initial costs can be high due to construction and installation, and effective thermal insulation is essential to minimize heat losses. The system also requires considerable space, which may limit its feasibility in certain locations. Overall, the Ecovat system demonstrates how cement water tanks can be effectively used for thermal energy storage, optimizing the use of renewable energy and waste heat. While there are considerations regarding cost, insulation, and space, the benefits of durability and scalability make it a valuable solution for sustainable energy management.

3.3. *Electrical energy storage*

Electrical energy storage in cementitious materials encompasses capacitive and conductive mechanisms. Capacitive energy storage involves the accumulation of electrical charge within the interfaces of cementitious composites, utilising the high surface area and porous structure to store energy electrostatically. Conductive energy storage exploits the incorporation of conductive additives, such as carbon nanotubes or graphene, enhancing the material's electrical conductivity and enabling the storage of electrical energy through the movement of electrons. Both approaches offer promising avenues for storing electrical energy within cement-based materials, paving the way for applications in smart infrastructure and renewable energy systems.

3.3.1. *Capacitive energy storage*

Capacitive energy storage is a technology that utilises electrical capacitors to store and release electrical energy. Unlike traditional batteries, which rely on chemical reactions for energy storage, capacitors store energy in an electric field between two conductive plates separated by a dielectric material. This allows capacitors to charge and discharge rapidly, making them well-suited for applications requiring high power density and fast response times. In the context of cementitious materials, capacitive energy storage can be achieved by incorporating conductive additives, such as carbon nanotubes or graphene, into the cement matrix. These additives enhance the material's electrical conductivity, allowing it to act as a capacitor and store electrical energy. Zhang et al. [184] innovatively integrated graphene, carbon fibre, and hierarchical porous carbon to create a flexible "carbon-concrete" capacitor film suitable for adaptable applications like wearable electronics. Shi & Zhang [147] introduced a 3D porous cementitious electrolyte with "stream-reservoir" channels, aiming to enhance structural electrochemical capacitor performance. Peri et al. [119] proposed an advanced in-plane device configuration for thin film electrochemical capacitors, exploring design innovations. Lal & Batabyal [89] extended carbon-cement applications to solar steam generation. Bilal et al. [20] focused on enhancing CO_2 capture with carbon-cement electrochemical capacitors, showcasing their adaptability. Collectively, these studies contribute to understanding the scalability, diverse applications, and innovative design features of carbon-cement electrochemical capacitors, paving the way for cross-disciplinary applications in energy storage and beyond. The Carbon-cement supercapacitors are shown in Fig. 7.

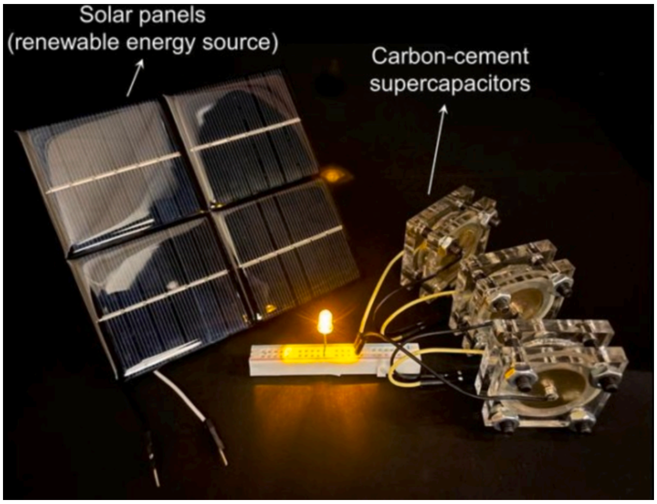

Fig. 7. Carbon-cement supercapacitors (Electronic [46].

Several recent studies have highlighted the scalability and diverse applications of carbon-cement electrochemical capacitors for energy storage solutions. Chanut et al. [26] emphasized scalability, addressing large-scale energy storage needs by assessing materials, fabrication processes, and electrochemical performance. Their fundings are summarised in Fig. 8. In this Figure (A) An Electric Double Layer Capacitor (EDLC) consists of two polished carbon-cement electrodes saturated with electrolyte (1 M KCl), separated by a glassy fibre membrane soaked in the same electrolyte, and covered by conductive graphite paper. The electrodes are prestressed within a closed cell to enhance contact between the charge collectors and electrodes. (B-1/B-2) Steady-state cyclic voltammetry (CV) measures current (I) during cyclic charge/discharge at different scan rates for two carbon-cement electrode samples prepared with varying carbon blacks, water-to-cement ratios, and electrode thickness. (C-1) Steady-state galvanostatic charge–discharge (GCD) measures voltage (U) with a constant current (I0) over time (t0), then removed until $U = 0$. (C-2) Fractional exponent α varies with applied current in GCD experiments. (D-1/D-2) Capacitance measurements converge from CV and GCD tests towards a rate-independent specific capacitance with the mass of carbon black in the electrode. (E) Eight different carbon-cement electrode materials exhibit a characteristic scaling of rate-dependent CV capacitance, indicating high-rate capability. (F) Hardness versus capacitance plot shows the trade-off between high-rate capability and material strength with varying water-to-cement ratios in electrode materials.

One of the primary advantages of capacitive energy storage in cementitious materials is its ability to facilitate self-monitoring and self-sensing capabilities. By integrating conductive additives, the material can detect changes in electrical properties, such as resistance or capacitance, in response to external stimuli, such as mechanical stress or temperature variations. This enables the material to function as a sensor, providing real-time feedback on structural integrity or environmental conditions. Capacitive energy storage offers potential applications in smart infrastructure and structural health monitoring. By embedding capacitive sensors within concrete structures, engineers can continuously monitor for signs of damage or deterioration, allowing for timely maintenance and repair. This proactive approach to infrastructure management can extend the lifespan of civil infrastructure and enhance public safety. Furthermore, capacitive energy storage in cementitious materials aligns with the growing demand for sustainable and resilient infrastructure solutions. By leveraging the inherent properties of concrete and incorporating advanced materials technology, capacitive energy storage can contribute to energy-efficient buildings, intelligent infrastructure networks, and sustainable urban development.

3.3.2. *Conductive energy storage*

Conductive energy storage is a burgeoning field that explores the integration of conductive materials into cementitious matrices to enable the storage and release of electrical energy. Unlike traditional batteries, which rely on chemical reactions, conductive energy storage relies on the movement of electrons within a conductive network embedded in the material. This approach offers several advantages, including high power density, rapid charging and discharging rates, and enhanced safety compared to conventional battery systems.

In cementitious materials, conductive energy storage can be achieved by incorporating conductive additives, such as carbon nanotubes, graphene, or carbon fibres, into the cement matrix. These additives create a network of pathways for electron transport, allowing the material to store and release electrical energy efficiently. One of the primary benefits of conductive energy storage in cementitious materials is its potential application in structural health monitoring and self-sensing

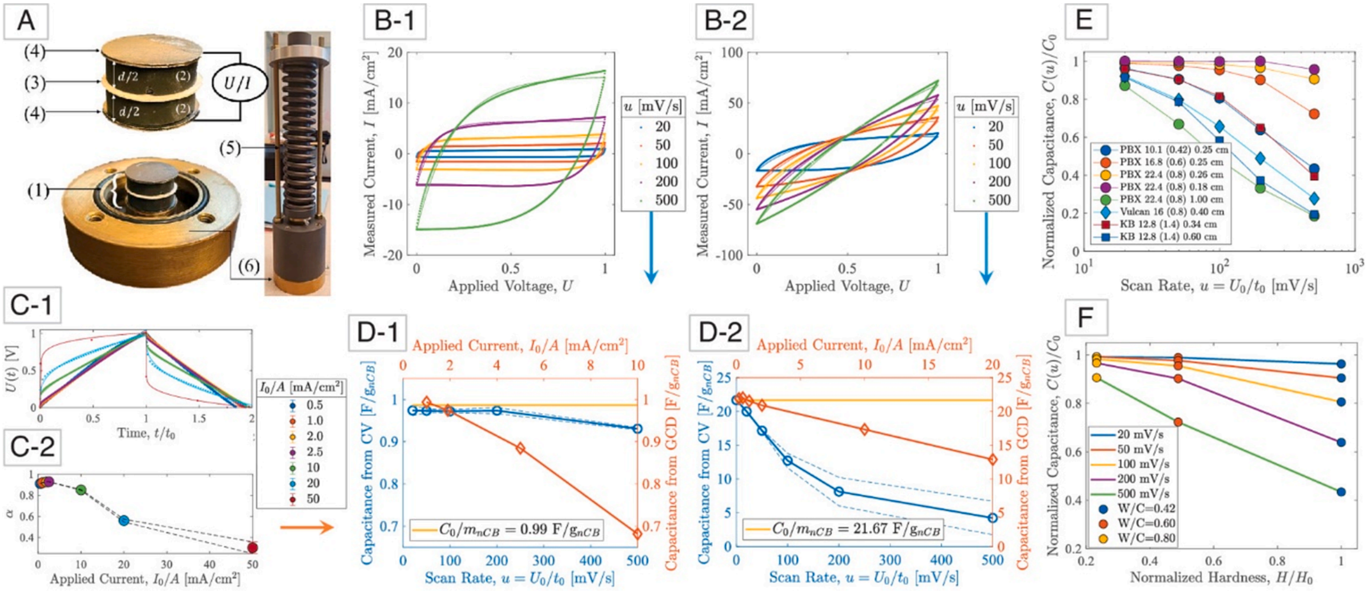

Fig. 8. Capacitance Measurements and Analysis [26].

technologies. By embedding conductive materials within concrete structures, engineers can create intelligent infrastructure networks capable of monitoring for signs of damage or deterioration in real-time. Changes in electrical conductivity or resistance can indicate the presence of cracks, corrosion, or other structural defects, enabling timely maintenance and repair.

Maglogianni et al. [103] examined the thermal conductivity (λ) and specific heat capacity (C_p) of mortars enhanced with varying amounts of carbon nanotubes (CNTs) (see Fig. 9). They observed that the addition of CNTs, up to the percolation threshold of 0.1 wt%, gradually boosts the thermal conductivity from 0.8 W/(m·K) to 1.44 W/(m·K). At this loading, a well-established thermally conductive network greatly facilitates uninterrupted phonon transport when an electrical charge is applied, limiting the thermal energy storage capacity, resulting in the highest thermal conductivity and lowest specific heat capacity values. However, increasing the CNT content leads to a decrease in thermal conductivity. This is attributed to the higher CNT concentration providing a larger surface area per unit volume of mortar, consequently increasing the CNT/matrix interfacial area significantly. It is speculated that this enlarged interfacial area potentially contributes to resistance in thermal flow, known as interfacial thermal resistance, leading to declines in the nanocomposites' thermal conductivity. Further investigation is necessary for a comprehensive understanding of this mechanism.

Conductive energy storage offers opportunities for energy harvesting and self-powered sensors in civil infrastructure. By harnessing ambient energy sources, such as vibrations, temperature differentials, or electromagnetic radiation, conductive materials embedded in concrete structures can generate electrical power for sensing and monitoring applications. This self-powered approach eliminates the need for external power sources or batteries, reducing maintenance costs and environmental impact. Additionally, conductive energy storage in cementitious materials aligns with the growing demand for sustainable and resilient infrastructure solutions. By leveraging the structural capabilities of concrete and integrating advanced materials technology, conductive energy storage can contribute to energy-efficient buildings, smart infrastructure networks, and sustainable urban development.

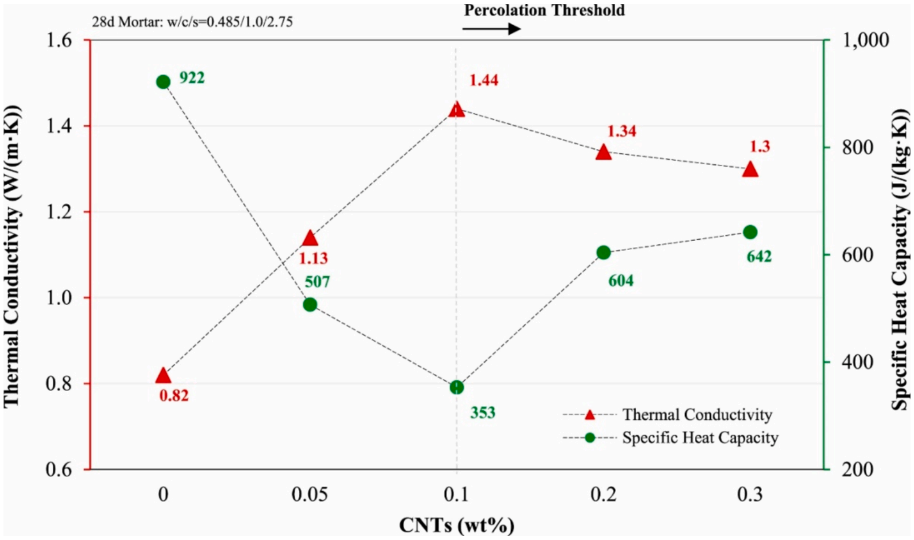

Fig. 9. Thermal conductivity (λ) and Specific heat capacity (C_p) of 28-day mortars reinforced with CNTs at amounts of 0.05%, 0.1%, 0.2%, and 0.3 wt% [103].

3.4. Potential synergies and integration of cementitious materials with other energy storage technologies

The potential synergies between cementitious materials and various energy storage technologies offer significant advantages for enhancing the performance and sustainability of energy systems. Cementitious materials, such as concrete, can be effectively integrated with electrochemical storage technologies like batteries to improve thermal management. Concrete's thermal mass helps absorb and store excess heat generated by batteries, which can mitigate temperature fluctuations and enhance battery performance, extending its lifespan and efficiency. Furthermore, concrete structures can provide durable and safe housing for electrochemical storage systems.

Incorporating cementitious materials with mechanical storage systems, such as pumped hydro storage or compressed air energy storage (CAES), leverages their structural strengths. Concrete is extensively used in constructing reservoirs for pumped hydro systems, offering the necessary durability and stability. For CAES, concrete provides a robust solution for containing compressed air, ensuring the system's reliability and efficiency. This synergy enhances the overall effectiveness of mechanical storage systems by utilizing the resilience and longevity of cementitious materials. Additionally, cementitious materials naturally support thermal energy storage due to their high thermal mass. When combined with phase change materials (PCMs), concrete can significantly improve the storage and release of thermal energy. This integration allows buildings to store excess thermal energy from renewable sources or waste heat, which can then be used during peak demand periods or when renewable energy availability is low. This approach not only boosts building energy efficiency but also reduces reliance on traditional heating and cooling systems, leading to energy savings and improved thermal comfort.

Overall, the integration of cementitious materials with various energy storage technologies creates hybrid systems that enhance energy management, improve system resilience, and support sustainable energy practices. These combined approaches offer a comprehensive solution for optimizing performance and contributing to a more efficient and sustainable energy infrastructure.

3.5. Potential synergies between the use of cementitious materials for energy storage and other sustainable construction practices

Integrating cementitious materials for energy storage with other sustainable construction practices, such as the use of recycled materials and waste reduction, offers substantial synergistic benefits. The use of recycled materials, like concrete aggregates and industrial by-products such as fly ash and slag, significantly reduces the demand for virgin resources and lowers carbon emissions associated with cement production. These practices not only enhance sustainability but also contribute to a circular economy by reusing materials that would otherwise be discarded.

Recycling and incorporating industrial by-products into cementitious materials can also improve their performance. For instance, adding recycled glass can enhance thermal insulation properties, complementing the thermal energy storage capabilities of concrete. This synergy results in more efficient energy storage and reduced heating and cooling demands, leading to greater overall energy efficiency in buildings. Moreover, waste reduction strategies align well with energy storage systems. By repurposing waste products, such as using waste glass or plastic fibres in concrete, construction waste is minimized, reducing landfill use and repurposing materials that would otherwise contribute to environmental pollution. This approach supports a more sustainable construction cycle by integrating waste reduction into energy storage infrastructure.

Economically, the use of recycled materials and waste reduction can lower construction costs. Recycled materials typically cost less than virgin resources, and utilizing waste products can reduce disposal expenses. This economic advantage makes energy storage systems more financially feasible and encourages their broader adoption. Finally, the lifecycle impact of materials is significantly improved by these practices. By incorporating recycled materials and focusing on waste reduction, the environmental footprint of cementitious materials is reduced, aligning with broader sustainability goals and contributing to a more resource-efficient and resilient built environment. Overall, the integration of these practices with energy storage systems represents a holistic approach to sustainable construction, offering both environmental and economic benefits.

4. Performance evaluation of cementitious materials for energy storage

4.1. Criteria for assessing energy storage capabilities

Table 4 presents a comprehensive overview of the criteria for evaluating the energy storage potential of cementitious materials. It highlights key factors such as thermal conductivity, specific heat capacity, durability, and cycling stability, which are crucial for assessing the performance of these materials in energy storage applications. Additionally, the table includes considerations related to scalability, environmental impact, and phase change behaviour, providing insights into the feasibility and sustainability of cementitious energy storage systems. By addressing these criteria, researchers and engineers can make informed decisions when selecting and designing cementitious materials for efficient and reliable energy storage solutions.

4.2. Experimental techniques and characterisation methods

Table 5 offers a comprehensive summary of experimental techniques and characterisation methods essential for evaluating the energy storage potential of cementitious materials. It delineates various approaches, including thermal analysis, microstructural analysis, mechanical testing, and long-term stability testing, each serving distinct purposes in assessing material properties. Furthermore, additional techniques such as thermal conductivity and specific heat capacity measurements, X-ray diffraction, and Fourier transform infrared spectroscopy provide further insights into thermal behaviour, structural composition, and chemical characteristics. By delineating advantages and limitations, the table equips researchers and engineers with valuable information for selecting appropriate methods to comprehensively evaluate cementitious materials for energy storage applications.

4.3. Case studies and real-world examples

In regions with high daytime temperatures and cooler nights, such as the Middle East, optimising thermal comfort in buildings is essential. The Dubai Municipality's Al Mamzar Beach Development project addresses this challenge by incorporating PCM-enhanced concrete into the walls of beach cabanas [35]. These PCM-enhanced walls act as thermal batteries, absorbing excess heat during the day and releasing it at night when temperatures drop. By reducing the need for mechanical cooling during peak daytime hours, the PCM-enhanced concrete contributes to energy savings and improved occupant comfort.

The University of California, Los Angeles (UCLA) has developed an innovative concrete-based solar thermal energy storage system designed to offer a sustainable and efficient solution for capturing and utilizing solar energy. Unlike traditional photovoltaic solar panels that convert sunlight directly into electricity, this system addresses the challenge of energy storage, which is critical for ensuring the availability of solar energy during periods when sunlight is not available. UCLA's system employs cementitious materials enhanced with specialized heat-absorbing particles. These particles are integrated into the concrete matrix, allowing the material to absorb and store thermal energy during the day when solar radiation is at its peak. As sunlight strikes the

Table 4
Criteria for Assessing Energy Storage Potential of Cementitious Materials.

Criteria	Description	Importance	Examples
Thermal Conductivity	Measure of the material's ability to conduct heat efficiently. Higher values indicate better heat transfer capability.	High	High thermal conductivity concrete, aerogel-based cementitious composites
Specific Heat Capacity	Amount of heat energy required to raise the temperature of a unit mass of material by one degree Celsius. Higher values indicate greater energy storage capacity.	High	Cementitious materials with high specific heat capacity, PCM-infused concretes
Durability and Stability	Long-term ability of the material to withstand environmental conditions, mechanical stresses, and thermal cycling without significant degradation.	High	Fiber-reinforced cementitious composites, alkali-activated cements
Cycling Stability	Capacity of the material to maintain performance over repeated cycles of energy storage and release.	Medium	Carbon nanotube-enhanced cementitious materials, self-healing concrete
Scalability and Manufacturability	Assessment of the material's feasibility for large-scale production and deployment. Includes considerations such as material availability, production processes, and installation costs.	Medium	Standard Portland cement, fly ash-based concretes, alternative binder formulations
Environmental Impact	Evaluation of the material's environmental footprint, including embodied energy, carbon footprint, and potential for recycling or reuse.	Medium	Eco-friendly additives, recycled aggregates, low-carbon footprint cements
Phase Change Behaviour	Incorporation of phase change materials (PCMs) to store energy through reversible phase transitions. Evaluation includes PCM selection, phase change temperature(s), and compatibility with cementitious matrices.	Low	PCM-infused concretes, PCM microcapsules embedded in cementitious composites

concrete, the embedded particles absorb the solar heat and transfer it to the surrounding concrete. This stored heat remains within the concrete even after the sun has set, thanks to the thermal mass of the material, which has the ability to retain and gradually release heat. This stored thermal energy can be utilized for various applications, such as space heating, water heating, or other thermal processes. By leveraging the thermal storage capabilities of the concrete, UCLA's system provides a reliable means to utilize solar energy beyond daylight hours. This approach not only enhances the efficiency of solar energy systems by addressing the intermittency of solar power but also contributes to sustainability by reducing reliance on conventional energy sources. The use of concrete-based systems for solar thermal storage presents several advantages. Concrete, being a widely available and durable material, makes the system cost-effective and practical for large-scale applications. Additionally, the integration of heat-absorbing particles into the concrete improves its energy storage capacity and performance, making it a promising solution for advancing solar energy technologies and supporting sustainable energy practices.

Energy Vault's grid-scale energy storage system is a pioneering application of cementitious materials designed to address the intermittent nature of renewable energy sources such as wind and solar power [87]. Traditional energy storage systems, including batteries, often struggle with issues like high costs, limited lifespan, and resource constraints. Energy Vault's approach offers a scalable and economically viable alternative by leveraging the physical properties of concrete. The system utilizes large concrete blocks, each weighing up to 35 metric tons. These blocks are strategically lifted and stacked using cranes, storing potential energy in their elevated positions. This process is akin to a massive mechanical battery, where the potential energy is stored as gravitational energy. When there is a need for electricity, the blocks are carefully lowered. As they descend, the gravitational energy is converted into electrical power through a series of mechanical and electrical systems designed to capture and convert the energy efficiently. This innovative method capitalizes on the abundance and low cost of concrete, making the system both affordable and sustainable. By using concrete blocks, which are durable and have a long lifespan, Energy Vault's technology minimizes the environmental impact and operational costs associated with conventional battery storage systems. The system's reliance on gravitational potential energy also allows for large-scale energy storage and release, making it a promising solution for stabilizing the grid and enhancing the reliability of renewable energy sources.

In the Netherlands, researchers are investigating an innovative concept that involves transforming roads into energy storage systems [38]. This approach leverages the existing infrastructure to enhance energy efficiency and support the transition to renewable energy sources. The key idea is to embed cementitious materials in road surfaces with conductive additives such as graphene or carbon nanotubes. These additives enhance the material's electrical conductivity, enabling the roads to function as dynamic energy storage and transmission systems. The integration of conductive materials into the road surface allows the roads to store and transmit electrical energy. This capability could facilitate inductive charging for electric vehicles (EVs) that are equipped with compatible technology. As these vehicles travel over electrified roads, they can receive a charge wirelessly, eliminating the need for stationary charging stations and potentially extending the range of EVs. This development could significantly reduce the reliance on traditional charging infrastructure and support more efficient and flexible transportation options. Moreover, the road infrastructure could serve as a repository for excess energy generated from renewable sources, such as solar or wind power. During times of low energy demand, this surplus energy could be stored within the road system. When demand spikes, the stored energy could be released and utilized, helping to balance the grid and reduce strain on conventional power sources. This dual functionality—supporting EV charging and stabilizing the energy grid—demonstrates a forward-thinking approach to integrating renewable energy and sustainable transportation solutions into everyday infrastructure.

RMIT University's research on hydrogen storage in concrete offers a promising advancement for the future of renewable hydrogen storage and transportation [4]. Hydrogen is celebrated for its potential as a clean and renewable energy carrier due to its zero-emission byproducts. However, one of the significant challenges with hydrogen is finding efficient and safe methods for its storage and transport. RMIT's innovative approach addresses this challenge by integrating a magnesium-based compound into concrete. The process involves impregnating concrete with this compound, which has the capability to absorb and release hydrogen gas. Concrete's inherently porous structure is advantageous for this application, as the numerous pores increase the surface area available for hydrogen absorption. This allows the material to hold a substantial amount of hydrogen. The core of this technology is the reversible chemical reaction between hydrogen and the magnesium-based compound. During storage, hydrogen gas is absorbed by the concrete, where it chemically interacts with the magnesium compound, forming a stable hydride. When the hydrogen is needed, the reaction is reversed, releasing the hydrogen gas in a controlled manner. This process allows for efficient and manageable storage and release of hydrogen. This advancement could significantly impact the hydrogen economy by enabling decentralized storage solutions. Instead of relying on centralized storage facilities, hydrogen could be stored directly within concrete structures at various locations, making it more accessible and reducing transportation costs. This innovation supports the broader adoption of hydrogen fuel cell technology, which has applications in transportation (e.g., hydrogen-powered vehicles) and energy systems. By enhancing the feasibility and safety of hydrogen storage,

Table 5
Experimental Techniques and Characterisation Methods for Assessing Energy Storage Potential of Cementitious Materials.

Technique	Description	Advantages	Limitations
Thermal Analysis	Measures heat flow and weight changes during phase transitions, providing insights into thermal properties and phase change behaviour.	Quantifies thermal properties, identifies phase transitions.	Limited to small sample sizes, may not capture macroscopic effects.
Microstructural Analysis	Examines the microstructure, crystalline phases, and morphology of cementitious materials using techniques such as SEM, XRD, and AFM.	Provides insights into material structure and composition.	Requires specialized equipment and expertise.
Mechanical Testing	Evaluates mechanical properties such as strength, stiffness, and durability through tensile, compressive, and flexural testing.	Assesses structural integrity and long-term performance.	Does not directly measure thermal properties.
Long-Term Stability Testing	Conducts accelerated aging tests and cyclic thermal cycling experiments to assess material durability and stability under simulated operating conditions.	Provides insights into long-term performance and degradation mechanisms.	Time-consuming, may not fully replicate real-world conditions.
Thermal Conductivity Measurement	Determines the thermal conductivity of cementitious materials using techniques such as the guarded hot plate method or transient plane source (TPS) method.	Quantifies heat transfer capabilities for energy storage.	Requires specialized equipment and calibration.
Specific Heat Capacity Measurement	Measures the specific heat capacity of cementitious materials using calorimetry techniques such as differential scanning calorimetry (DSC) or heat flow calorimetry.	Quantifies energy storage capacity per unit mass.	Limited by sample size and thermal stability.
X-ray Diffraction (XRD)	Analyses the crystalline phases and chemical composition of cementitious materials by bombarding samples with X-rays and observing diffraction patterns.	Provides detailed information on mineralogical composition.	Limited to crystalline phases, may not detect amorphous materials.
Fourier Transform Infrared (FTIR) Spectroscopy	Investigates the chemical composition and bonding characteristics of cementitious materials by measuring the absorption of infrared radiation.	Identifies functional groups and chemical bonds present in the material.	Requires careful sample preparation and interpretation of spectra.

RMIT's research could accelerate the transition to a sustainable hydrogen economy.

These examples highlight the diverse applications and benefits of utilising cementitious materials for energy storage, ranging from improving building energy efficiency to enabling grid-scale renewable energy integration and facilitating sustainable transportation solutions. As research and development in this field continue to advance, cementitious materials are poised to play a crucial role in addressing the global challenges of energy sustainability and climate change mitigation.

4.4. Scalability and feasibility of implementing cementitious materials for energy storage in real-world applications

The scalability and feasibility of implementing cementitious materials for energy storage in real-world applications are pivotal considerations for advancing this technology from theoretical research to practical deployment. Cementitious materials, such as concrete, have shown promise in energy storage due to their durability and adaptability, but several factors must be addressed to ensure their effective large-scale application. Scalability involves evaluating how well these materials can be produced and used in varying quantities to meet demand. Cementitious materials are widely available and used in construction, which offers an inherent advantage for scaling up energy storage applications. Their integration into existing infrastructure, such as building foundations and walls, allows for seamless incorporation into large-scale projects without significant additional costs. However, challenges such as the consistency of material properties, large-scale production methods, and the integration of additives like phase change materials (PCMs) or conductive agents need to be addressed to ensure uniform performance across different applications.

Feasibility encompasses the practicality of implementing these materials in real-world settings. Key factors include cost-effectiveness, technical complexity, and regulatory considerations. The initial costs of incorporating advanced additives and modifying cementitious materials can be high, but the long-term benefits, such as reduced energy consumption and enhanced building efficiency, may offset these expenses. Technical challenges include ensuring that modified cementitious materials perform reliably over time and under varying environmental conditions. Moreover, standardizing procedures for their use and establishing industry guidelines will be crucial for widespread adoption.

Real-world applications have demonstrated the feasibility of using cementitious materials for both thermal and electrical energy storage. For instance, concrete with embedded PCMs has been successfully used in building designs to improve thermal management. The integration of conductive additives in concrete for energy storage systems is also showing promise in pilot projects. Continued research, development, and pilot testing are essential to overcoming current limitations and proving the technology's scalability and practicality on a broader scale.

5. Applications and future Prospects

5.1. Integration of cementitious materials in energy infrastructure

The integration of cementitious materials in energy infrastructure presents a transformative opportunity to enhance sustainability, resilience, and efficiency across various sectors. Cementitious materials, primarily concrete, are ubiquitous in construction and offer unique properties that can be leveraged to address energy challenges. One significant application is in the construction of energy storage systems. Concrete's durability and thermal mass make it an ideal candidate for storing thermal energy generated from renewable sources or waste heat recovery systems. By incorporating phase change materials or embedding thermal storage units within concrete structures, energy can be stored and released as needed, contributing to grid stability and load management. Furthermore, cementitious materials play a crucial role in supporting renewable energy deployment [19,22]. Concrete is used in the construction of wind turbine foundations, solar power plants, and hydropower infrastructure, providing the necessary structural support for these renewable energy technologies. Additionally, concrete's ability to withstand harsh environmental conditions ensures the longevity and reliability of renewable energy installations.

In the realm of transportation, cementitious materials contribute to the development of sustainable infrastructure. Concrete is used in the construction of roads, bridges, and tunnels, providing durable and long-lasting transportation networks. Incorporating cementitious materials into infrastructure projects can improve fuel efficiency, reduce greenhouse gas emissions, and enhance overall transportation sustainability [172,110,152,24]. Moreover, cementitious materials offer opportunities for carbon capture and utilisation (CCU). The carbonation of concrete over time sequesters carbon dioxide from the atmosphere, effectively reducing the environmental footprint of cementitious materials. Additionally, advances in carbon capture technologies aim to capture CO_2 emissions from cement production processes, further mitigating the industry's environmental impact. However, challenges such as optimising material composition, minimising environmental impacts, and ensuring economic viability remain. Research and innovation efforts focus on developing sustainable cementitious materials, improving energy efficiency in production processes, and exploring new applications in energy infrastructure. [138,139,111].

The integration of cementitious materials into energy infrastructure offers substantial benefits, including enhanced sustainability, resilience, and efficiency. Concrete's durability and thermal mass make it suitable for energy storage applications, such as incorporating phase change materials to manage thermal energy and contribute to grid stability. Its role in supporting renewable energy technologies, like wind, solar, and hydropower infrastructure, underscores its importance in advancing green energy solutions. Additionally, concrete's use in transportation infrastructure supports sustainability by improving fuel efficiency and reducing emissions. However, challenges persist, including optimizing material composition, minimizing environmental impacts, and ensuring economic viability, which necessitates ongoing research and innovation.

5.2. Potential applications in buildings and construction

The integration of energy storage using cementitious materials in buildings and construction represents a significant advancement in enhancing energy efficiency, sustainability, and resilience in the built environment. One key application lies in thermal energy storage (TES) systems incorporated within building structures [189,78,157,101,21,162,163]. Cementitious materials, notably concrete, possess excellent thermal mass properties, enabling them to absorb and store thermal energy efficiently. By embedding phase change materials (PCMs) or TES units within concrete elements like floors, walls, or ceilings, buildings can store excess thermal energy generated from renewable sources or waste heat recovery systems [53,99,88,182,142,93,177]. This stored energy can then be utilised during peak demand periods or when renewable energy availability is low, reducing the reliance on conventional heating and cooling systems and improving overall energy efficiency.

The integration of cementitious material-based energy storage facilitates the development of hybrid systems combining both thermal and electrical energy storage [150,148,52,131,77]. By coupling TES systems with batteries, supercapacitors, or other electrical storage technologies, buildings can benefit from a dual energy storage approach. This allows for more effective management of energy demand, optimisation of renewable energy utilisation, and provision of grid services such as demand response or peak shaving, enhancing overall grid stability. Furthermore, cementitious materials contribute to the sustainability and resilience of building envelopes. Concrete structures offer durability and longevity, providing robust protection against external environmental factors and enhancing building resilience to natural disasters. By incorporating energy storage capabilities into concrete elements, buildings can ensure uninterrupted energy supply during emergencies or grid outages, further enhancing their resilience. However, challenges such as optimising material composition, scalability, and economic viability need to be addressed. Research and development efforts focus on advancing cementitious materials with enhanced energy storage properties, optimising manufacturing processes, and exploring new applications in building design and construction.

The integration of energy storage using cementitious materials in buildings and construction holds immense potential for improving energy efficiency, sustainability, and resilience in the built environment. By leveraging the inherent properties of cementitious materials and embracing innovative energy storage technologies, buildings can play a pivotal role in advancing the transition to a more sustainable and resilient energy future. Integrating energy storage with cementitious materials in buildings represents a significant advancement in enhancing energy efficiency and sustainability. Concrete's thermal mass is beneficial for thermal energy storage (TES), allowing buildings to effectively store and utilize excess thermal energy from renewable sources or waste heat recovery. Combining TES with electrical storage systems like batteries can optimize energy management and grid stability. While the approach offers durability and resilience against environmental factors, challenges such as material optimization, scalability, and economic feasibility must be addressed. Ongoing research is essential for developing advanced cementitious materials and manufacturing processes to fully realize this technology's potential.

5.3. Technological advancements and emerging trends

Technological advancements in energy storage have spurred innovative solutions to address the growing demand for sustainable energy sources and the need for efficient storage systems. Among these advancements, the exploration of cementitious materials as potential energy storage mediums has gained significant attention. Cementitious materials, primarily known for their use in construction and infrastructure, possess unique properties that make them promising candidates for energy storage. One notable feature is their thermal mass capacity, which allows them to absorb and release heat energy effectively [143,66,156,133], [8,85,1], [112]. This characteristic forms the basis for leveraging cementitious materials in thermal energy storage (TES) systems.

In TES applications, cementitious materials can store excess thermal energy generated from renewable sources such as solar or wind power during periods of low demand. This stored energy can then be released when needed to meet peak demand or during periods when renewable energy generation is insufficient. By integrating TES systems with renewable energy infrastructure, cementitious materials contribute to enhancing the reliability and stability of renewable energy grids. Furthermore, ongoing research focuses on enhancing the energy storage potential of cementitious materials through the incorporation of additives or modifying their microstructure. Nanostructured materials, such as carbon nanotubes or graphene, are being investigated for their ability to improve the thermal conductivity and energy storage capacity of cementitious composites [126,60,129], [72,122].

Another emerging trend is the integration of phase change materials (PCMs) into cementitious matrices. PCMs have the ability to store and release large amounts of energy through phase transitions, such as solid–liquid or solid–gas transitions. By embedding PCMs within cementitious materials, researchers aim to create composite systems capable of storing both sensible and latent heat, thereby increasing energy storage density and efficiency [44,6,97,48,149,80,165,84]. Moreover, the development of smart cementitious materials with embedded sensors and actuators opens up possibilities for real-time monitoring and control of energy storage processes. These materials can autonomously adjust their properties based on external conditions, optimising energy storage and release according to demand fluctuations.

5.4. Performance and design parameters for applications of cementitious materials

Cementitious materials, including advanced concrete formulations, are increasingly recognized for their potential in energy storage applications due to their inherent durability and adaptability. The successful application of these materials hinges on optimizing both performance and design parameters. Performance is critically assessed through various metrics. Thermal conductivity is vital as it determines the material's ability to manage heat effectively, ensuring stable operation in systems like thermal batteries or phase-change materials. High thermal conductivity aids in heat dissipation, preventing overheating. Compressive strength is equally important, as it ensures that the material can withstand the mechanical stresses encountered during energy storage and discharge cycles. This attribute is crucial for applications where the material also serves a structural role, such as in load-bearing batteries. Electrical conductivity becomes significant in applications like capacitive energy storage. Incorporating conductive additives can enhance the material's ability to conduct electricity, thereby improving energy storage efficiency.

Design parameters also play a key role. The mix design must be carefully tailored, selecting the right types and proportions of binders, aggregates, and additives to achieve the desired properties. For energy storage applications, incorporating materials such as carbon nanotubes or graphene can enhance both electrical and thermal performance. Adjusting the material's porosity and density impacts its strength and thermal behaviour, with increased porosity improving thermal insulation but potentially reducing mechanical strength. Optimizing curing processes is essential to ensure the material reaches its full potential in terms of strength and durability, allowing it to handle thermal and mechanical stresses over its service life. By fine-tuning these aspects, cementitious materials can be engineered to meet the specific demands of various energy storage solutions, offering both enhanced performance and structural benefits.

5.5. Impact of various additives and modifications to cementitious materials on their energy storage performance and properties

The impact of various additives and modifications on the energy storage performance and properties of cementitious materials is a critical area of research that has yielded significant insights. Additives and modifications can fundamentally alter the characteristics of cementitious materials, enhancing their suitability for energy storage applications. One prominent modification is the incorporation of phase change materials (PCMs) into cementitious composites. PCMs, which absorb and release thermal energy during phase transitions, improve the thermal storage capacity of cementitious materials. When embedded in concrete, PCMs can store excess thermal energy and release it when needed, significantly enhancing the material's ability to manage thermal fluctuations and improve building energy efficiency.

Another important modification involves using conductive additives, such as carbon nanotubes or graphene, to enhance the electrical conductivity of cementitious materials. These additives enable concrete to function as a supercapacitor or contribute to electrical energy storage systems. Enhanced conductivity improves the efficiency of electrical storage by facilitating better charge and discharge cycles, making cementitious materials more versatile in applications requiring electrical storage capabilities. Additionally, the inclusion of chemical additives can modify the hydration process of cementitious materials, leading to improved energy storage properties. For example, certain chemical admixtures can control the setting time and enhance the microstructure of cementitious materials, resulting in better mechanical properties and energy storage performance.

Polymer-based additives are also significant in modifying the physical properties of cementitious materials. These polymers can increase flexibility, reduce permeability, and enhance thermal insulation properties, further contributing to the effectiveness of thermal energy storage systems. Improved durability and reduced heat loss through enhanced insulation make these modified materials more suitable for integrating into energy-efficient building designs. Overall, the strategic use of various additives and modifications has led to substantial improvements in the energy storage performance of cementitious materials. These advancements enable better thermal management, enhanced electrical storage capabilities, and improved overall durability, broadening the applications and effectiveness of cementitious materials in energy storage systems.

5.6. Challenges and opportunities for future research

The exploration of cementitious materials for energy storage presents both challenges and opportunities that shape the trajectory of future research in this field. One significant challenge lies in optimising the energy storage capacity and efficiency of cementitious materials. While cementitious composites exhibit promising thermal mass properties, further enhancements are needed to achieve competitive energy storage performance compared to conventional storage systems. Researchers are tasked with developing innovative strategies to enhance the heat storage capacity, thermal conductivity, and cycling stability of cementitious materials while ensuring cost-effectiveness and scalability.

Another challenge involves addressing the durability and long-term performance of cementitious energy storage systems. Cementitious materials are susceptible to degradation over time due to factors such as moisture ingress, chemical reactions, and mechanical stresses. Ensuring the structural integrity and reliability of energy storage structures in harsh environmental conditions remains a key research focus. Solutions may involve the development of advanced coating materials, additives, or surface treatments to enhance the durability and lifespan of cementitious composites. Furthermore, the integration of cementitious energy storage systems into existing infrastructure poses technical and logistical challenges. Researchers must consider factors such as compatibility with construction materials, system integration complexity, and retrofitting requirements. Interdisciplinary collaboration between materials scientists, engineers, architects, and policymakers is essential to overcome these challenges and streamline the adoption of cementitious energy storage technologies.

Traditional cementitious materials, such as ordinary Portland cement (OPC), inherently possess low electrical conductivity, which is a major limitation for their use in electrochemical energy storage applications. Recent efforts to enhance conductivity by incorporating additives like graphene or carbon nanotubes have shown promise. However, achieving a uniform distribution of these additives within the cement matrix remains a significant challenge. Inconsistent dispersion can lead to variable electrical performance, which impacts the reliability and efficiency of the energy storage system. Research is ongoing to develop better mixing techniques and optimize the composition of these composites to overcome these issues.

The integration of phase change materials (PCMs) into cementitious matrices aims to enhance thermal energy storage capabilities. While this approach can improve the material's ability to store and release thermal energy, it introduces challenges related to thermal stability and structural integrity. PCMs undergo expansion and contraction during phase changes, which can affect the mechanical strength and durability of the cementitious material. Addressing these issues involves developing composites that maintain structural integrity while accommodating PCM behaviour. Long-term stability of PCMs within cementitious matrices is another concern, as repeated thermal cycles may lead to degradation and reduced performance.

Cementitious materials embedded with piezoelectric fibres or particles are used for energy harvesting from mechanical stress. While promising, the piezoelectric response of these materials is generally lower than that of specialized piezoelectric materials. Additionally, incorporating piezoelectric components can impact the mechanical properties of the cement matrix, such as compressive strength and durability. Balancing piezoelectric efficiency with the material's structural properties is a key challenge that requires further research and optimization. Although incorporating low-carbon cements and recycled aggregates can reduce the environmental impact of cementitious materials, the overall sustainability of these materials must be assessed comprehensively. The production and processing of advanced additives, as well as the energy required for their integration, can offset some of the environmental benefits. Lifecycle assessments are necessary to ensure that the overall carbon footprint and environmental impact are minimized. The high cost of advanced materials and specialized processing techniques can limit the commercial viability of energy storage systems based on cementitious materials. Scaling up from laboratory prototypes to industrial applications involves significant investment and logistical challenges. Ensuring cost-effectiveness while maintaining performance and sustainability is crucial for the widespread adoption of these technologies.

Despite these challenges, the field of cementitious energy storage offers promising opportunities for future research and innovation. One avenue is the exploration of novel materials and composites tailored specifically for energy storage applications. By leveraging advancements in nanotechnology, additive manufacturing, and material design, researchers can develop customized cementitious materials with tailored properties optimised for energy storage performance. Additionally, there is ample room for exploring multifunctional cementitious materials that can serve dual purposes, such as structural support and energy storage. Integrating energy storage functionalities directly into building components or infrastructure elements could lead to more efficient use of space and resources, paving the way for sustainable and integrated energy solutions. Moreover, future research can focus on optimising the scalability, manufacturability, and cost-effectiveness of cementitious energy storage systems to facilitate widespread deployment and adoption. By addressing these challenges and seizing opportunities for innovation, researchers can unlock the full potential of cementitious materials as a cornerstone of sustainable energy storage solutions for the future.

6. Environmental and economic considerations

Leveraging cementitious materials for energy storage necessitates a comprehensive evaluation of environmental and economic factors. Sustainability implications include reduced reliance on fossil fuels and minimised carbon emissions. Life cycle assessments are vital for gauging environmental impact, encompassing resource extraction, manufacturing, deployment, and disposal. Concurrently, cost analyses are imperative to assess economic viability, encompassing upfront investments, operational costs, and potential long-term savings. Balancing environmental benefits with economic feasibility is critical for fostering widespread adoption of cementitious material-based energy storage solutions.

6.1. Sustainability implications

The integration of cementitious materials into energy storage systems carries significant sustainability implications, touching upon various aspects of environmental impact, resource management, and societal well-being. Cementitious materials offer the potential to reduce the environmental footprint of energy storage solutions [82,73,160,68,48,130]. By utilising concrete or other cement-based composites, which often incorporate industrial by-products like fly ash or slag, these systems can leverage materials that would otherwise contribute to waste streams or require additional energy-intensive processes for disposal. This repurposing of materials aligns with principles of circular economy and resource efficiency, reducing the overall environmental burden associated with construction and infrastructure development.

The deployment of cementitious materials for energy storage contributes to the mitigation of greenhouse gas emissions. Traditional cement production is a significant source of carbon dioxide emissions due to the calcination process, which releases CO_2 [144,56,34,116]. However, by incorporating carbon capture and utilisation techniques or promoting carbonation reactions within concrete structures, these emissions can be mitigated or even offset, effectively turning concrete structures into carbon sinks. This dual-purpose approach not only enhances the sustainability of energy storage systems but also contributes to broader climate change mitigation efforts. Furthermore, the use of cementitious materials for energy storage supports the resilience and longevity of infrastructure. Concrete structures have a long service life and require minimal maintenance compared to alternative materials, reducing the need for resource-intensive repairs or replacements. This durability not only enhances the sustainability of energy storage infrastructure but also ensures reliable performance over extended periods, contributing to the overall resilience of energy systems.

The societal implications of leveraging cementitious materials for energy storage are significant. By promoting the adoption of sustainable construction practices and infrastructure development, these systems contribute to improved quality of life, enhanced community resilience, and equitable access to clean energy resources. Furthermore, the localisation of materials and manufacturing processes for cementitious materials can stimulate local economies and create job opportunities, fostering sustainable development at both local and global scales. The sustainability implications of integrating cementitious materials into energy storage systems are wide-ranging and multifaceted, encompassing environmental, economic, and societal considerations. By embracing these implications and adopting holistic approaches to energy storage development, we can accelerate the transition towards a more sustainable and resilient energy future.

6.2. Life cycle Assessment and environmental impact analysis

Life Cycle Assessment (LCA) and Environmental Impact Analysis (EIA) are indispensable methodologies for evaluating the environmental footprint of energy storage systems incorporating cementitious materials. These assessments provide a holistic view of environmental implications throughout a product or system's life cycle, from raw material extraction to disposal. Central to LCA and environmental impact analysis is quantifying various environmental burdens, including greenhouse gas emissions, energy consumption, water usage, and waste generation. For energy storage systems utilising cementitious materials, this involves examining impacts associated with sourcing raw materials like limestone, clay, and supplementary cementitious materials, as well as energy-intensive processes in cement production and concrete manufacturing. Furthermore, assessments consider energy consumption and emissions related to transportation, installation, operation, and maintenance of energy storage infrastructure. This comprehensive approach helps identify environmental hotspots and areas for improvement.

Table 6 highlights key environmental factors examined in life cycle assessments and environmental impact analyses of cementitious materials. It identifies areas of concern such as resource depletion, global warming potential, air and water pollution, and land use changes. Each

Table 6
Key Environmental Factors in Life Cycle Assessments and Environmental Impact Analyses of Cementitious Materials.

Environmental Factor	Description	Example	Impact
Resource Depletion	Evaluation of natural resource depletion, such as aggregates and minerals used in cement production and construction activities.	Quarrying of limestone for cement	Decreased availability of resources
Global Warming Potential	Assessment of greenhouse gas emissions, particularly carbon dioxide (CO_2), throughout the life cycle, including production, transportation, and energy usage.	CO_2 emissions from cement production	Contribution to climate change
Air and Water Pollution	Analysis of emissions like particulate matter, nitrogen oxides (NOx), sulphur oxides (SOx), and pollutants during cement kiln operations and construction.	Dust emissions from quarrying	Air and water quality degradation
Land Use and Habitat Disruption	Examination of land use changes due to quarrying raw materials and constructing energy storage facilities, including habitat disruption and ecosystem effects.	Land clearing for construction	Loss of biodiversity and ecosystems

factor is described with examples, offering insights into the environmental impacts associated with cement production and construction activities. This overview facilitates a comprehensive understanding of the environmental considerations essential for evaluating the sustainability of cementitious material-based energy storage systems.

These factors collectively provide insights into the environmental implications associated with energy storage systems utilising cementitious materials. By addressing these considerations comprehensively, stakeholders can make informed decisions to mitigate environmental impacts, optimise resource utilisation, and promote sustainability in energy infrastructure development. Robust LCA and environmental impact analyses facilitate informed decision-making to minimise impacts, optimise resource use, and promote sustainability in energy storage solutions using cementitious materials. They are integral in shaping policies, driving technological innovations, and fostering sustainable practices in the energy sector.

Adeoye et al. [5] conducted a comparative LCA of thermal energy storage systems for the Shams1 concentrated solar power plant, contrasting molten salt and concrete-based systems. By assessing various environmental indicators, including greenhouse gas emissions, energy consumption, and resource depletion, the study highlighted the trade-offs between different storage materials. Such analysis aids in informed decision-making regarding the selection of energy storage technologies with lower environmental footprints. Similarly, Lalau et al. [90] investigated the environmental impacts of a thermal energy storage unit for industrial waste heat valorization, considering both conventional and recycled storage materials. Through LCA, they evaluated material choices, energy efficiency, and end-of-life considerations, offering recommendations for optimising sustainability in industrial applications. This underscores the importance of considering the entire life cycle of energy storage systems to identify opportunities for environmental improvement. Struhala & Ostrý [151] focused on phase-change materials (PCMs) in buildings, conducting an LCA to assess their environmental performance compared to traditional construction materials. By analyzing factors such as building performance and long-term sustainability, the study emphasized the potential of PCM integration for reducing energy consumption and mitigating environmental impacts in the built environment. Furthermore, Hatzfeld et al. [68] proposed an innovative approach to residential energy storage by integrating supercapacitors into a Carbon Reinforced Concrete facade. Through LCA, they evaluated the greenhouse gas minimization potential of this system, considering material innovation and system integration. Such studies highlight the importance of technological innovation in advancing sustainable energy storage solutions.

6.3. *Cost analysis and economic viability*

Analysing the cost implications and economic viability of energy storage systems utilising cementitious materials is crucial for their widespread adoption and integration into the energy landscape. Firstly, upfront investment costs play a significant role. Cement production and concrete manufacturing involve substantial capital expenditures for raw materials, equipment, and construction. The scale of the project, technological choices, and local market conditions influence these costs. However, advancements in manufacturing processes, material sourcing, and construction techniques can help mitigate initial investment outlays.

Operational expenses represent another aspect of economic evaluation. Beyond the upfront investment, ongoing costs encompass energy consumption, maintenance, monitoring, and management. While cementitious material-based storage solutions may require periodic maintenance, advancements in material engineering and construction practices aim to minimise these expenses over the system's lifetime. Long-term savings and revenue generation opportunities are crucial factors in economic viability. Energy storage systems can yield savings through peak shaving, load shifting, and grid balancing, leading to reduced electricity bills for end-users. Moreover, participation in energy markets, such as ancillary services and capacity markets, can generate additional revenue streams. Cementitious material-based storage solutions must demonstrate favourable returns on investment (ROI) and reasonable payback periods to attract investors and secure financing.

Assessing economic viability also requires consideration of the broader economic and regulatory framework. Supportive policies, subsidies, tax incentives, and favourable regulatory environments can enhance the attractiveness of energy storage projects. Additionally, evolving energy market dynamics, technological advancements, and changing consumer preferences shape the economic landscape for energy storage solutions. Ultimately, a comprehensive economic analysis must weigh upfront investment costs against long-term savings and revenue streams, considering operational expenses and external economic factors. Robust financial modelling and scenario analysis can help stakeholders evaluate various deployment strategies and optimise project economics. By addressing economic considerations and demonstrating favourable returns, energy storage systems utilising cementitious materials can play a pivotal role in the transition to a sustainable energy future.

Mikkelson & Frick [109] analysed controls for an integrated energy storage system in an energy arbitrage configuration with concrete thermal energy storage. This study likely considered the upfront costs associated with implementing concrete-based energy storage, including material procurement, construction, and installation. Additionally, operational costs such as maintenance and monitoring may have been evaluated. Economic viability may have been assessed by comparing the potential revenue generated from energy arbitrage (buying electricity when prices are low and selling when prices are high) against the investment and operational expenses. González-Gómez et al. [61] explored a hybrid storage solution combining a steam accumulator with concrete blocks to save energy during startups of combined cycles. This study may have investigated the cost-effectiveness of integrating concrete-based energy storage into combined cycle power plants. Factors such as the savings in fuel consumption during startup periods and the reduction in wear and tear on equipment due to smoother startups could contribute to the economic viability assessment.

Prieto et al. [123] conducted a techno-economic analysis of a concrete storage concept for parabolic trough solar power plants. This study likely involved evaluating the lifecycle costs of implementing concrete thermal energy storage in solar power plants, including construction, maintenance, and decommissioning expenses. Economic viability may have been determined by comparing the cost per unit of stored energy with alternative storage technologies, such as molten salt or battery storage, and considering the potential for revenue generation through increased plant efficiency or participation in energy markets. Barbhuiya et al. [16] provided a comprehensive review of thermal energy storage in concrete, which likely included discussions on the sustainability and economic aspects of using concrete as a storage material. This review may have highlighted cost-saving benefits associated with using concrete, such as its abundance and low cost compared to other storage materials. Additionally, considerations regarding the environmental impact and long-term economic sustainability of concrete-based storage systems may have been addressed. The cost analysis and economic viability of using cementitious materials for energy storage involve assessing upfront investment, operational costs, revenue potential, and long-term performance. By considering these factors in conjunction with technological advancements and market dynamics, researchers and stakeholders can make informed decisions regarding the adoption of concrete-based energy storage solutions.

Table 7 provides a comprehensive economic analysis of cementitious energy storage systems, vital for understanding their viability and integration into the energy landscape. It examines various aspects, including upfront investment costs, operational expenses, long-term savings, and the economic and regulatory framework. Key factors such as technological innovations, market demand, environmental impact, and financing options are explored, shedding light on the complex dynamics shaping the feasibility of these systems. By offering insights into regulatory compliance, supply chain resilience, scalability, and social acceptance, the table equips stakeholders with essential information for informed decision-making and strategic planning in advancing sustainable energy solutions.

6.4. Potential safety and reliability concerns associated with the use of cementitious materials for energy storage

The use of cementitious materials for energy storage presents several potential safety and reliability concerns that must be managed to ensure their effective and secure application. While materials like concrete offer durability and thermal mass benefits, integrating them into energy storage systems introduces specific challenges. One key safety concern involves the chemical interactions between cementitious materials and additives. Incorporating phase change materials (PCMs) or conductive agents could lead to unforeseen chemical reactions that might compromise the integrity of the concrete. It is essential to ensure these additives are chemically compatible and do not adversely affect the material's properties. Additionally, for electrical storage applications such as concrete-based supercapacitors, risks like short circuits or electrical failures could arise if conductive additives are not evenly distributed or if there is inadequate insulation.

The structural performance of cementitious materials can also be impacted by integrating energy storage components. For example, embedding PCMs or other additives might alter the concrete's mechanical properties, including compressive strength and durability. Ensuring that these modifications do not undermine the structural integrity of the concrete is critical. Rigorous testing and validation are necessary to confirm that modified materials can endure environmental stressors and load conditions over time. Long-term reliability is another concern. The durability of cementitious materials under cyclic thermal and electrical stresses needs thorough evaluation to prevent degradation or failure. Ongoing maintenance and monitoring may be required to identify and address potential issues early, ensuring continued performance. Environmental impacts must also be considered. The production of cement is known for significant CO_2 emissions. Therefore, strategies to reduce these impacts, such as incorporating recycled materials or alternative binders, are essential to ensure that the overall environmental benefits of energy storage systems are not outweighed by their production footprint.

Addressing safety and reliability concerns is essential for the successful integration of cementitious materials in energy storage applications. Comprehensive research and rigorous testing are necessary to understand the interactions between additives and the base materials, ensuring structural integrity and long-term performance. Adherence to industry standards and protocols will help mitigate risks associated with chemical reactions, electrical failures, and structural degradation. Ongoing monitoring and maintenance are also crucial to maintaining performance and addressing issues promptly. By focusing on these aspects, we can ensure that cementitious materials are effectively and safely utilized in energy storage systems, maximizing their potential benefits.

6.5. Potential impact of cementitious materials for energy storage on the overall energy system and grid integration

The potential impact of cementitious materials for energy storage on the overall energy system and grid integration is substantial, offering both enhancements and challenges. Cementitious materials, such as concrete, can significantly contribute to energy systems by improving grid stability, integrating renewable energy sources, and enhancing energy efficiency. One major benefit is the ability of cementitious materials to support grid stability through energy storage solutions. Concrete's inherent thermal mass allows it to store excess thermal energy generated during periods of high renewable energy output. This stored

Table 7
Comprehensive Economic Analysis of Cementitious Energy Storage Systems: Implications for Adoption and Integration in the Energy Sector.

Aspect	Description	Example	Economic Implications
Regulatory Compliance	Compliance with local, national, and international regulations and standards is essential for project approval and operation. Failure to meet regulatory requirements can lead to delays and additional costs.	Environmental regulations, safety standards	Legal risks, project delays, potential fines
Supply Chain Resilience	Ensuring resilience in the supply chain, including sourcing raw materials and components, is crucial for project continuity and cost management.	Diverse supplier base, supply chain monitoring	Mitigation of supply chain disruptions, cost stability
Scalability	The ability to scale energy storage systems to meet changing energy demands and project requirements is essential for long-term viability and flexibility.	Modular design, scalable infrastructure	Adaptability to market changes, growth opportunities
Techno-Economic Analysis	Conducting comprehensive techno-economic analyses helps evaluate the financial viability and risks associated with energy storage projects, considering technical, economic, and environmental factors.	Cost-benefit analysis, sensitivity analysis	Informed decision-making, risk management
Social Acceptance	Public perception and community acceptance of energy storage projects can influence project development and implementation. Engaging stakeholders and addressing community concerns are essential for project success.	Community outreach programs, public consultations	Reputation management, project support

energy can be released during peak demand or low renewable energy availability, helping to balance supply and demand. By integrating phase change materials (PCMs) or other thermal storage components into building infrastructure, cementitious materials can act as thermal batteries, smoothing out fluctuations in energy supply and reducing the need for additional grid infrastructure.

Furthermore, cementitious materials contribute to the broader integration of renewable energy sources. Concrete is widely used in the construction of critical infrastructure for renewable technologies, including wind turbine foundations, solar panel mounts, and hydropower facilities. By providing durable and reliable structural support, cementitious materials facilitate the deployment and stability of renewable energy systems. Enhanced energy storage within these structures also allows for better management of intermittent renewable energy sources, thereby increasing their overall reliability and contribution to the grid. However, integrating cementitious materials into the energy system also presents challenges. The scalability and economic feasibility of deploying large-scale energy storage systems using these materials must be addressed. Additionally, the performance of cementitious materials under varying environmental conditions and their long-term reliability need thorough evaluation to ensure they meet grid demands. Overall, the strategic use of cementitious materials for energy storage can play a pivotal role in creating a more resilient and efficient energy system. By enhancing grid stability, supporting renewable energy integration, and improving energy efficiency, these materials offer promising benefits for the future of energy management.

6.6. Potential regulatory and policy implications related to the use of cementitious materials for energy storage

The use of cementitious materials for energy storage has significant regulatory and policy implications that could shape its integration into the broader energy system. As this technology advances, various regulatory and policy considerations must be addressed to facilitate its adoption and ensure its effective deployment. Firstly, building codes and standards will need to be updated to incorporate guidelines for energy storage systems using cementitious materials. These codes should address the structural integrity and safety of such systems, ensuring that modifications to cementitious materials, such as incorporating phase change materials (PCMs) or conductive additives, do not compromise the material's durability or the building's overall safety. Ensuring that these guidelines are developed in collaboration with industry experts and stakeholders is crucial for setting appropriate standards and best practices.

Additionally, policies that incentivize the use of innovative energy storage technologies are vital. Governments and regulatory bodies could introduce financial incentives, such as tax credits or subsidies, to encourage the adoption of cementitious materials for energy storage. These incentives could help offset the initial costs associated with integrating advanced additives or modifying existing infrastructure, promoting wider implementation and accelerating technology adoption. Regulatory frameworks should also address environmental impacts. Cement production is known for its significant carbon footprint, and integrating energy storage solutions must consider the lifecycle emissions of the materials used. Policies that support carbon capture technologies or promote the use of low-carbon or recycled materials in cementitious products can help mitigate these impacts and align with broader climate goals.

Finally, there is a need for clear guidelines on the monitoring and maintenance of cementitious energy storage systems. Regulators should establish protocols for assessing the long-term performance and safety of these systems, ensuring that they continue to meet regulatory standards throughout their operational life.

In summary, regulatory and policy implications related to cementitious materials for energy storage involve updating building codes, providing financial incentives, addressing environmental impacts, and establishing maintenance protocols. Effective policies and regulations will be essential for integrating these materials into energy systems, ensuring their safety, performance, and contribution to sustainable energy solutions.

7. Conclusions

7.1. Summary of key findings

- Concrete's high heat capacity and thermal conductivity make it an effective medium for storing thermal energy from renewable sources (e.g., solar, wind) and waste heat recovery, contributing to sustainable energy infrastructure and improved energy efficiency.
- Integrating PCMs into cementitious composites enhances their ability to absorb, store, and release thermal energy during phase transitions, improving energy storage capacity and helping to stabilize indoor temperatures or optimize renewable energy systems.
- Combining cementitious materials with other storage technologies, such as batteries or supercapacitors, enables simultaneous storage of thermal and electrical energy. These hybrid systems offer versatility and address diverse energy storage needs across various applications.
- The carbonation process of cementitious materials not only strengthens concrete but also sequesters CO_2 from the atmosphere, contributing to carbon capture and offering a novel approach to energy storage. However, challenges like material optimization, scalability, and economic viability need ongoing research and development.

7.2. Implications for sustainable energy development

The implications of integrating cementitious materials into sustainable energy development strategies are multifaceted and hold significant promise for addressing various challenges in the energy sector. One of the primary implications lies in the advancement of renewable energy deployment. Renewable sources such as solar and wind power are inherently intermittent, generating electricity only when the sun shines or the wind blows. This intermittency poses challenges for grid stability and reliability. However, by coupling renewable energy generation with energy storage systems utilising cementitious materials, excess energy can be stored during periods of high generation and discharged when demand exceeds supply. This enhances the reliability and stability of renewable energy sources, facilitating their greater integration into the grid. Moreover, the use of cementitious materials for energy storage has substantial implications for decarbonizing the built environment. Buildings and infrastructure are major consumers of energy, particularly for heating, cooling, and lighting. By incorporating thermal energy storage systems made from cementitious materials into building design, energy demand for heating and cooling can be optimised. This leads to reduced reliance on fossil fuels for space conditioning, consequently lowering greenhouse gas emissions associated with energy consumption in the built environment.

The utilisation of cementitious materials for energy storage aligns with the principles of the circular economy. Cement production is a significant source of carbon dioxide emissions due to the calcination process, which releases CO_2. However, by capturing and storing CO_2 within concrete structures through processes like carbonation, cementitious materials can serve as carbon sinks, effectively sequestering emissions. This contributes to climate change mitigation efforts by reducing the net carbon footprint associated with cement production and utilisation. Additionally, the development of hybrid energy storage systems that combine cementitious materials with other storage technologies presents opportunities for innovation and collaboration across sectors. These integrated systems offer flexibility and resilience in energy management, enabling more efficient and sustainable resource utilisation. Leveraging cementitious materials for energy storage not only enhances the performance and reliability of renewable energy sources but also contributes to the decarbonization of the built environment and fosters the transition towards a circular economy. By addressing challenges and embracing opportunities in research, policy, and industry collaboration, we can accelerate the adoption of these technologies and drive progress towards a cleaner, more sustainable energy future.

The integration of cementitious materials into sustainable energy development holds considerable promise but also presents challenges. While these materials can enhance renewable energy reliability by storing excess energy and improving grid stability, their effectiveness is contingent on overcoming technical hurdles in energy storage efficiency and scalability. Their potential for decarbonising buildings by optimizing thermal energy storage and reducing fossil fuel reliance is significant, yet it requires effective implementation strategies. Although using cementitious materials as carbon sinks aligns with circular economy principles, the process of capturing and storing CO_2 in concrete structures is complex and may not fully offset the emissions from cement production. Hybrid storage systems offer innovative potential, but their practical integration and impact need further exploration.

7.3. Recommendations and a clear roadmap for future research and development efforts

To advance the utilization of cementitious materials for energy storage, several key recommendations and a clear roadmap for future research and development are proposed.

Firstly, enhancing material development is crucial. Researchers should focus on optimizing the chemical, thermal, and electrical storage properties of cementitious materials by experimenting with different compositions, additives, and structural modifications. Incorporating advanced materials such as nanomaterials or composites could significantly improve energy storage performance.

A robust performance evaluation framework must be established. This includes developing standardized criteria and methodologies for assessing various aspects of energy storage, such as energy density, storage capacity, charge/discharge rates, and long-term stability. Consistent experimental techniques and comparative benchmarks against existing storage technologies will help in evaluating the efficacy of cementitious materials. Conducting comprehensive lifecycle assessments (LCAs) is also important. These assessments should evaluate the environmental and economic impacts of cementitious energy storage systems, including raw material sourcing, production energy consumption, and disposal or recycling. Understanding these factors will ensure that the development of these materials aligns with sustainability goals.

Practical applications should be explored to test the feasibility of cementitious energy storage systems in real-world scenarios. Integrating these systems into building materials and infrastructure projects, and aligning them with renewable energy sources, will provide valuable insights into their practical benefits and effectiveness. Pilot projects and case studies will be instrumental in demonstrating their potential. Fostering interdisciplinary collaboration will drive innovation. Combining expertise from materials science, engineering, and energy storage fields can address complex challenges and accelerate the advancement of cementitious materials in energy storage.

In the short term (1–2 years), research should focus on developing new formulations and additives, and establishing standardized evaluation protocols for comparing cementitious materials with existing technologies. In the medium term (3–5 years), pilot studies and field trials should be implemented to test these materials in practical applications, alongside performing lifecycle and cost analyses. Long-term efforts (5–10 years) should focus on scaling up successful projects for commercialization and collaborating with regulatory bodies to create supportive standards and policies. By following these recommendations and roadmap, research and development can effectively advance the use of cementitious materials for energy storage, significantly contributing to sustainable energy solutions.

7.4. Limitations of this review

This review paper presents a comprehensive analysis of cementitious materials for energy storage, but it has several limitations. Firstly, while it addresses various energy storage mechanisms within cementitious materials, the discussion lacks depth regarding the practical limitations and performance challenges these materials face in real-world applications. Detailed case studies and experimental data that provide concrete evidence of performance in different scenarios are underrepresented. Additionally, the review does not sufficiently explore the economic implications and scalability of cementitious energy storage systems. This oversight may limit the understanding of the cost-effectiveness and feasibility of large-scale implementation. Moreover, the paper's treatment of emerging technologies and recent advancements in energy storage is somewhat superficial, missing an opportunity to delve into cutting-edge developments and their potential impact on the field. The review also does not address the integration challenges and long-term sustainability aspects of using cementitious materials for energy storage, which are crucial for evaluating their practical viability. Lastly, while it provides a broad overview, a more focused examination of specific innovations, performance metrics, and detailed comparisons with other energy storage technologies would enhance the review's comprehensiveness and applicability. Addressing these limitations would provide a more robust and practical understanding of cementitious energy storage systems.

CRediT authorship contribution statement

Salim Barbhuiya: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Bibhuti Bhusan Das:** Writing – review & editing. **Dibyendu Adak:** Writing – review & editing.

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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