Journal of Building Engineering 82 (2024) 108302

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Thermal energy storage in concrete: A comprehensive review on fundamentals, technology and sustainability

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ARTICLE INFO

Keywords:
Thermal energy storage
Thermal conductivity
Specific heat capacity
Thermal diffusivity

ABSTRACT

This comprehensive review paper delves into the advancements and applications of thermal energy storage (TES) in concrete. It covers the fundamental concepts of TES, delving into various storage systems, advantages, and challenges associated with the technology. The paper extensively explores the potential of concrete as a medium for thermal energy storage, analysing its properties and different storage methods. Additionally, it sheds light on the latest developments in concrete technology specifically geared towards thermal energy storage. The evaluation section discusses measurement techniques, experimental evaluations and performance metrics. Environmental and economic aspects, including sustainability and cost analysis, are thoughtfully addressed. The review concludes by underlining the significance of thermal energy storage in concrete, emphasizing its role in efficient energy management and the promotion of sustainable practices.

1. Introduction

Thermal energy storage (TES) offers a promising solution to address energy management, sustainability and renewable energy integration challenges. TES efficiently captures and stores excess thermal energy produced during periods of low demand or high renewable energy generation, effectively balancing energy supply and demand. By optimising energy consumption and reducing peak loads, TES systems enhance overall energy system efficiency, leading to a more sustainable energy landscape ([1,2]; Zhang et al., 2022). This technology facilitates the efficient utilisation of renewable energy, enhances grid stability and enables seamless integration of intermittent energy sources. TES plays a critical role in establishing a sustainable and resilient energy infrastructure capable of meeting growing energy demands while minimising environmental impact.

Concrete's extensive usage in construction has sparked interest in its potential as a TES medium. It boasts advantages, including availability and cost-effectiveness, making large-scale implementation viable. Its high thermal mass allows concrete to adeptly absorb and store significant heat energy, rendering it effective for heat transfer and redistribution. Consequently, concrete proves promising for TES, offering opportunities for sustainable and efficient energy management [3,4]. Leveraging concrete's TES capabilities can contribute to balancing energy supply and demand, enhancing renewable energy integration and optimising overall energy efficiency in various applications, ranging from buildings to infrastructure projects. This growing interest in utilising concrete for TES reflects a quest for more environmentally friendly and effective approaches to energy storage and management.

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https://doi.org/10.1016/j.jobe.2023.108302
Received 21 September 2023; Received in revised form 3 December 2023; Accepted 10 December 2023

Thermal Energy Storage (TES) involves storing and retrieving thermal energy for later use. Various storage media are employed, each with unique properties affecting efficiency and applications. Concrete, as a common medium, has moderate thermal conductivity but may face challenges compared to others. Phase Change Materials (PCMs) exhibit high energy density and adaptability, undergoing phase transitions for efficient heat storage. Liquids, like molten salts, boast high thermal conductivity and wide operating temperatures. Metals offer excellent thermal conductivity but can be cost-prohibitive. Overall, the choice of TES medium depends on factors like application, cost, and specific thermal requirements.

Concrete's robust thermal stability, as highlighted by Khaliq & Waheed [5] and Malik et al. [6], positions it as a reliable long-term medium for Thermal Energy Storage (TES). This stability ensures the integrity of concrete-based TES systems over extended periods, contributing to overall efficiency and reliability. Its durability and longevity enhance TES robustness. Research efforts, exemplified by Lucio-Martin [7], Haider et al. [8], and Wang et al. [9], focus on optimising concrete for TES. Modification of concrete mixes, incorporating additives to improve thermal properties, and fine-tuning composition enhance heat transfer efficiency and storage capacity. These advancements make concrete-based TES systems more efficient and adaptable.

Innovative approaches involve additives and reinforcement techniques to enhance concrete's specific thermal properties. The integration of phase change materials (PCMs), explored by researchers like Khudhair & Farid [10] and Soares et al. [11], augments concrete's thermal energy storage capabilities. These endeavours broaden the potential applications of concrete-based TES systems, making them versatile and efficient. However, challenges in employing concrete for TES require meticulous solutions. Designing systems to achieve optimal heat transfer efficiency while minimising energy losses, as noted by Vigneshwaran et al. [12] and Palacios et al. (2020), demands careful consideration. Implementing proper insulation measures, as emphasized by Al-Homoud [13] and Liu et al. [14], is essential to mitigate heat losses during storage and retrieval processes.

Accurate modelling techniques, a critical aspect per Ferone et al. [15] and Cui et al. [16], are imperative for assessing concrete-based TES system efficiency. Moreover, considering environmental impact and sustainability is crucial. The energy-intensive nature of concrete production and its associated carbon footprint necessitate evaluating life cycle impacts and emissions. Strategies such as incorporating alternative cementitious materials or implementing carbon capture technologies enhance the sustainability of concrete-based TES systems. Extensive research on phase change materials (PCMs) focuses on enhancing efficiency and sustainability in thermal energy storage applications. Tyagi et al. [17] and Singh et al. [18] delve into the development, characterization, and stability of PCMs, emphasizing their potential in various thermal storage contexts. Additionally, Tyagi et al. [19] explore PCM utilisation in solar thermal energy storage, outlining a strategic approach for future research. The diverse applications of PCMs, as discussed by Pandey et al. [20], highlight their evolving role in sustainable energy solutions.

The implementation of phase change materials (PCMs) in various thermal energy storage applications has been a subject of extensive research, with a focus on enhancing efficiency and sustainability. Tyagi et al. [17] presented a comprehensive review focusing on the development, characterization, thermal, and chemical stability of phase change materials for heat storage applications. The study provides an in-depth analysis of the advancements in PCM technology, highlighting key characteristics such as stability and efficacy in various thermal storage contexts. Singh et al. [18] conducted a comprehensive review on the development of eutectic organic phase change materials and their composites, specifically targeting low and medium range thermal energy storage applications. The study offers a detailed examination of the advancements in PCM technology, shedding light on the potential for optimising energy storage in these temperature ranges. In a prospective research approach, Tyagi et al. [19] explored the utilisation of phase change materials in advance solar thermal energy storage systems designed for building heating and cooling applications. The study emphasizes the significance of PCMs in enhancing the efficiency of such systems and outlines a strategic approach for future research endeavours in this domain. Pandey et al. [20] delved into novel approaches and recent developments related to potential applications of phase change materials in solar energy. The review provides a comprehensive overview of the diverse applications of PCMs, ranging from solar thermal energy storage to other innovative uses. The authors highlight the evolving landscape of PCM technology and its contribution to sustainable energy solutions.

This review paper aims to explore and present the recent advancements and applications of TES in concrete. TES has emerged as a promising solution for energy management, renewable energy integration and sustainability. Concrete, being a widely used construction material, possesses unique properties that make it a potential medium for thermal energy storage. By summarising the existing research and developments in this field, the paper aims to offer a comprehensive understanding of the current state-of-the-art in concrete-based TES. It discusses the advantages, challenges and future research directions in this domain. By disseminating this knowledge, the paper seeks to contribute to the implementation of efficient and sustainable energy storage solutions. Furthermore, it provides valuable insights for researchers, engineers, policymakers and industry professionals interested in exploring the potential of thermal energy storage in concrete applications.

The paper's scope may not encompass every aspect of concrete-based thermal energy storage due to the rapid evolution of this field. The limitations of a single review paper make it challenging to cover all specific applications, case studies, or technological advancements comprehensively. The findings and conclusions presented are based on existing literature and research available at the time of writing. As new research emerges, subsequent studies may challenge or expand upon these conclusions. For a more up-to-date and comprehensive understanding of the advancements and applications of thermal energy storage in concrete, readers are advised to consult recent studies and sources to stay abreast of the latest developments in this dynamic field.

2. Concrete as a thermal energy storage medium

Concrete is a widely used construction material that has gained attention as a thermal energy storage (TES) medium. It offers several advantageous properties that make it suitable for TES applications. Concrete has a high thermal mass, enabling it to absorb and store significant amounts of heat energy. Its ability to store thermal energy allows for efficient heat transfer and redistribution when required. Concrete also possesses excellent thermal conductivity, ensuring effective heat transfer throughout its structure. Additionally, its durability, longevity and availability make it suitable for long-term storage applications. Ongoing research focuses on enhancing the thermal properties of concrete through modifications to improve thermal conductivity, specific heat and thermal diffusivity, further optimising its performance as a TES medium.

2.1. *Overview of concrete as a material*

Concrete is a versatile and widely used construction material known for its exceptional strength, durability and versatility. It is composed of a mix of cement, aggregates (such as sand and gravel), water and sometimes admixtures. The combination of these components undergoes a chemical reaction known as hydration, resulting in a solid and cohesive material with remarkable properties.

One of the key advantages of concrete is its compressive strength. It can withstand significant loads and provide structural stability, making it suitable for a wide range of applications, from residential buildings to bridges, roads, dams and high-rise structures. The compressive strength of concrete can be further enhanced through proper mix design, reinforcement and curing techniques [21–23]. Another important property of concrete is its fire resistance. Concrete is inherently non-combustible and has a high resistance to fire. It does not burn or release toxic gases when exposed to high temperatures. This characteristic makes it a preferred choice in fire-resistant construction, such as in tunnels, firewalls and structures requiring high fire ratings. Durability is another significant advantage of concrete. It can withstand harsh environmental conditions, including exposure to moisture, chemicals and freeze-thaw cycles ([24,25]; Wang et al., 2022). Properly designed and maintained concrete structures can have a long service life, reducing the need for frequent repairs or replacements. Concrete's resistance to corrosion, weathering and deterioration ensures its performance and structural integrity over time.

Concrete is a versatile material that can be moulded into various shapes and sizes. It can be poured, moulded and cast into different forms, allowing for flexibility in design and construction. This versatility contributes to its widespread use in both architectural and structural applications, accommodating a wide range of aesthetic and functional requirements. Additionally, concrete offers excellent thermal mass properties, which make it suitable for TES applications. Concrete has the ability to absorb and store significant amounts of heat energy [26,27]. This enables it to act as a thermal energy storage medium, where excess thermal energy can be captured and released when needed to balance energy supply and demand. Concrete's thermal mass also contributes to energy efficiency in buildings by providing thermal inertia, helping to regulate indoor temperatures and reduce heating and cooling loads. While concrete offers numerous advantages, it does have limitations. Its low tensile strength makes it prone to cracking under tension, but this can be addressed by incorporating reinforcement materials like steel bars or fibres. Additionally, concrete is a heavy material, which necessitates careful consideration in structural design and logistics during transportation and construction. Proper planning and engineering can effectively address these limitations, allowing for the successful and durable use of concrete in various applications.

2.2. *Properties of concrete relevant to thermal energy storage*

Concrete possesses several properties that are relevant to thermal energy storage (TES) applications. These include thermal conductivity, specific heat and thermal diffusivity.

2.2.1. *Thermal conductivity of concrete*

Thermal conductivity is a fundamental property of concrete that determines its ability to conduct heat. It quantifies the rate at which heat is transferred through the material. Concrete typically exhibits moderate thermal conductivity, meaning it has a moderate capacity to conduct heat compared to other materials. The thermal conductivity of concrete is influenced by various factors, including the composition of the concrete mix, the type and size of aggregates used and the water-to-cement ratio [28–31]. These factors affect the density and porosity of the concrete, which, in turn, impact its thermal conductivity. The water-to-cement ratio also plays a role, as higher water content can increase the porosity and decrease the thermal conductivity of concrete. Fig. 1 illustrates the correlation between the density and thermal conductivity of concrete, based on analysis of 185 experimental data points from various types of cement mortar and concrete. The relationship displayed in the figure demonstrates strong correlations between these two properties.

The thermal conductivity of concrete plays a crucial role in TES applications. It directly impacts the effectiveness of heat transfer within the material, which is essential for efficient storage and retrieval of thermal energy [32–34]. A higher thermal conductivity facilitates faster and more efficient heat transfer, ensuring effective heat storage and release in concrete-based TES systems. It also contributes to the uniform distribution of thermal energy throughout the concrete structure, maximising the storage capacity of heat [35–37]. By understanding and optimising the thermal conductivity of concrete, engineers can design TES systems that maximise the efficiency and performance of thermal energy storage, enabling effective management and utilisation of thermal energy resources.

The thermal conductivity of concrete is a topic of interest in the field of construction materials and thermal energy storage. Several studies have been conducted to investigate the thermal conductivity behaviour of concrete and its influencing factors. Kim et al. [38] conducted an experimental study on the thermal conductivity of concrete, providing valuable insights into the relationship between thermal conductivity and factors such as water-to-cement ratio and aggregate type. Their study involved measuring the thermal conductivity of different concrete mixes and analysing the data to understand the impact of these factors on thermal conductivity. The findings of their study contribute to the understanding of how variations in concrete composition can affect its thermal conductivity, helping researchers and engineers make informed decisions when designing concrete-based thermal energy storage systems. Choktaweekarn et al. [39] developed a model for predicting the thermal conductivity of concrete. They considered factors such as aggregate type, cement content and water-to-cement ratio in their model. By utilising experimental data, they established mathematical relationships between these factors and the thermal conductivity of concrete. Their model provides a valuable tool for estimating the

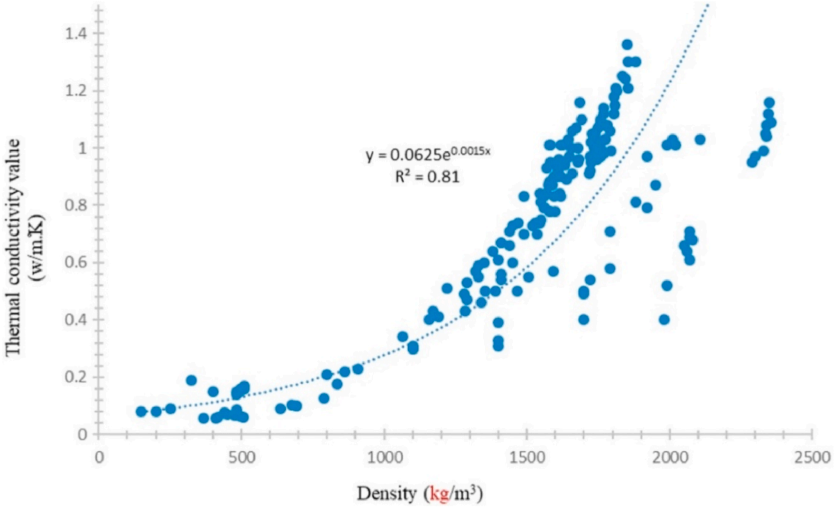

Fig. 1. General correlation between thermal conductivity and density of concrete [27].

thermal conductivity of concrete without the need for extensive testing, facilitating the design and optimisation of thermal energy storage systems.

In a study conducted by Kim et al. [38], a series of fully saturated specimens were tested at different curing ages to investigate the influence of thermal conductivity on the age of concrete. Fig. 2(a) demonstrates that the thermal conductivities of cement, mortar and concrete mixes remained independent of curing age, although significant variations were observed among different mixes. Additionally, the thermal conductivity of cement paste was found to be the lowest, dropping to almost half that of concrete. Fig. 2(b) indicates

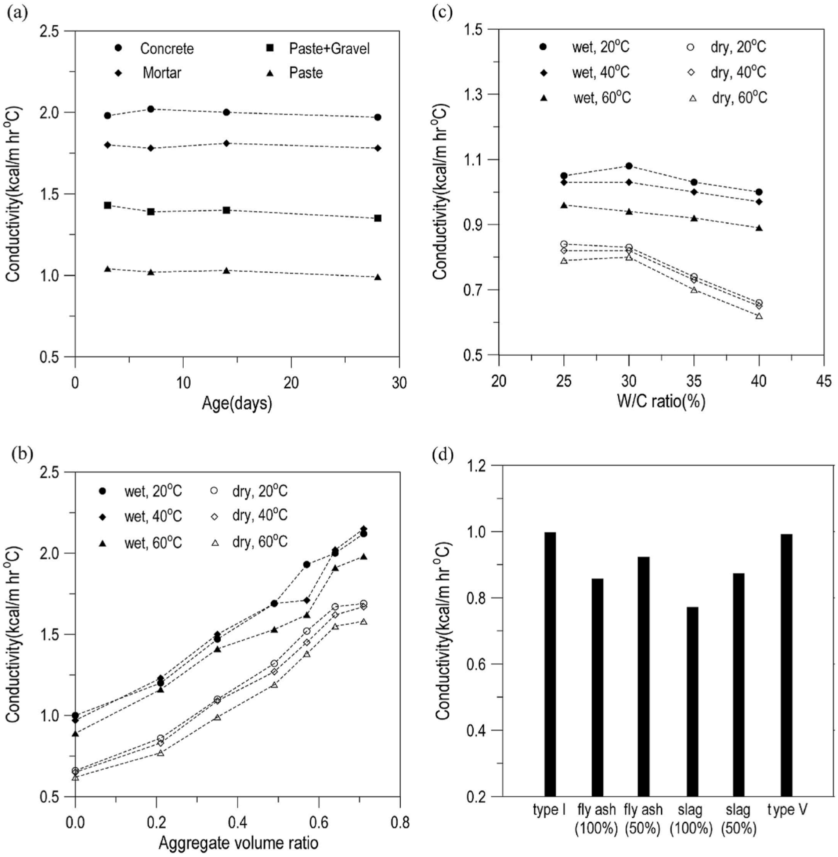

Fig. 2. Experimental results for thermal conductivity. (a) Age; (b) Aggregate content; (c) W/C ratio of paste; (d) Type of cementitious materials [38].

that increasing the volume fractions of aggregates led to a linear increment in thermal conductivity, regardless of temperature or moisture conditions. This suggests that concrete with a higher aggregate content would exhibit a higher thermal conductivity, as aggregates have the highest thermal conductivity among the constituents of the concrete mix. Fig. 2(c) shows that the coefficient of thermal conductivity of the cement paste decreased under various moisture and temperature conditions. Furthermore, increasing the amount of cement (lower W/C ratio) resulted in an increase in the thermal conductivity of the paste specimens, as cement possesses a higher thermal conductivity compared to water. Fig. 2 (d) reveals that the thermal conductivity of paste made with type I cement was similar to that of type V cement, while the incorporation of fly ash or slag in place of cement led to a reduction in the coefficient of thermal conductivity.

Zhang et al. [40] proposed a mesoscale model to predict the thermal conductivity of concrete. They took into account the microstructure of the material, considering factors such as the size, shape and arrangement of the aggregate particles, as well as the cementitious matrix. By simulating the heat transfer behaviour at a microscale level, their model offers a more detailed and accurate prediction of the thermal conductivity of concrete. This contributes to a deeper understanding of the factors influencing thermal conductivity and assists in the development of concrete mixes with improved thermal properties. Real et al. [41] focused on the thermal conductivity of lightweight aggregate concrete. They conducted experiments to investigate the effect of lightweight aggregates on the thermal properties of concrete. Their study provided insights into the thermal conductivity behaviour of lightweight aggregate concrete, which is commonly used in construction applications where thermal insulation is desired. By understanding how lightweight aggregates affect the thermal conductivity, engineers can make informed decisions when selecting materials for specific thermal energy storage applications.

Asadi et al. [27] presented a comprehensive review of the thermal conductivity of concrete, summarising and analysing various studies conducted in this field. They discussed factors such as mix design, aggregate type, moisture content and temperature that influence the thermal conductivity of concrete. Their review provides a comprehensive overview of the topic, highlighting the importance of considering these factors when designing and optimising thermal energy storage systems using concrete as a medium. Sargam et al. [42] investigated the effects of modern concrete materials on thermal conductivity. They explored the influence of supplementary cementitious materials (SCMs) and nanomaterials on the thermal properties of concrete. Their study examined how incorporating SCMs or nanomaterials can enhance the thermal conductivity of concrete, opening up opportunities for improving the efficiency of thermal energy storage systems. The findings contribute to the understanding of the potential benefits of incorporating innovative materials in concrete for thermal energy storage applications.

Lucio-Martin et al. [7] conducted experimental analysis to investigate the thermal conductivity of concrete at high temperatures, particularly for thermal energy storage applications. They measured the thermal conductivity of concrete samples subjected to elevated temperatures and analysed the data to understand the behaviour of thermal conductivity under such conditions. Their study provides insights into the thermal performance of concrete for high-temperature applications, enabling the design and optimisation of thermal energy storage systems that can operate effectively at elevated temperatures. Dai et al. [43] conducted research on the influencing factors and time-varying model of thermal conductivity in early-age concrete. They studied how factors such as curing conditions, cement hydration and age affect the thermal conductivity of concrete during the early stages of its development. Their work contributes to understanding the evolution of thermal conductivity in concrete as it matures, providing insights into the design and optimisation of thermal energy storage systems using early-age concrete.

The discussed studies collectively contribute to the understanding of the thermal conductivity of concrete and its implications for thermal energy storage. They provide valuable insights into the factors influencing thermal conductivity, develop predictive models, explore the effects of different materials and conditions and analyse the behaviour of thermal conductivity at various stages and temperature ranges. These findings aid in the development of efficient and optimised concrete-based thermal energy storage systems for various applications.

In the pursuit of optimising the thermal conductivity of concrete for TES applications, researchers and engineers employ various approaches. One approach involves incorporating additives, such as conductive fillers or fibres, into the concrete mix. These additives enhance the thermal conductivity of concrete by facilitating the efficient transfer of heat. Another approach involves modifying the proportions of the concrete mix, including the type and grading of aggregates. Adjusting these factors can have a significant impact on the thermal conductivity of concrete, allowing engineers to tailor it according to the specific requirements of TES systems. By carefully selecting and adjusting these factors, engineers can optimise the thermal conductivity of concrete, ensuring its efficacy in storing and releasing thermal energy in TES applications.

Understanding the thermal conductivity of concrete is crucial in the design and optimisation of TES systems. By taking into account the factors that affect thermal conductivity, engineers can make informed choices in selecting concrete mixes that facilitate efficient heat transfer and storage. Ongoing research efforts are focused on developing concrete materials with enhanced thermal conductivity properties. These advancements aim to improve the performance and effectiveness of concrete-based TES systems in various applications. By continually improving our understanding of thermal conductivity in concrete, engineers can enhance the overall efficiency and reliability of TES systems, contributing to more sustainable and efficient energy management.

2.2.2. Specific heat of concrete

The specific heat of concrete is a fundamental property that describes its capability to absorb and release thermal energy. It quantifies the amount of heat required to raise the temperature of a unit mass of concrete by 1 °C. Concrete generally possesses a comparatively high specific heat in comparison to other construction materials. This attribute enables concrete to store substantial amounts of thermal energy efficiently. The high specific heat of concrete is advantageous for thermal energy storage applications, as it allows for effective heat absorption and retention [26,44,45]. By understanding and leveraging this property, engineers can design and optimise concrete-based thermal energy storage systems to achieve efficient heat storage and release. The specific heat of some of the common substances are summarised in Table 1.

The specific heat of concrete is determined by several factors, including the composition of the concrete mix and the properties of its constituents [46,47]. Cement, aggregates and water content collectively contribute to the overall specific heat of concrete. The specific heat can be influenced by the type and proportions of these materials, with variations in aggregate type, size and grading, as well as the selection of cementitious materials and additives, potentially affecting the heat storage capacity of the concrete. Understanding these factors allows engineers to manipulate the specific heat of concrete to optimise its thermal energy storage capabilities for various applications.

The high specific heat of concrete enables it to effectively absorb and store significant amounts of thermal energy. When there is excess thermal energy during periods of high production or low demand, concrete can readily absorb this energy, resulting in an increase in its temperature and the storage of thermal energy within its mass. This stored thermal energy can later be released when required, such as during periods of high energy demand or low energy production, allowing for the balancing of energy supply and demand. The specific heat of concrete plays a crucial role in thermal energy storage systems, facilitating the efficient storage and release of thermal energy to optimise energy management and utilisation. The specific heat of concrete is a key factor considered by engineers and researchers in the design and optimisation of TES systems. By selecting concrete mixes with appropriate specific heat capacities, they can maximise the energy storage capacity of the system and ensure efficient utilisation of thermal energy. Accurate measurement and characterisation of the specific heat at relevant operating temperatures are crucial for precise system design and performance evaluation of concrete-based TES systems. Understanding the specific heat allows for informed decisions in selecting concrete materials and optimising the storage and release of thermal energy, ultimately enhancing the efficiency and effectiveness of TES systems.

Several studies have explored different aspects of concrete's specific heat and its influence on energy storage and thermal performance. The study conducted by Pomianowski et al. [48] focused on developing a new experimental method to determine the specific heat of concrete with incorporated microencapsulated phase change material (PCM). The research aimed to improve the understanding of thermal properties in concrete materials that contain PCM, which can enhance the thermal energy storage capacity of concrete. By investigating the specific heat of concrete with embedded PCM, the study provided insights into the potential for utilising such materials in TES applications.

Abid et al. [49] conducted a comprehensive review that examined the high-temperature properties of reactive powder concrete. The study discussed the specific heat of this specialized concrete material and its potential for applications in extreme thermal environments. By exploring the specific heat and other properties, the research contributed to the understanding of concrete's behaviour under high-temperature conditions, which is crucial for applications that require resistance to elevated temperatures. The review by Shafigh et al. [4] focused on concrete as a thermal mass material for building applications. It examined the specific heat of concrete and its role in regulating indoor temperature and reducing energy consumption in buildings. By exploring the specific heat of concrete as a thermal mass, the study highlighted the importance of incorporating concrete in building designs to improve energy efficiency and thermal comfort. In the study by Song et al. [50], a specific heat model was proposed for concrete walls containing phase change material (PCM) based on field experiments. The research aimed to optimise the design and performance of concrete walls with integrated PCM for enhanced thermal energy storage capabilities. By investigating the specific heat of the composite material, the study provided insights into the potential for utilising PCM-embedded concrete walls in TES applications.

Overall, these studies collectively contribute to the understanding of the specific heat of concrete and its implications for thermal energy storage and building applications. By investigating various aspects such as the incorporation of PCM, high-temperature properties and building thermal performance, researchers aim to improve the design and optimisation of concrete-based TES systems and enhance energy efficiency in buildings. These findings have the potential to guide the development of innovative concrete materials and improve the overall performance and sustainability of TES systems and building designs.

2.2.3. Thermal diffusivity of concrete

Thermal diffusivity is an important parameter that characterises the ability of a material, such as concrete, to conduct and distribute heat. It represents the speed at which thermal energy propagates through the material. The thermal diffusivity of concrete is determined by the ratio of its thermal conductivity to its volumetric heat capacity [51–53]. A higher thermal diffusivity indicates that

Table 1
Specific heat of some of the common substances.

Material	Specific Heat (J/kg/^{o}C)	Specific Heat (Btu/lb/^{o}F)
Water	4168	1.00
White pine	2800	0.67
Ice	2090	0.50
Air	1004	0.24
Concrete	960	0.23
Aluminium	900	0.22
Glass	840	0.20
Rock	840	0.20
Iron	448	0.12
Copper	387	0.093

heat is conducted more rapidly within the material. This property is crucial for understanding the thermal behaviour of concrete in various applications, including thermal energy storage systems. Accurate knowledge of the thermal diffusivity of concrete enables engineers to design and optimise systems for efficient heat transfer and storage.

The thermal diffusivity of concrete is affected by various factors, such as the ingredients used in the concrete mix, the presence of aggregates, the moisture content and the curing conditions. Aggregates, in particular, play a significant role in influencing the thermal diffusivity of concrete due to their typically lower thermal conductivity compared to the cementitious matrix [54]. The size, type and distribution of aggregates can impact the overall heat transfer properties of concrete. Additionally, the moisture content and curing conditions during the concrete's setting process can affect its thermal diffusivity [51,55]. Understanding the influence of these factors is important for designing concrete structures and thermal energy storage systems with optimal heat transfer capabilities.

Accurate determination of the thermal diffusivity of concrete is crucial for gaining insights into its thermal behaviour and for optimising thermal energy storage systems. Researchers utilise experimental methods like the laser flash method and the transient plane source method to measure the thermal diffusivity of concrete [56–58]. These techniques involve subjecting the concrete sample to a heat pulse and analysing the resulting temperature response. By quantifying the thermal diffusivity, engineers and researchers can better understand how heat is transferred and distributed within the concrete material. This knowledge is invaluable for designing and optimising concrete-based thermal energy storage systems to ensure efficient heat storage, release and overall system performance. The thermal diffusivity of concrete plays a critical role in applications involving rapid temperature changes, such as TES systems and structures exposed to fluctuating environmental conditions. Understanding and controlling the thermal diffusivity of concrete enables engineers and researchers to optimise heat transfer and utilisation within concrete-based thermal energy storage systems, resulting in enhanced performance and energy efficiency. By tailoring the thermal diffusivity of concrete, engineers can ensure that thermal energy is effectively stored, released and distributed within the material, maximising the overall efficiency of the system and minimising energy losses. This knowledge contributes to the development of more efficient and reliable thermal energy storage solutions for various applications.

Researchers have conducted studies to investigate the thermal diffusivity of concrete and its related factors. De Schutter & Taerwe [59] conducted an experimental study focusing on the specific heat and thermal diffusivity of hardening concrete. The research aimed to understand the development of thermal properties during the concrete curing process. They measured the specific heat and thermal diffusivity of concrete at various ages and investigated the effects of cement type and water-cement ratio on these properties. Luca & Mrawira [60] carried out measurements to determine the thermal properties of superpave asphalt concrete, which is widely used in road construction. Their study involved measuring the specific heat and thermal diffusivity of asphalt concrete samples under different temperature conditions. The results provided valuable insights into the thermal behaviour of asphalt concrete and its performance in various environmental conditions.

Krishnaiah & Singh [61] focused on the thermal properties of supplementary cementing materials used in cement and concrete. They determined the specific heat and thermal diffusivity of materials such as fly ash and slag, which are commonly used as partial replacements for cement. The study aimed to understand the influence of these materials on the thermal behaviour of concrete and their potential impact on energy efficiency. Taoukil et al. [51] investigated the influence of moisture content on the thermal conductivity and diffusivity of wood-concrete composites. The study involved measuring the thermal properties of composite materials with different moisture contents. The findings highlighted the importance of moisture content in affecting the thermal behaviour of wood-concrete composites, which has implications for the design and performance of these materials in applications such as building construction and structural engineering.

Zhang & Yan [62] studied the temperature dependence of thermal diffusivity in ordinary Portland cement and calcium aluminate cement paste. The research involved measuring the thermal diffusivity of cementitious materials at different temperatures to assess their thermal behaviour under varying conditions. Fig. 8 illustrates the thermal diffusivity of OPC paste determined using LFA. The results demonstrate that the thermal diffusivity tends to decrease as the temperature rises. Interestingly, the thermal diffusivity values of both the reference specimen and the preheated specimens were nearly identical. This suggests that the process of de-hydration and moisture transfer has minimal impact on the intrinsic thermal diffusivity of the OPC paste. The thermal diffusivity of OPC paste obtained by LFA is shown in Fig. 38. It was found that the thermal diffusivity generally decreases with increasing temperature. The values of thermal diffusivity of the reference specimen and the preheated specimens were almost identical. This indicated that the dehydration and moisture transfer hardly changed the intrinsic thermal diffusivity. The study provided insights into the temperature-dependent properties of cement paste and their implications for heat transfer in concrete structures. Pan et al. [63] examined the effect of freezing-thawing and ageing on the thermal characteristics and mechanical properties of conductive asphalt concrete. The research involved investigating the changes in thermal diffusivity of asphalt concrete due to environmental factors such as freeze-thaw cycles and ageing. The study contributed to understanding the thermal performance and durability of conductive asphalt concrete under adverse conditions.

The studies reviewed on the thermal diffusivity of concrete and related materials offer valuable insights into the behaviour of heat transfer in various conditions. The data generated from these studies can significantly contribute to the design and optimisation of concrete structures, thermal energy storage systems and other applications that require precise heat transfer analysis. By improving our understanding of thermal diffusivity, these findings have the potential to enhance the development of more efficient and sustainable construction materials and practices. This knowledge is essential for promoting energy efficiency and achieving greater sustainability in the construction industry.

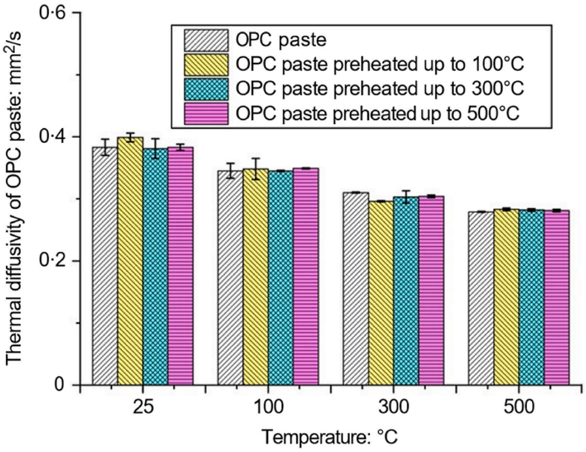

Fig. 3. Thermal diffusivity of OPC paste at elevated temperature [62].

2.3. Thermal energy storage methods in concrete

Thermal energy storage (TES) in concrete can be achieved through various methods. One common approach is sensible heat storage, where the excess thermal energy is stored by raising the temperature of the concrete itself. This can be done by circulating heated fluids through embedded pipes or by direct contact with a heat source. Another method is latent heat storage, which involves incorporating phase change materials (PCMs) into the concrete. These PCMs absorb and release thermal energy during the phase transition, effectively storing and releasing heat. Thermochemical heat storage is another technique, where chemical reactions within the concrete absorb or release heat energy for storage and retrieval. These different methods offer flexibility in designing concrete-based TES systems to meet specific energy storage requirements.

2.3.1. Embedded pipe systems

Embedded pipe systems are widely used for TES in concrete structures due to their efficient capability to capture and store thermal energy. These systems involve a network of pipes embedded within the concrete, through which a heat transfer fluid is circulated. When there is excess thermal energy during low demand or high production periods, the fluid is heated and stored within the concrete, effectively storing the thermal energy for later use. This approach allows for the efficient balancing of energy supply and demand, making it suitable for various applications such as building heating and cooling systems or industrial processes. The design and configuration of the embedded pipe system are crucial for optimising heat transfer efficiency and achieving effective thermal energy storage in concrete structures [64–66]. Fig. 4 illustrates the composition of a concrete core, comprising a deck slab situated between multiple levels. The concrete core serves the dual purpose of providing heating or cooling, with the heat flux directed towards either the upper top surface as a radiant floor or the bottom surface as a radiant ceiling. To achieve the desired design objectives, insulation can be implemented to regulate the heat flux, allowing it to pass through only one surface as required.

Embedded pipe systems for thermal energy storage in concrete provide numerous advantages. The large surface area of the pipes facilitates efficient heat exchange between the circulating fluid and the concrete, resulting in effective heat transfer. The concrete acts as a thermal mass, enabling the absorption and storage of heat energy, allowing for prolonged energy storage periods. This characteristic makes embedded pipe systems suitable for applications that require consistent and manageable heat supply, such as building heating and cooling systems or industrial processes. The combination of efficient heat exchange and the thermal storage capacity of concrete makes embedded pipe systems an attractive choice for thermal energy storage applications [68,69].

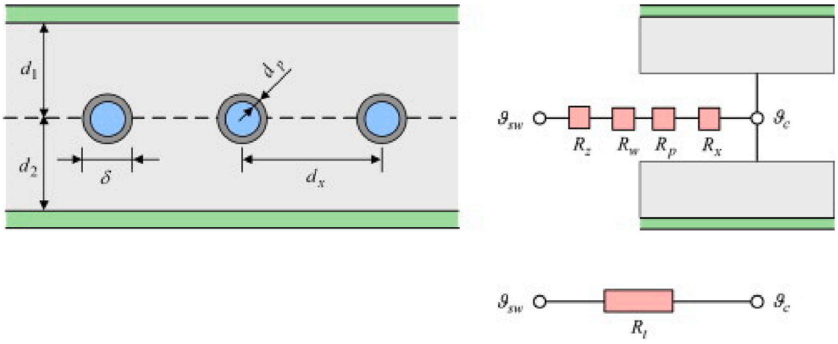

Fig. 4. Piping system embedded in a slab and corresponding representation as TABS model [67].

The design and configuration of the embedded pipe system play a critical role in maximising heat transfer efficiency. Factors such as the layout, spacing, diameter and flow rates of the pipes must be carefully considered to ensure uniform heat distribution throughout the concrete and minimise energy losses [70,71]. Proper insulation measures are also crucial to minimise heat losses during the storage and retrieval processes, thereby improving the overall efficiency of the system. By optimising these design parameters and implementing effective insulation strategies, engineers can enhance the performance of the embedded pipe system, ensuring efficient heat transfer and maximising the storage and retrieval of thermal energy in concrete.

Ongoing research and development endeavours aim to improve the performance of embedded pipe systems in concrete for thermal energy storage [45,72]. These efforts involve advancements in pipe materials, focusing on materials with high thermal conductivity to enhance heat transfer efficiency. Researchers are also exploring the selection of appropriate heat transfer fluids to optimise the system's overall performance. Furthermore, control strategies and optimisation techniques are being developed to improve the management and operation of embedded pipe systems, ensuring efficient energy storage and retrieval. By continually advancing these aspects, engineers can enhance the effectiveness and reliability of embedded pipe systems in concrete for thermal energy storage applications.

Modelling and simulation techniques are indispensable for the design and analysis of embedded pipe systems used in thermal energy storage. These tools enable engineers to predict and evaluate the thermal behaviour and performance of the system under various operating conditions. By utilising these models, engineers can assess different design configurations, optimise system parameters and identify potential performance improvements. Modelling and simulation also provide valuable insights into heat transfer characteristics, temperature distributions and energy storage capacities. This information aids in the development of efficient and reliable embedded pipe systems, ensuring optimal thermal energy storage performance and facilitating the integration of these systems into diverse applications.

2.3.2. Phase Change Materials (PCMs) in concrete

Phase Change Materials (PCMs) are substances with exceptional thermal energy storage properties, allowing them to store and release large amounts of heat energy during phase transitions. These transitions occur when PCMs change from one physical state to another, such as solid to liquid or liquid to gas. PCMs are extensively used in TES systems to augment the heat storage capacity and efficiency of concrete. By incorporating PCMs into concrete structures, the thermal energy can be stored and released at desired temperatures, regulating temperature fluctuations, improving energy efficiency and enhancing thermal comfort in buildings and other applications.

In concrete applications, PCMs can be incorporated in different forms to harness their thermal energy storage capabilities. One commonly used method is microencapsulation, where tiny capsules filled with PCM are dispersed throughout the concrete matrix [73–76]. These capsules act as protective shells, preventing PCM leakage and ensuring its stability within the concrete. Another approach is macro-encapsulation, which involves the use of larger containers or tubes filled with PCM that are embedded within the concrete structure. This method allows for controlled placement and retrieval of PCM. Additionally, direct mixing is another technique where PCM is directly blended into the concrete mix as particles or granules, enabling uniform distribution throughout the material. The selection of the appropriate PCM incorporation method depends on factors such as the specific application requirements and the desired thermal performance of the concrete structure. The physical properties of some of the PCMs are summarised in Table 2.

The integration of PCMs in concrete brings several advantages. PCMs have the ability to absorb or release a substantial amount of latent heat energy during phase transitions, allowing for efficient storage and release of thermal energy. This characteristic enables PCMs to regulate temperature fluctuations in buildings, reduce peak energy demand and enhance overall energy efficiency [11,77,78]. Additionally, the inclusion of PCMs enhances the thermal mass of concrete, improving its capacity to absorb, store and distribute heat. As a result, buildings with PCM-enhanced concrete experience more stable indoor temperatures and increased thermal comfort for occupants. This integration of PCMs in concrete contributes to sustainable and energy-efficient construction practices.

The selection of suitable PCMs for concrete applications involves considering various factors to ensure optimal performance ([79,80]; Wang et al., 2022; [81]). One crucial aspect is the desired phase change temperature range, as different PCMs have specific transition points that determine when heat storage or release occurs. The heat storage capacity of the PCM is another critical consideration, as it determines the amount of thermal energy that can be stored within the material. The thermal stability of the PCM is important to ensure that it can withstand repeated phase transitions without degradation. Compatibility with concrete materials is also essential to ensure proper integration and durability of the PCM-concrete composite. Long-term durability is a crucial factor, as the

Table 2
Physical properties of Phase change materials (PCMs).

Phase Change Materials			Melting Point (^{o}C)	Latent Heat (kJ/kg)
Paraffins	Hexadecane	$C_{16}H_{34}$	18.2	237
	Octadecane	$C_{18}H_{38}$	29.0	244
Fatty acids	Caprylic acid	$C_8H_{16}O_2$	16.7	149
	Capric acid	$C_{10}H_{20}O_2$	31.6	152
	Lauric acid	$C_{12}H_{24}O_2$	43.8	178
Polyols	Glycerine	$C_3H_8O_3$	17.9	199

PCM should maintain its performance and stability over the expected service life. By carefully considering these factors, engineers and researchers can select suitable PCMs that meet the specific requirements of concrete-based thermal energy storage systems.

Ongoing research and development efforts in the field of PCM-concrete composites aim to optimise their performance and expand their applications. Researchers focus on enhancing the thermal conductivity of PCMs to improve heat transfer efficiency within the concrete matrix [65,82,83]. This involves developing techniques to increase the conductivity of PCMs or incorporating conductive additives into the composite. Additionally, innovative encapsulation methods are being explored to ensure uniform distribution and containment of the PCM within the concrete structure, preventing leakage or segregation. Furthermore, researchers are investigating novel PCM compositions with improved properties and compatibility with concrete materials, such as increased thermal stability and durability [14,84–86]. These advancements aim to enhance the overall effectiveness and reliability of PCM-concrete systems, making them more suitable for various thermal energy storage applications.

Modelling and simulation techniques are essential for understanding and predicting the thermal behaviour and performance of PCM-concrete systems. These tools enable engineers to analyse the impact of various factors, such as PCM concentration, encapsulation methods and concrete composition, on the overall thermal energy storage performance. Through simulations, engineers can study heat transfer mechanisms, assess the effectiveness of different PCM configurations and optimise the design of PCM-concrete systems for specific applications. By evaluating different scenarios and design parameters, these techniques help in identifying the most efficient use of PCMs in concrete structures, ensuring effective storage and release of thermal energy for enhanced energy efficiency and sustainability.

The integration of PCM into building elements represents a promising avenue for enhancing thermal performance and energy efficiency in the built environment. Gencel et al. [87] investigated a silica fume/capric acid-stearic acid PCM included-cementitious composite for thermal control of buildings. The study not only explored the thermal energy storage capabilities but also delved into the mechanical properties of the composite. This research emphasizes the multifunctionality of PCM-cementitious composites, suggesting a potential dual role in structural and thermal aspects. In Gencel et al. [88], the focus shifted to a cement-based thermal energy storage mortar incorporating blast furnace slag and capric acid as a shape-stabilized PCM. This study delved into the physical, mechanical, and thermal properties, as well as the solar thermoregulation performance of the composite. The findings highlight the versatility of PCM integration in building materials, showcasing its potential for solar energy utilisation.

Hekimoğlu et al. [89] explored a novel cementitious composite containing fly ash and lauric acid-myristic acid as a form-stable PCM. The study provided insights into both the thermal management performance and mechanical properties of the composite. This research adds to the growing body of knowledge on tailoring PCM-cementitious materials for specific applications, such as in the construction industry. In Gencel et al. [90], the investigation extended to shape-stable attapulgite-based composite PCM in foam concrete. This research not only explored physico-mechanical and thermal properties but also assessed the solar thermoregulation performance. The study underscores the potential of PCM integration in foam concrete, a lightweight construction material widely used in building applications. The use of glass fibre reinforced gypsum composites with microencapsulated PCM was studied by Gencel et al. [91], focusing on its application as a novel building thermal energy storage material. This research contributes to the development of innovative building materials that serve both structural and thermal roles, showcasing the versatility of PCM integration.

Erdogmus et al. [92] presented a thermal performance analysis of novel foam concrete composites with PCM, emphasizing energy storage and environmental benefits in buildings. This study reflects a broader perspective on the environmental impact and sustainability of PCM-integrated building materials. In Kocyigit et al. [93], the research delved into thermal energy saving and physico-mechanical properties of foam concrete incorporating a form-stabilized basalt powder/capric acid-based composite PCM. The study showcases the potential of utilising alternative materials for PCM integration, aiming for enhanced thermal and mechanical performance. Gencel et al. [94] explored a light-transmitting glass fiber reinforced cementitious composite containing microencapsulated PCM for thermal energy saving. This innovative approach not only enhances thermal performance but also introduces light-transmitting properties, demonstrating the versatility of PCM in contributing to daylighting strategies.

Properties of eco-friendly foam concrete containing PCM-impregnated rice husk ash for thermal management of buildings were investigated by Gencel et al. [95]. This study reflects a sustainable approach to PCM integration, considering the use of environmentally friendly materials to enhance the thermal performance of buildings. In Yaras et al. [96], the characteristics, energy saving, and carbon emission reduction potential of gypsum wallboard containing PCM were explored. This research expands the scope of PCM integration to interior building elements, such as wallboards, aiming for a holistic approach to energy efficiency in buildings. Gencel et al. [87] investigated eco-friendly building materials containing micronized expanded vermiculite and PCM for solar-based thermoregulation applications. This study reflects the ongoing efforts to develop sustainable building materials that utilise renewable energy sources for thermal regulation. In Gencel et al. [97], a novel energy-effective and carbon-emission reducing mortar with bottom ash and PCM was studied. This research aligns with the broader goal of reducing carbon emissions in the construction industry while emphasizing the energy efficiency of PCM-integrated materials. The evaluation of pumice for the development of low-cost and energy-efficient composite PCMs in cementitious plasters was conducted by Sarı et al. [98]. This study highlights the importance of exploring cost-effective materials for PCM integration, with a focus on practical applications in construction. Sarı et al. [99] presented the preparation, characterization, and thermal regulation performance of a cement-based composite PCM. This foundational research contributes to the understanding of the fundamental properties of PCM-integrated materials, paving the way for further advancements in the field.

In summary, the critical discussion on PCM integration into building elements based on the referenced studies reveals a growing trend toward multifunctional building materials that not only provide structural support but also contribute significantly to thermal energy storage and management. The studies collectively showcase the diverse approaches, materials, and applications in PCM integration, emphasizing the potential for energy-efficient and sustainable building practices. However, challenges such as cost, scalability, and long-term performance need further exploration to facilitate widespread adoption in the construction industry.

2.3.3. Concrete Matrix heat storage

'Concrete Matrix Heat Storage' is a distinct third approach, separate from sensible storage and PCM storage. Concrete matrix heat storage utilises the inherent properties of concrete to effectively store and release thermal energy. The concrete matrix acts as a thermal mass, capable of absorbing and retaining heat energy. Sensible heat storage involves raising the temperature of the concrete, storing thermal energy in its mass. Latent heat storage, on the other hand, involves incorporating PCMs within the concrete, which absorb or release heat energy during phase transitions. By leveraging the thermal storage capacity of the concrete matrix, this approach allows for efficient and reliable heat storage, enabling balanced energy usage and improved energy efficiency in various applications. Concrete matrix heat storage offers several advantages in TES applications. Firstly, concrete is a widely available and cost-effective material, making it suitable for large-scale energy storage systems. The high thermal conductivity of concrete allows for efficient heat transfer, facilitating the storage and retrieval of thermal energy. The high volumetric heat capacity of concrete enables it to store a significant amount of thermal energy per unit volume. Additionally, the durability and longevity of concrete make it a reliable and long-lasting solution for heat storage applications.

The selection of suitable PCMs is crucial, taking into account factors such as the desired phase change temperature range, compatibility with concrete and long-term stability. Additionally, the system configuration, including the arrangement of concrete elements and the incorporation of heat transfer mechanisms like embedded pipes or fins, plays a significant role in optimising heat transfer and distribution within the concrete matrix. By carefully considering these factors, engineers can design concrete matrix heat storage systems that effectively store and release thermal energy, contributing to improved energy management, thermal comfort and energy efficiency in various applications.

Proper insulation measures play a crucial role in concrete matrix heat storage systems ([100]; Alva et al., 2018; [101]). Insulation materials are used to reduce heat losses from the concrete structure, thereby improving the overall system efficiency. These materials are applied to the external surfaces of the concrete to minimise heat transfer to the surroundings during both the storage and retrieval processes. By preventing excessive heat losses, insulation helps maintain the stored thermal energy within the concrete for longer periods, allowing for efficient energy utilisation when needed. Additionally, insulation contributes to the stability of the thermal energy storage system by reducing temperature fluctuations and optimising the overall performance of the system.

Modelling and simulation techniques are essential tools in the design and optimisation of concrete matrix heat storage systems. These techniques enable engineers to analyse and predict the thermal behaviour and performance of the system under different operating conditions. By simulating various scenarios and configurations, engineers can optimise the concrete mix proportions, PCMs content and system parameters to achieve the desired thermal energy storage performance. Modelling and simulation help in identifying potential design improvements, optimising insulation strategies and assessing the overall system efficiency. These tools provide valuable insights into the thermal dynamics and enable engineers to make informed decisions in the design and operation of concrete matrix heat storage systems.

Concrete matrix heat storage is a versatile technology that finds applications in various sectors, including buildings, district heating systems and industrial processes. By storing excess thermal energy during periods of low demand or high energy production, concrete matrix heat storage systems contribute to energy efficiency and load balancing in the energy grid. This allows for the efficient utilisation of renewable energy sources, as the stored energy can be released when demand exceeds production. In buildings, concrete matrix heat storage systems help regulate indoor temperatures, reduce reliance on conventional heating and cooling systems and improve overall energy efficiency. In district heating systems and industrial processes, these systems provide a reliable and controllable heat supply, reducing the need for peak energy generation and optimising energy utilisation.

3. Performance evaluation and modelling

Performance evaluation and modelling play a crucial role in the development and optimisation of TES systems. Through performance evaluation, engineers can assess the effectiveness and efficiency of TES systems in terms of energy storage and release, temperature control and overall system performance. Various metrics, such as heat storage capacity, energy losses and thermal response, are analysed to evaluate the system's performance. Modelling, on the other hand, involves the use of mathematical and computational techniques to simulate and predict the behaviour of TES systems. Models can capture the complex interactions between the concrete matrix, phase change materials (PCMs), heat transfer fluids and surrounding environment. By utilising these models, engineers can optimise the design, configuration and operation of TES systems, considering various factors such as material properties, system parameters and external conditions. This allows for a more efficient and cost-effective development of TES systems tailored to specific applications.

3.1. Measurement techniques for thermal properties of concrete

Measurement techniques for thermal properties of concrete are crucial for understanding and characterising its behaviour in TES applications. These techniques allow engineers and researchers to determine key parameters such as thermal conductivity, specific heat and thermal diffusivity, which are essential for designing and optimising TES systems. By accurately measuring these properties, it becomes possible to evaluate the heat transfer performance, energy storage capacity and overall thermal behaviour of concrete. This information is critical for the development of efficient and effective TES systems, enabling the storage and utilisation of thermal energy in a wide range of applications, including buildings, industrial processes and renewable energy integration. Fig. 5 provides an overview of the various measurement techniques available for determining the thermal conductivity of concrete.

The transient heat flow method, also known as the hot-wire method, is a widely used technique for measuring the thermal properties of concrete [102–104]. It involves applying a heat pulse to a concrete sample and then monitoring the resulting temperature change over time. The temperature response is used to determine the thermal conductivity and thermal diffusivity of the concrete. In this method, a small wire or sensor, typically made of a material with known thermal properties, is embedded in the concrete sample. A known amount of heat is then applied to the wire, creating a heat pulse. As the heat travels through the concrete, it causes a temperature change in the wire, which is measured using a thermocouple or resistance thermometer. The temperature response is recorded over a specified time period. By analysing the temperature change over time, researchers can calculate the thermal conductivity and thermal diffusivity of the concrete sample. The transient heat flow method is versatile and can be applied to various types of concrete, making it a valuable tool for evaluating the thermal properties of concrete in thermal energy storage applications.

The steady-state heat flow method is a commonly employed technique for measuring the thermal conductivity of concrete [105–107]. It involves creating a steady temperature gradient across a concrete specimen and measuring the heat flow through the specimen. This method relies on the principle of Fourier's Law of heat conduction, which states that the heat flow is directly proportional to the temperature gradient and the thermal conductivity of the material. To perform the steady-state heat flow measurement, a concrete specimen of known dimensions is prepared. Heat is then applied to one side of the specimen, while the other side is maintained at a different temperature. The temperature difference and the heat flow through the specimen are measured. By knowing the dimensions of the specimen, the temperature difference and the heat flow, the thermal conductivity of the concrete can be calculated using Fourier's Law. The steady-state heat flow method is a reliable and widely used technique for measuring thermal conductivity in various materials, including concrete. It provides valuable data for understanding the thermal properties of concrete and optimising thermal energy storage systems.

Differential scanning calorimetry (DSC) is a widely used technique for characterizing the thermal properties of materials, including PCMs incorporated in concrete. DSC measures the heat flow associated with phase transitions as a function of temperature (Fig. 6). In DSC analysis, a small sample of the material, typically in the form of a powder or solid, is placed in a specially designed cell. The cell is then subjected to a controlled temperature program, where the temperature is ramped up or down at a specified rate. During the temperature changes, the heat flow into or out of the sample is measured and recorded. DSC analysis provides valuable information about the specific heat and the latent heat of PCMs [108–111].

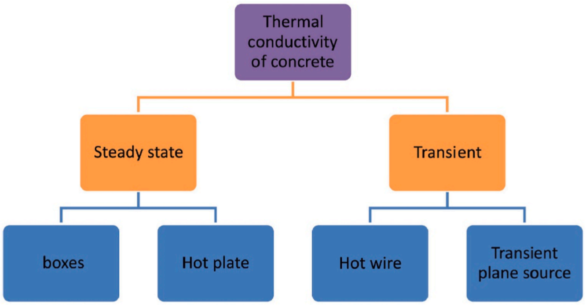

Fig. 5. Different thermal conductivity measurement methods [27].

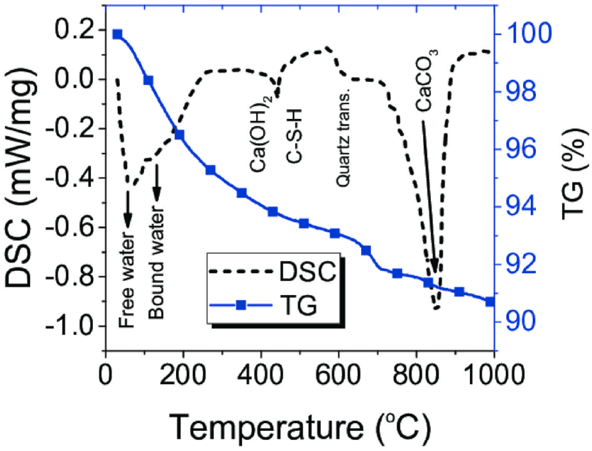

Fig. 6. Thermogravimetric (TG) and differential scanning calorimetry (DSC) curves for Reactive Powder Concrete at different temperatures [112].

The specific heat is the amount of heat energy required to raise the temperature of the material by a certain amount. The latent heat is the heat energy absorbed or released during a phase transition, such as melting or solidification. These properties are essential for understanding the energy storage and release characteristics of PCMs in concrete. DSC analysis is a powerful tool for evaluating the thermal behaviour of PCMs in concrete and optimising their integration in thermal energy storage systems. It helps in selecting suitable PCMs, determining the optimal operating temperatures and assessing the overall performance and efficiency of the system.

Infrared thermography is a non-destructive technique that utilises thermal imaging cameras to capture and visualise the surface temperature variations of concrete structures. It relies on the principle that all objects emit infrared radiation based on their temperature. By using an infrared camera, the surface temperature of the concrete structure can be measured and displayed as a thermal image. This allows for the visualization of heat distribution patterns and the identification of areas with significant temperature variations. Infrared thermography is particularly valuable for large-scale concrete structures, such as buildings, bridges, or pavements, as it enables the detection of potential anomalies or areas of concern, such as thermal bridging, moisture intrusion, or heat loss. It can also be used for real-time monitoring, providing valuable data on the performance and thermal behaviour of the concrete structure over time. By using infrared thermography, engineers and researchers can assess the effectiveness of thermal energy storage systems, identify areas of heat loss or poor insulation and optimise the design and performance of concrete structures for thermal applications. It offers a non-invasive and efficient method for evaluating the thermal behaviour of concrete and helps in the decision-making process for maintenance, repairs, or improvements.

Fig. 7 illustrates representative infrared thermography (IRT) images of concrete specimens with a water-to-cement ratio (W/C) of 0.3 before and after heat exposure. When the maximum temperature applied remains below 400 °C, the temperature distribution on the dried concrete surface after heat exposure appears relatively uniform with a slight increase in temperature compared to before. However, when the concrete specimens with a W/C of 0.3 are heated to 600 °C, certain areas of the concrete surface exhibit a significant temperature elevation. As the temperature rises to 800 °C, the region with higher temperatures expands after IRT scanning. Notably, in the 50 % saturated specimens, the temperature distribution appears more uniform than in the dried and fully saturated specimens.

The combination of measurement techniques for thermal properties of concrete with modelling and simulation approaches allows for a comprehensive evaluation of the thermal behaviour and performance of concrete-based TES systems. Measurement techniques, such as the transient heat flow method, steady-state heat flow method and differential scanning calorimetry, provide valuable data on thermal conductivity, specific heat and phase change behaviour of materials, including concrete and PCMs. These measurements serve as input parameters for modelling and simulation. Modelling techniques, such as finite element analysis, utilise mathematical models to simulate the heat transfer processes within the concrete structure. By incorporating the measured thermal properties and boundary conditions, these models can predict temperature distribution, heat fluxes and heat storage capacities of concrete-based TES systems under various operating conditions. Simulations allow engineers to optimise the design of TES systems, assess their performance and make informed decisions regarding material selection, system configuration and insulation measures. By iteratively ad-

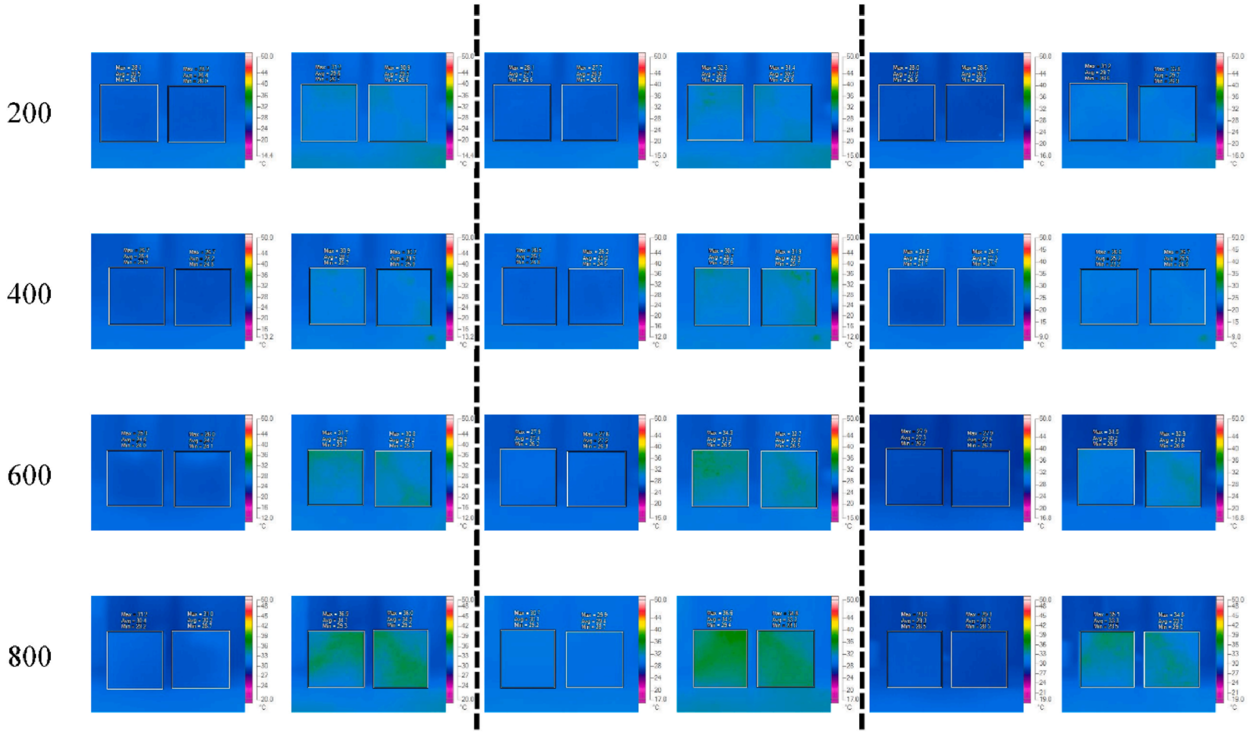

Fig. 7. Representative IRT images of the tested concrete specimens with W/C = 0.3.

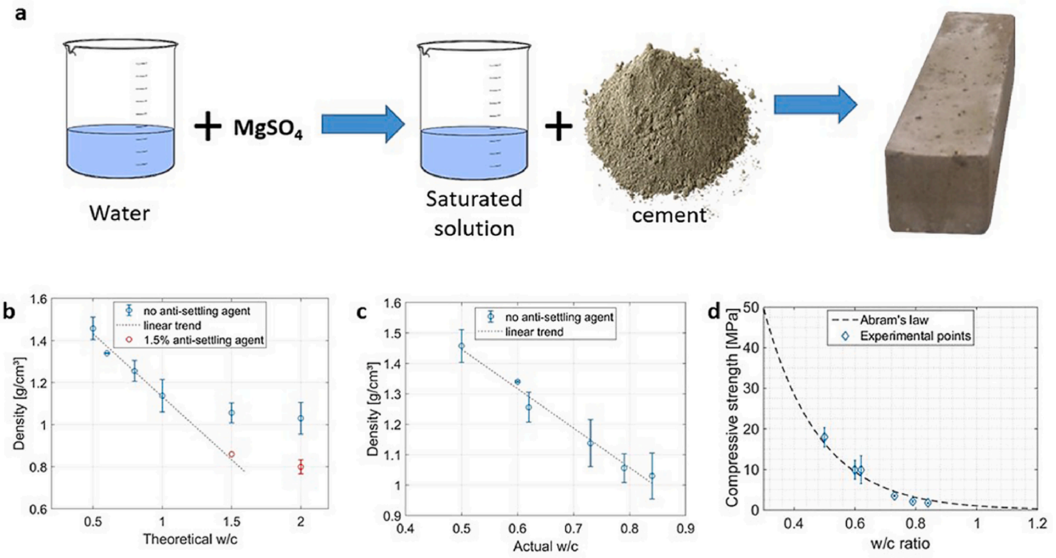

Fig. 8. (**a**) Preparation scheme for composite samples containing magnesium sulphate (**b**) Samples density dependence on theoretical *w/c* ratio, (**c**) on actual *w/c* ratio and (**d**) the correlation between cement compressive strength and *w/c* ratio fitted with the Abrams' Law [113].

justing parameters and evaluating different scenarios, engineers can identify the most efficient and effective design options for concrete-based TES systems. The integration of measurement techniques and modelling approaches provides a powerful toolset for the evaluation and optimisation of thermal properties in concrete. It enables engineers to understand the thermal behaviour of concrete structures and TES systems, validate their performance and refine their designs for enhanced energy efficiency and thermal storage capabilities.

3.2. *Experimental evaluation of concrete-based thermal energy storage systems*

The experimental evaluation of concrete-based thermal energy storage (TES) systems is a critical process that involves conducting tests and measurements to assess their performance and validate their thermal behaviour. By evaluating the efficiency, reliability and effectiveness of TES systems, engineers can gain insights into their operational characteristics and make informed decisions to optimise their design and operation. These evaluations provide valuable data that helps in understanding heat storage and release patterns, identifying thermal irregularities and assessing the overall performance of the TES systems. The experimental evaluation plays a vital role in enhancing the efficiency and effectiveness of concrete-based TES systems in various applications.

This study by Lavagna et al. [113] (Fig. 8) addresses the obstacle of cost-effective and robust sorbent materials for long-term storage of thermal energy, particularly in Adsorptive Heat Transformations (AHT). The research introduces a novel method to synthesize cement-based composite sorbents by incorporating hygroscopic salts into a cementitious matrix. Focusing on magnesium sulphate within a class G cement matrix, the study presents preliminary characterization of material samples, allowing for theoretical estimation of energy density. Results indicate a range of 0.088–0.2 GJ/m3 for optimal samples, competitive in specific cost of stored energy. Furthermore, the sorbent's stability under water sorption-desorption cycling exhibits promising durability.

Experimental evaluations of concrete-based TES systems are essential for assessing their thermal performance and validating their behaviour in real-world conditions [114–116]. These evaluations involve constructing scaled-down or full-scale prototypes that mimic the TES system's configuration and operating conditions. During the experimental evaluations, the TES system is subjected to controlled thermal cycles that replicate the anticipated operating scenarios. This could involve heating or cooling the system, varying the thermal loads, or simulating environmental conditions. The goal is to evaluate the system's ability to store and release thermal energy efficiently. A wide range of parameters is measured and monitored during these experiments to obtain comprehensive insights into the thermal behaviour of the TES system. Temperature profiles are recorded at multiple points within the system using thermocouples or infrared cameras to analyse heat distribution and flow. Heat flux sensors provide information about the rate of heat transfer through the system.

The thermal properties of the concrete, such as thermal conductivity, specific heat and thermal diffusivity, are measured using specialized probes and equipment. These measurements allow engineers to understand how effectively the concrete absorbs, stores and releases thermal energy. In cases where PCMs are incorporated, additional measurements are conducted to observe the phase change behaviour, including melting and solidification temperatures, latent heat storage and heat transfer characteristics during phase transitions. By analysing the collected data, engineers can assess the system's thermal performance, identify areas for improvement and validate computer models used for simulation and optimisation. These experimental evaluations are crucial for the development and optimisation of concrete-based TES systems, ensuring their reliability, efficiency and suitability for various applications, such as building heating and cooling, renewable energy integration and industrial processes [117,118].

Experimental evaluations play a crucial role in validating and refining mathematical models and simulations of concrete-based TES systems. By comparing the results obtained from the experiments with the data generated by the simulations, engineers can assess the accuracy and reliability of the models. Any discrepancies between the experimental and simulated data can be identified and analysed to understand the underlying factors contributing to the differences. This iterative process allows for the refinement and improvement of the mathematical models, enabling more accurate predictions of the thermal behaviour and performance of the TES systems. The validation of models through experimental evaluations enhances the confidence in their use for optimising TES system design, operation and performance.

Experimental efforts on concrete TES systems have been pivotal in advancing sustainable energy solutions. Numerous studies have focused on fabricating and testing concrete TES prototypes, showcasing their viability for efficient energy storage. These experiments explore the thermal performance, conductivity, and storage capacity of concrete-based systems under diverse conditions. Researchers have examined variables such as concrete composition, phase change materials, and geometric configurations to optimise thermal properties. These investigations contribute valuable insights into the real-world feasibility of concrete TES, offering a foundation for enhancing the technology's reliability and scalability in renewable energy applications.

The research conducted by Vigneshwaran et al. [12] focuses on a concrete-based high-temperature thermal energy storage system. Through a combination of experimental and numerical analyses, the study likely explores the intricacies of concrete composition, phase change materials, and thermal conductivity in the context of high-temperature energy storage. Doretti et al. [119] contributed a simplified analytical approach for simulating concrete sensible thermal energy storage. This analytical framework, outlined in their study, is likely to be a valuable tool for assessing the efficiency and performance of concrete-based TES systems, providing practical insights for engineers and researchers. Rao et al. [120] conducted performance tests on lab-scale sensible heat storage prototypes. Their work likely yields crucial data on the operational characteristics of smaller-scale concrete TES systems, offering insights into scalability and efficiency for potential real-world applications. Hoivik et al. [34] present long-term performance results of a concrete-based modular thermal energy storage system. This study is likely to provide essential data on the durability and reliability of concrete TES solutions, crucial for evaluating their long-term feasibility and economic viability. Wang et al. [9] explore the enhancement of conventional concrete mix designs for sensible thermal energy storage applications. By optimising concrete compositions, their work likely aims to improve the thermal properties of concrete, potentially increasing its energy storage capacity and providing guidelines for designing mixes tailored for efficient thermal energy storage.

These studies collectively deepen our understanding of concrete TES systems, covering aspects from high-temperature applications to long-term performance and mix design enhancements. The findings contribute to the broader landscape of sustainable energy solutions, shaping the future development and implementation of concrete-based thermal energy storage systems.

3.3. *Performance metrics for assessing thermal energy storage efficiency*

When assessing the efficiency of thermal energy storage (TES) systems, several performance metrics are commonly used to evaluate their effectiveness in storing and releasing thermal energy. These metrics serve as valuable indicators of the system's performance, reliability and economic viability. By analysing these metrics, engineers and researchers can gain insights into the overall efficiency of TES systems and make informed decisions regarding system design, operation and optimisation. These performance metrics play a crucial role in assessing the effectiveness of TES systems in meeting energy storage requirements, improving energy efficiency, reducing carbon emissions and enhancing the sustainability of energy systems. Some key performance metrics for assessing TES efficiency include:

Round-trip efficiency: Round-trip efficiency is a crucial performance metric that quantifies the energy losses associated with the charging and discharging processes of TES systems. It considers factors like insulation performance, heat transfer inefficiencies and auxiliary equipment losses. A high round-trip efficiency indicates that a larger proportion of the energy input is effectively stored and retrieved from the TES system, resulting in improved overall system performance and energy utilisation [121–124]. By evaluating round-trip efficiency, engineers and researchers can identify opportunities for enhancing system design, optimising operating parameters and minimising energy losses. This metric is essential for assessing the economic viability and sustainability of TES systems and plays a vital role in supporting the transition towards more efficient and reliable energy storage solutions.

Storage efficiency: Storage efficiency is a performance metric that measures the effectiveness of energy storage in TES systems. It quantifies the ratio of the energy effectively stored in the system to the total energy input during the charging process. Storage efficiency is influenced by various factors, including heat leaks, temperature gradients and energy dissipation within the storage medium. A higher storage efficiency indicates a more efficient utilisation of the energy input and better preservation of thermal energy within the TES system ([1]; Pielichowska & Pielichowska,2014; Lin et al., 2018). By evaluating storage efficiency, engineers and researchers can assess the system's ability to store and retain thermal energy, optimise the design and operation of TES systems and ensure effective utilisation of stored energy during the discharge phase.

Energy density: Energy density is a performance metric that quantifies the amount of thermal energy that can be stored per unit volume or mass of a TES system. It provides insights into the compactness and efficiency of the storage system. A higher energy density means that a larger amount of thermal energy can be stored in a smaller space or mass. This is particularly important in applications where space availability is limited. By improving energy density, TES systems can become more compact and cost-effective, allowing for efficient storage of thermal energy in a smaller footprint (Pelay et al., 2017; [125]). Higher energy density enables the storage of more energy in the same volume or mass, increasing the overall efficiency and effectiveness of the TES system.

Response time: Response time is a performance metric that evaluates the speed at which a TES system can deliver the stored thermal energy when required [126]. It measures the time taken for the system to respond to changes in energy demand and effectively release the stored energy. A shorter response time indicates a more responsive and efficient TES system, capable of meeting fluctuating energy demands promptly. This metric is particularly important in applications where rapid energy delivery is crucial, such as in building heating and cooling systems. By minimising the response time, TES systems can provide efficient and reliable energy supply, ensuring optimal comfort and performance in various thermal energy applications.

Cycling stability: Cycling stability is a critical performance metric used to assess the ability of a TES system to maintain its performance and efficiency over multiple charging and discharging cycles. It takes into account various factors that can impact the system's long-term durability and functionality, including material degradation, thermal fatigue and capacity degradation. A TES system with good cycling stability can withstand repeated thermal cycles without experiencing significant degradation or loss of performance (Rathod & Banerjee, 2013; [34,127]). This ensures the system's long-term reliability and efficiency, allowing it to consistently deliver the stored thermal energy over its operational lifespan. Evaluating and optimising cycling stability is crucial for ensuring the economic viability and sustainability of TES systems in practical applications.

Cost-effectiveness: Cost-effectiveness is an essential performance metric that assesses the economic viability of the TES system [128,129]. It considers the overall costs associated with the system, including capital costs, operational costs and the value of the stored and released energy. By evaluating the balance between system performance and costs, engineers and decision-makers can determine the cost-effectiveness of the TES system. This metric plays a vital role in identifying opportunities for system optimisation, such as selecting cost-effective materials and components, maximising the return on investment and ensuring the long-term financial sustainability of the TES system. Assessing the cost-effectiveness helps guide decision-making processes and supports the adoption of TESsystems in various applications, contributing to energy efficiency and sustainable energy management. Fig. 9 shows the KPIs definition methodology for the TES integration in systems [130].

These performance metrics collectively provide a comprehensive evaluation of the efficiency and effectiveness of TES systems. By considering these metrics, engineers and researchers can assess the system's performance in terms of energy storage capacity, energy conversion efficiency, thermal losses and overall system reliability. These metrics enable the optimisation of TES designs, identification of areas for improvement and informed decision-making to enhance the overall performance and economic viability of the systems. By analysing these metrics, stakeholders can determine the suitability of TES systems for specific applications, evaluate their cost-effectiveness and contribute to the advancement of sustainable energy solutions.

Several studies have focused on identifying and evaluating these metrics to provide insights into TES system performance. The review by Soares et al. [11] emphasized the importance of passive PCM latent heat TES systems and highlights the need for performance metrics to assess buildings' energy efficiency. Cabeza et al. [131] conducted a survey to identify key performance indicators (KPIs) for TES systems and assess their applicability. The study by Gibb et al. [130] presented an evaluation methodology for TES systems, considering process integration and showcasing case studies. Del Pero et al. [132] focussed on energy storage KPIs specifically for building applications, providing insights into measuring the performance of TES systems in the context of sustainable cities. Narula et al. [133] proposed a simulation method to assess energy flows in district heating systems with seasonal thermal energy storage. Opolot et al. [125] reviewed high-temperature latent heat TES systems, discussing the performance metrics and challenges associated with such systems.

These studies collectively highlight the importance of performance metrics in evaluating TES system efficiency. The identified metrics include round-trip efficiency, storage efficiency, energy density, response time, cycling stability and cost-effectiveness. Round-trip efficiency considers energy losses during charging and discharging processes, while storage efficiency evaluates the effectiveness of energy storage within the system. Energy density measures the amount of thermal energy stored per unit volume or mass, while response time assesses the system's speed in delivering stored energy upon demand. Cycling stability evaluates the system's ability to maintain performance and efficiency over multiple cycles and cost-effectiveness considers the economic viability of the TES system.

These metrics provide valuable insights for optimising TES system design, identifying areas for improvement and making informed decisions. They allow engineers and decision-makers to assess the performance, reliability and economic viability of TES systems, leading to more efficient, durable and cost-effective energy storage solutions. As the field of TES continues to advance, ongoing research and development will further refine and expand these performance metrics, enabling more accurate evaluation and optimisation of TES systems for a wide range of applications.

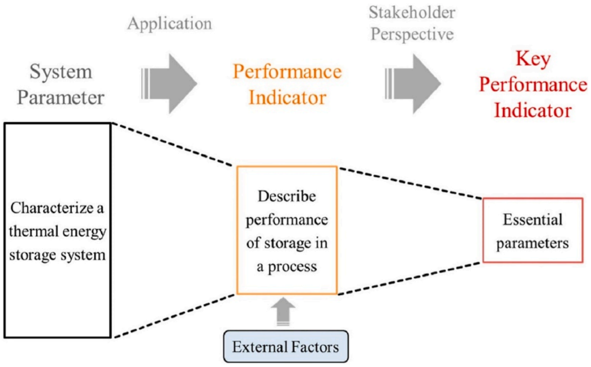

Fig. 9. KPIs definition methodology for the TES integration in systems [130].

3.4. Experimental studies on existing concrete TES prototypes

Experimental studies on existing concrete TES prototypes play a pivotal role in advancing sustainable energy solutions. These studies delve into the performance, efficiency, and scalability of concrete-based TES systems across diverse scales. Researchers explore variables such as concrete composition, phase change materials, and geometric configurations, offering crucial insights into real-world feasibility. By rigorously testing prototypes, these experiments contribute valuable data, informing the optimisation and design of concrete TES systems for enhanced thermal energy storage. The findings are essential for advancing the reliability and applicability of concrete-based TES in the broader context of renewable energy integration.

The experimental studies on concrete Thermal Energy Storage (TES) prototypes, as detailed in the referenced literature, provide comprehensive insights into various aspects of thermal energy storage, encompassing materials, designs, and applications. Each study contributes uniquely to the understanding of concrete TES systems. Ramakrishnan et al. [134] conducted a thorough thermal performance assessment of cementitious composites integrated with phase change materials. The study combined experimental evaluations with numerical simulations, providing a holistic understanding of the materials' behaviour in buildings. This work contributed not only to the understanding of concrete-based TES but also highlighted the importance of numerical modelling in predicting real-world performance.

De Gracia et al. [135] contributed by sharing lessons learned from experimental setups focused on active and passive energy-saving systems in buildings. This study provides practical insights into the challenges and successes encountered in real-world scenarios, offering valuable information for the development and implementation of concrete TES systems in building applications. Codd et al. [136] explored Concentrating Solar Power (CSP)–Thermal Energy Storage (TES) advanced concepts, emphasizing both development and demonstrations. This work is crucial for pushing the boundaries of concrete TES technologies, showcasing the potential for large-scale applications and the need for practical demonstrations to validate theoretical advancements. Ahmad et al. [137] conducted thermal testing and numerical simulation of a prototype cell using light wallboards coupled with vacuum isolation panels and phase change materials. The study focused on innovative combinations of materials, showcasing how various elements could be integrated to enhance the thermal performance of concrete TES systems, especially in building applications.

Kheradmand et al. [138] contributed experimental and numerical studies on hybrid Phase Change Material (PCM) embedded in plastering mortar. Their work demonstrates a practical application of PCM in construction materials, showcasing how such enhancements could improve the thermal behaviour of buildings, emphasizing the importance of materials science in concrete TES. Ndiaye et al. [139] provided an experimental evaluation of low-temperature energy storage prototypes based on innovative cementitious material. This study explored new materials specifically designed for energy storage, expanding the range of concrete TES applications to lower temperature regimes. Cot-Gores et al. [140] presented a state-of-the-art review of thermochemical energy storage and conversion, focusing on practical conditions in experimental research. This comprehensive review consolidated knowledge on various experimental approaches, providing a roadmap for future research directions in concrete TES. Lizana et al. [141] offered a detailed review of advanced low-carbon energy measures with a specific emphasis on thermal energy storage in buildings. This work contextualized concrete TES within the broader landscape of sustainable energy solutions, underlining its significance in reducing carbon footprints.

These studies collectively contributed to the experimental foundation of concrete TES systems, covering a spectrum of temperatures, materials, and applications. From fundamental assessments to practical lessons learned, the referenced literature provided a rich source of information for researchers and practitioners seeking to advance the field of concrete-based thermal energy storage.

3.5. Current numerical study on simulating concrete TES systems

The present numerical studies on simulating concrete Thermal Energy Storage (TES) systems represent a critical dimension of research, offering insights into the complex dynamics of energy storage. By employing advanced modelling techniques, researchers aim to simulate and optimise the performance of concrete TES systems under varying conditions. These simulations contribute valuable predictions on thermal behaviour, efficiency, and overall functionality, aiding in the design and enhancement of concrete TES technologies. The current numerical investigations play a pivotal role in bridging theoretical understanding with practical applications, facilitating the development of more efficient and sustainable concrete-based thermal energy storage solutions.

The critical examination of numerical studies on simulating concrete TES systems, as drawn from the referenced literature, reveals a diverse and comprehensive exploration of this complex field. Cui et al. [16] contributed by developing macro-encapsulated thermal energy storage concrete, emphasizing both the mechanical properties of the material and the importance of numerical simulations. The study integrates experimental findings with numerical models, providing a holistic perspective on the material's behaviour in practical applications. Martelletto et al. [142] focused on the validation of numerical simulations through experimental means, specifically investigating a latent and sensible concrete TES system. This approach bridges the gap between theoretical modelling and real-world performance, offering insights into the accuracy and reliability of numerical predictions. The study contributes not only to the advancement of concrete TES but also to the validation methodologies crucial for ensuring the fidelity of numerical models.

Nordbeck et al. [143] undertook a combined experimental and numerical analysis of a cement-based TES system, incorporating a helical heat exchanger. This dual approach allows for a more comprehensive understanding of the system's thermal behaviour and efficiency. The integration of experimental data with numerical simulations enhances the credibility of the findings, providing a robust basis for optimising and designing similar systems. Jaunet et al. [144] employed a numerical analysis to investigate a thermal energy storage system using a packed-bed configuration. This approach allows for a detailed exploration of heat transfer dynamics and efficiency in the chosen system. The study adds depth to the understanding of numerical simulations in the context of concrete TES, particularly when applied to configurations involving packed-bed materials.

Doretti et al. [119] contributed a simplified analytical approach for simulating concrete sensible thermal energy storage. This approach strikes a balance between numerical rigor and practical utility, offering a valuable tool for researchers and engineers seeking efficient yet accessible methods for simulating and optimising concrete TES systems. Liu and Yang [117] introduced a multi-objective optimisation approach to a concrete TES system, demonstrating a nuanced understanding of numerical techniques for system improvement. The study emphasizes the importance of considering multiple objectives, such as efficiency and cost, in the optimisation process. This approach aligns with real-world considerations, making the numerical simulation more applicable to practical implementation.

Lv et al. [145] extended numerical investigations to composite materials, conducting an experimental and numerical study on polyethylene glycol/expanded graphite composite phase change material. This expansion of the numerical approach to different material compositions broadens the scope of understanding and applications in concrete TES. Wang et al. [9] conducted a comprehensive review, testing, and simulation of thermal properties in concrete TES at elevated temperatures. This work not only consolidates existing knowledge but also provides a roadmap for future research, emphasizing the significance of numerical simulations in understanding and predicting the behaviour of concrete TES materials under extreme conditions.

Yang et al. [146] engaged in numerical evaluations to understand the effects of thermal properties on the thermo-mechanical behaviour of a phase change concrete energy pile. This study underscores the importance of numerical simulations in predicting not only thermal performance but also the structural aspects of concrete TES systems. Refaa et al. [147] performed a numerical study on the effect of phase change materials on heat transfer in asphalt concrete. This study, although focused on a different material, provides insights into how numerical simulations can be employed across various materials and applications within the broader domain of thermal energy storage.

The critical discussion reveals that numerical studies play a crucial role in advancing our understanding of concrete TES systems. From material development to optimisation and validation strategies, these studies employ numerical modelling as a powerful tool to unravel the intricacies of thermal energy storage. However, it is essential to acknowledge potential limitations, such as model assumptions and the need for validation against experimental data. As the field progresses, the integration of innovative numerical techniques with practical insights will further refine our ability to design, optimise, and implement efficient concrete TES systems.

4. Environmental and economic considerations

Thermal energy storage (TES) in concrete provides environmental benefits by promoting energy efficiency, reducing carbon emissions and facilitating the integration of renewable energy sources. It also offers economic advantages through cost savings and enhanced energy affordability. However, there are considerations such as the initial investment cost, material selection and life cycle impacts that need to be carefully evaluated. Sustainable practices, economic analysis and life cycle assessments play a vital role in ensuring the environmental and economic sustainability of TES in concrete. By addressing these considerations, TES in concrete can contribute to a greener and more economically viable energy storage solution.

4.1. Environmental impacts and sustainability of concrete-based systems

Concrete-based systems have significant environmental impacts due to factors such as carbon emissions during cement production, resource depletion from aggregate extraction and waste generation during construction. However, sustainability can be achieved through various strategies. These include using alternative cementitious materials, optimising aggregate usage, reducing water consumption, promoting recycling and reuse, designing for durability and conducting lifecycle assessments. By implementing these strategies, the environmental impacts of concrete-based systems can be minimised, promoting a more sustainable construction industry and contributing to the conservation of resources and reduction of greenhouse gas emissions.

One of the main environmental concerns associated with concrete production is its carbon footprint. The manufacturing of cement, which is a key ingredient in concrete, results in the release of a significant amount of CO_2 into the atmosphere. To address this issue, various strategies have been implemented. These include the utilisation of alternative cementitious materials such as fly ash and slag, which have lower carbon emissions compared to traditional cement [148–150]. Additionally, efforts are underway to develop low-carbon and carbon-neutral cements, which involve the use of alternative fuels, improved manufacturing processes and the integration of carbon capture and storage technologies. These measures aim to reduce the carbon footprint of concrete production and promote environmental sustainability in the construction industry.

Concrete production has significant environmental implications, particularly regarding resource depletion. The extraction of aggregates, sand and gravel can result in habitat destruction and disruption of ecosystems. To address this, sustainable practices aim to optimise aggregate usage by promoting efficient design and construction methods that minimise material waste. Additionally, the use of recycled aggregates from demolished concrete structures or industrial by-products offers a more sustainable alternative to virgin aggregates [151–154]. Water consumption is another environmental concern in concrete production. Strategies to mitigate water usage include improving batching and mixing techniques to minimise water requirements, as well as implementing water recycling and reclamation systems to reduce freshwater consumption. By adopting these sustainable practices, the concrete industry can contribute to resource conservation and reduce the environmental impact of concrete-based systems.

The construction phase of concrete-based systems has significant environmental impacts and sustainable construction practices are essential for mitigating these effects. One key focus is on minimising waste generation by adopting efficient construction methods and carefully planning material usage. Additionally, efforts are made to promote the recycling and reuse of concrete waste, reducing the need for new material extraction. Sustainable construction practices also aim to minimise energy consumption during construction activities by optimising processes, utilising energy-efficient equipment and incorporating renewable energy sources. Responsible waste management strategies, such as sorting and recycling construction waste, further contribute to reducing environmental impacts [155,156]. By implementing these sustainable practices, the construction phase of concrete-based systems can become more environmentally friendly and contribute to overall sustainability goals.

The durability and longevity of concrete structures play a crucial role in their environmental sustainability. Designing concrete structures with durability in mind can significantly reduce their environmental impact. Factors such as incorporating effective corrosion protection measures, using high-quality materials and implementing proper maintenance and repair practices contribute to extending the service life of concrete structures [157–159]. By increasing the lifespan of these structures, the need for frequent reconstruction and resource consumption is minimised. This results in reduced material extraction, energy consumption and waste generation, leading to a more sustainable and environmentally friendly approach to concrete construction. Designing for durability is therefore a key consideration in ensuring the long-term environmental sustainability of concrete-based systems.

Addressing the environmental impacts and promoting sustainability in concrete-based systems requires a multifaceted approach that encompasses various aspects of the construction process. This includes incorporating technological advancements such as low-carbon cement production, exploring alternative materials and implementing energy-efficient manufacturing processes. Material innovations such as the use of recycled aggregates and supplementary cementitious materials further contribute to sustainability goals. Sustainable design practices that prioritise durability, efficient use of resources and waste reduction are essential. Responsible construction techniques, such as proper waste management and minimising energy consumption during construction activities, also play a significant role. Ongoing monitoring and assessment of environmental performance ensure that sustainability goals are met and provide opportunities for continuous improvement. By embracing these strategies, the construction industry can mitigate the environmental impacts of concrete-based systems and contribute to a more sustainable built environment.

4.2. Life Cycle Analysis and carbon footprint

Life Cycle Analysis (LCA) is a systematic approach to evaluate the environmental impacts associated with the entire life cycle of a product or system. When applied to TES systems in concrete, LCA assesses the environmental implications of various stages, including raw material extraction, manufacturing, transportation, installation, operation, maintenance and end-of-life disposal. This analysis allows for a comprehensive understanding of the environmental burdens associated with TES systems in concrete and helps identify areas for improvement to enhance their sustainability. By considering factors such as energy consumption, greenhouse gas emissions, resource depletion and waste generation, LCA enables stakeholders to make informed decisions and develop strategies to minimise the environmental impact of TES systems in concrete. The LCA of TES systems in concrete involves evaluating various stages, including:

Raw material extraction: The extraction of raw materials such as aggregates, cement and additives for TES systems in concrete can have significant environmental impacts. The extraction process involves energy-intensive operations and can result in the release of greenhouse gas emissions, contributing to climate change. Additionally, the extraction of aggregates can lead to habitat destruction and ecosystem disruption. To address these impacts, sustainable practices focus on optimising material usage, promoting the use of recycled materials and exploring alternative materials with lower environmental footprints [160,161]. By reducing the reliance on virgin materials and adopting more sustainable sourcing methods, the environmental impact of TES systems in concrete can be minimised.

Manufacturing: The production of concrete and other components of TES systems, including insulation materials and storage tanks, involves energy-intensive processes that contribute to the emissions of greenhouse gases, particularly CO_2. The manufacturing of cement, a key component of concrete, is a major source of CO_2 emissions due to the chemical reactions involved in its production. Additionally, the production of insulation materials and storage tanks often requires the use of fossil fuels and energy-intensive manufacturing processes, further contributing to CO_2 emissions. To mitigate these emissions, efforts are being made to develop low-carbon alternatives, improve energy efficiency in production processes and explore the use of sustainable materials in TES systems (Parameshwaran et al., 2012; [141,162]).

Transportation: The transportation of raw materials, manufactured components and the TES system to the construction site incurs energy consumption and emissions associated with transportation activities. This includes the transportation of aggregates, cement, insulation materials, storage tanks and other components required for the TES system. The energy consumption and emissions are influenced by factors such as the distance travelled, mode of transportation (e.g., trucks, ships, or trains) and the efficiency of the transportation process ([163,164]; Li et al., 2021). To minimise the environmental impact, strategies such as optimising logistics, utilising local suppliers and promoting sustainable transportation methods are implemented to reduce energy consumption and emissions during the transportation phase of TES systems.

Installation: The construction process of TES systems, including site preparation, foundation construction and system installation, can result in energy consumption and emissions from construction equipment and machinery. This phase involves the use of heavy machinery, such as excavators, cranes and concrete mixers, which typically run-on fossil fuels and emit greenhouse gases. Additionally, construction activities may require the use of energy-intensive processes, such as concrete mixing and curing, which contribute to energy consumption and associated emissions. Sustainable construction practices, including the use of energy-efficient equipment, optimising construction schedules and implementing emissions reduction strategies, can help minimise the environmental impact of the construction phase of TES systems.

Operation: The energy consumption during the operation of the TES system, including the charging and discharging processes, contributes to its environmental impact. The energy source used for heating or cooling the system plays a crucial role in determining its carbon footprint [165,166]. If the energy source is derived from fossil fuels, such as coal or natural gas, it can result in significant greenhouse gas emissions. On the other hand, utilising renewable energy sources, such as solar or wind power, can significantly reduce the environmental impact of the TES system's operation. Therefore, the choice of energy source and the efficiency of the TES system in utilising the energy play important roles in minimising its carbon footprint during operation.

Maintenance and repair: The maintenance activities required to keep the TES system in optimal condition may involve energy consumption and the use of materials that have their own environmental impacts [167,168]. For example, regular inspections, repairs and cleaning may require the use of energy-intensive equipment and the application of chemical substances. Additionally, the replacement of components or materials over the lifespan of the TES system can contribute to waste generation and resource depletion. Therefore, it is important to consider sustainable maintenance practices, such as using energy-efficient equipment, opting for eco-friendly cleaning agents and promoting the reuse or recycling of materials, to minimise the environmental impact of maintenance activities in TES systems.

End-of-life disposal: The disposal of TES system components at the end of their life cycle, such as concrete and insulation materials, can have environmental implications. These components may contribute to waste generation, occupying valuable landfill space and potentially releasing harmful substances into the environment if not properly managed. Sustainable disposal practices, such as recycling or reusing the materials, can help mitigate these impacts [155,169]. Additionally, considering the end-of-life implications during the design phase of the TES system, such as using recyclable or biodegradable materials, can facilitate more sustainable disposal options. Proper waste management and adherence to environmental regulations are crucial to minimise the environmental impacts associated with the disposal of TES system components. The carbon footprint of TES systems in concrete is a specific aspect considered within the broader context of LCA. The carbon footprint refers to the total amount of greenhouse gas emissions, primarily CO_2, associated with the system's life cycle. It takes into account emissions from raw material production, energy consumption and other relevant processes. To reduce the environmental impact and carbon footprint of TES systems in concrete, several strategies can be implemented. These include:

Using low-carbon cementitious materials: Incorporating alternative cementitious materials, such as fly ash, slag, or calcined clays, in the production of concrete for TES systems can have a significant positive impact on reducing the carbon footprint. These materials can partially replace traditional cement, which is responsible for a significant amount of CO_2 emissions during its production (Aorianti, 2017; [170,171]). By using alternative cementitious materials, the amount of CO_2 released into the atmosphere can be reduced, as these materials typically have lower carbon content or are by-products of other industrial processes. This approach promotes sustainable concrete production and contributes to the overall environmental performance of TES systems.

Optimal design and construction: Designing the TES system for efficient operation, insulation and energy conservation is crucial to minimising energy consumption and reducing greenhouse gas emissions. By optimising the system's design, including the size and capacity of the storage unit, the efficiency of the charging and discharging processes and the insulation properties, energy losses can be minimised, resulting in lower energy consumption and reduced greenhouse gas emissions. Additionally, incorporating energy-efficient components and utilising renewable energy sources for the heating or cooling of the TES system further enhances its environmental performance [116,172,173]. Such design considerations contribute to the overall energy efficiency and sustainability of the TES system, making it more environmentally friendly. Designing the TES system for efficient operation, insulation and energy conservation can minimise energy consumption and subsequent greenhouse gas emissions.

Renewable energy integration: Utilising renewable energy sources, such as solar or wind power, to charge and discharge the TES system is a key strategy to reduce reliance on fossil fuels and decrease the carbon footprint. By integrating renewable energy sources into the TES system, the reliance on traditional energy sources is minimised, leading to a significant reduction in greenhouse gas emissions [174–176]. Renewable energy sources offer a sustainable and clean alternative, ensuring that the TES system operates with minimal environmental impact. This not only reduces carbon emissions but also promotes the use of renewable energy, contributing to the overall transition towards a more sustainable and low-carbon energy system.

Recycling and reuse: Implementing strategies to recycle or reuse components of the TES system and waste materials can significantly reduce the environmental impact associated with their disposal and minimise resource consumption. Recycling and reusing TES system components, such as concrete or insulation materials, can divert them from landfills and reduce the need for new material production, thus conserving resources and reducing energy consumption [177,178]. Additionally, proper waste management practices, including sorting and recycling, can minimise environmental pollution and promote a more circular economy. By incorporating recycling and reuse strategies, the TES system can contribute to a more sustainable and resource-efficient approach to construction and energy storage.

By conducting a detailed LCA and assessing the carbon footprint, stakeholders can gain valuable insights into the environmental impacts of TES systems in concrete. This analysis enables them to identify the hotspots and areas with the highest environmental burdens, such as energy-intensive production processes or high emissions during operation. With this information, stakeholders can make informed decisions and prioritise efforts to improve the sustainability of TES systems. This may involve optimising material choices, implementing energy-efficient technologies, promoting renewable energy sources and adopting recycling or reuse strategies. By considering the LCA results and actively addressing the identified environmental issues, TES systems in concrete can be optimised for reduced carbon emissions and enhanced sustainability.

4.3. *Economic feasibility and cost analysis of thermal energy storage in concrete*

When conducting an economic feasibility and cost analysis of thermal energy storage (TES) in concrete, various aspects need to be considered. One of the primary factors is the assessment of initial investment costs. This involves evaluating the expenses associated with designing and constructing the TES system, including the cost of materials such as concrete, insulation, storage tanks and other components. The costs of engineering design, permits and project management should also be taken into account. Additionally, any required modifications to the existing infrastructure, such as electrical connections or piping systems, should be considered in the overall cost analysis.

Operational and maintenance costs play a significant role in determining the long-term economic feasibility of a TES system (Alva et al., 2018; [179,180]). These costs encompass various ongoing expenses incurred throughout the system's lifespan. Key components of operational and maintenance costs include energy consumption for charging and discharging the TES system, routine maintenance and inspections, equipment servicing and potential repairs or replacements. It is crucial to consider the expected lifespan of the TES system and accurately estimate the associated maintenance and replacement costs over that period. By accounting for these factors, stakeholders can better evaluate the financial sustainability of the TES system and make informed decisions regarding its implementation. In addition to considering costs, assessing the potential economic benefits of implementing TES in concrete is crucial. Energy cost savings are a significant consideration, as TES systems allow for the shifting of energy usage to off-peak periods when electricity rates are typically lower (Dincer & Rosen, 2001; Ruddell et al., 2014). By charging the TES system during times of lower energy demand and discharging it during peak-demand periods, users can take advantage of lower electricity rates and reduce their energy costs. It is essential to conduct a thorough analysis of projected energy savings, taking into account the specific application and the structure of energy tariffs to accurately assess the economic feasibility and potential financial gains of incorporating TES in concrete systems.

Furthermore, TES systems in concrete have the potential to participate in demand response programs or provide ancillary services to the electricity grid. By leveraging the flexibility of the TES system, it can assist in balancing supply and demand or providing grid stabilisation services ([181–183]; Li et al., 2021). Participating in such programs can generate additional revenue streams, further enhancing the economic feasibility of the TES system. Evaluating the potential revenue opportunities from these programs is essential to assess the overall economic viability of incorporating TES in concrete systems. This analysis should consider the market conditions, regulatory frameworks and potential partnerships with grid operators or energy service providers to maximise the financial benefits of participating in these programs.

Other important economic metrics to consider when assessing the feasibility of TES in concrete systems include the payback period, return on investment (ROI) and net present value (NPV). The payback period is the length of time it takes for the energy cost savings or revenue generated by the TES system to offset the initial investment costs. ROI measures the profitability of the investment by comparing the gains (energy cost savings or revenue) to the investment amount over the system's lifespan. NPV calculates the present value of the project's future cash flows, accounting for the time value of money and providing a comprehensive assessment of the economic viability. These metrics help stakeholders make informed decisions by considering the financial implications of implementing TES in concrete systems.

When considering the economic feasibility of TESsystems in concrete, it is essential to explore the availability of financial incentives, grants, or subsidies. These financial support mechanisms can play a significant role in reducing the upfront costs and improving the overall economic viability of the project. Governments, energy agencies, or sustainability programs often offer financial incentives to encourage the adoption of energy-efficient technologies and renewable energy solutions, including TES systems [184,185]. Evaluating the eligibility criteria and potential financial support from such initiatives is crucial for accurately assessing the economic feasibility and determining the project's financial viability. It is advisable to conduct thorough research and consult with relevant authorities to identify and leverage any available financial incentives to optimise the project's economic outcomes.

By conducting a comprehensive economic feasibility and cost analysis, stakeholders can gain valuable insights into the financial viability of implementing TES in concrete applications. This analysis involves evaluating the upfront costs associated with system installation, including equipment, materials and labour, as well as the ongoing operational and maintenance expenses. Additionally, potential energy cost savings, revenue generation opportunities and financial incentives should be considered. By quantifying these factors and assessing the return on investment (ROI), payback period and net present value (NPV), stakeholders can make informed decisions and develop robust business cases for TES implementation. This analysis also supports discussions with investors or funding agencies, facilitating the acquisition of necessary financing for TES projects.

5. Challenges and future directions

Challenges and future directions in thermal energy storage (TES) in concrete systems involve addressing technical, economic and environmental considerations. One of the key challenges is the development of cost-effective and efficient TES technologies that can reliably store and release thermal energy. This requires advancements in material science, system design and control strategies. Additionally, integrating TES systems into existing infrastructure and optimising their performance within different applications present challenges. Furthermore, economic factors such as high upfront costs and uncertain financial incentives need to be overcome. From an environmental perspective, reducing the carbon footprint and minimising the environmental impacts associated with TES systems remain important goals. Future directions involve exploring advanced materials, improving system efficiency, integrating renewable energy sources and developing innovative storage technologies to enhance the performance and sustainability of TES systems in concrete.

5.1. Technical and design challenges

Technical and design challenges in thermal energy storage (TES) in concrete systems revolve around optimising the storage and release of thermal energy while ensuring system efficiency, reliability and longevity. These challenges include:

1. Heat transfer and thermal performance: Efficient heat transfer is a critical factor in the performance of TES systems in concrete. The challenge lies in designing the system to optimise heat transfer between the storage medium and the concrete matrix,

ensuring effective energy storage and retrieval. Strategies to enhance heat transfer include selecting materials with high thermal conductivity, designing an optimal geometry and configuration of the storage medium within the concrete and improving the interface contact between the storage medium and the concrete matrix [186,187]. Additionally, minimising thermal losses through insulation and implementing heat transfer enhancement techniques, such as fins or heat exchangers, can further improve heat transfer efficiency. By addressing this challenge, TES systems can maximise energy storage capacity and overall system performance.

2. Material selection and compatibility: Selecting the right materials for the storage medium, insulation and concrete matrix is a crucial technical challenge in TES systems. The materials must possess properties such as good thermal conductivity to facilitate efficient heat transfer, high heat storage capacity to store and release thermal energy effectively, compatibility with concrete to ensure structural integrity and long-term stability to withstand repeated heating and cooling cycles (Lin et al., 2018; Reddy et al., 2018; [188]). Additionally, considerations such as cost, availability and environmental impact should be taken into account when choosing materials. The development and utilisation of advanced materials, such as phase change materials or high-performance insulation, can help overcome this challenge and enhance the performance and reliability of TES systems in concrete.
3. Integration with the existing infrastructure: Retrofitting TES systems into existing buildings or infrastructure poses technical and design challenges [130,189]. Space availability is often limited, requiring innovative solutions for integrating the TES system without disrupting the existing structures. The system must be designed to fit within the available space while still providing adequate storage capacity and efficient heat transfer. Compatibility with the existing heating and cooling systems is another consideration, as the TES system needs to seamlessly integrate with the building's infrastructure without compromising its functionality. System retrofitting may require modifications or upgrades to the existing systems, necessitating careful planning and coordination to ensure compatibility and optimal performance.
4. System control and management: Developing efficient control strategies for TES systems is essential for optimising the charging and discharging processes and ensuring reliable operation. These control systems enable precise monitoring of energy storage levels, allowing for effective management and utilisation of stored thermal energy (Arteconi et al., 2013; [190]). By implementing intelligent control algorithms, the TES system can respond dynamically to changing energy demands, optimising the charging and discharging cycles to match the building's heating and cooling requirements. This not only maximises energy utilisation but also minimises energy losses and improves overall system performance. Furthermore, robust control strategies contribute to the stability and reliability of the TES system, ensuring its seamless integration with other building systems and efficient operation over time.
5. Durability and structural integrity: Designing TES systems in concrete involves ensuring the long-term durability and structural integrity of the concrete structures. Special considerations must be given to address potential challenges such as material degradation, thermal stresses and the effects of thermal expansion and contraction. The selection of suitable concrete mixes and reinforcement designs, along with proper insulation measures, is crucial to minimise the risk of structural damage or failure. It is important to conduct thorough analyses and simulations to assess the thermal behaviour and performance of the concrete structures, considering factors such as temperature gradients, thermal cycling and compatibility between the concrete and storage medium. By addressing these design challenges, TES systems can be integrated effectively into concrete structures while maintaining their durability and structural integrity over the system's lifetime ([68,191]; Jouhara et al., 2020).
6. Scalability and flexibility: Designing TES systems that are scalable and adaptable to different applications and energy demands is a significant challenge. TES systems should be flexible enough to accommodate changes in energy requirements or potential future expansions. This involves considering the capacity and size of the storage system, as well as the integration with existing or future energy systems. Modular designs and flexible configurations can allow for easy expansion or modification of the TES system as needed ([192]; Groulx et al., 2021; Li et al., 2021).
7. Additionally, the system should be designed to support different energy sources and be compatible with various heating and cooling technologies. By addressing these challenges, TES systems can be effectively implemented in different contexts and adapted to meet evolving energy demands.
8. System efficiency and optimisation: Achieving high energy storage and release efficiency is a significant technical challenge in TES systems [48,193]. To optimise efficiency, several factors must be considered. This includes selecting the appropriate storage medium with high heat storage capacity, optimising insulation materials to minimise thermal losses and designing effective heat transfer mechanisms to facilitate efficient energy storage and retrieval. Furthermore, system design plays a crucial role in ensuring optimal performance and minimising energy losses. This involves optimising the geometry and configuration of the TES system, considering the integration of heat exchangers and control systems and implementing advanced monitoring and control strategies. By addressing these challenges, TES systems can achieve high energy storage and release efficiency, maximising the overall system performance and effectiveness.

Addressing the technical and design challenges associated with TES systems in concrete requires collaborative efforts from various disciplines. Engineers, material scientists, architects and system designers need to work together to develop innovative solutions. Advances in materials science, such as the development of high-performance storage media and insulation materials, can improve the efficiency and effectiveness of TES systems. Simulation modelling and computational tools enable accurate performance predictions and optimisation of system design. Integration techniques, including the seamless integration of TES systems with existing heating and cooling systems, require expertise from multiple disciplines. By fostering interdisciplinary collaboration and leveraging technological advancements, the challenges associated with TES systems in concrete can be effectively addressed, paving the way for more sustainable and energy-efficient solutions.

5.2. Optimisation and control strategies

Optimisation and control strategies are vital for maximising the performance and efficiency of thermal energy storage (TES) systems. These strategies utilise advanced algorithms, control systems and operational techniques to optimise charging and discharging processes, monitor energy storage levels and ensure reliable operation. They enable efficient utilisation of stored thermal energy, minimise energy losses and align energy supply and demand. Integration with building management systems and smart grid technologies allows for real-time monitoring and proactive management. Overall, these strategies play a crucial role in improving energy efficiency and system performance of TES systems.

One important aspect of optimisation in TES systems is determining the optimal operating conditions and control parameters. This involves analysing historical energy demand patterns, weather data and pricing tariffs to identify the most efficient scheduling of charging and discharging cycles. By dynamically adjusting the operation of the TES system based on real-time data, optimal energy utilisation can be achieved [12,194]. This optimisation minimises energy losses and maximises the system's overall efficiency. Through advanced algorithms and control strategies, TES systems can respond to varying energy demand and pricing conditions, resulting in improved energy management and cost savings.

Control strategies play a vital role in ensuring the safety and reliability of TES systems [195–197].These strategies involve implementing control measures to prevent overcharging or over-discharging, which can lead to system inefficiencies and potential damage. Effective control strategies also manage thermal stresses within the system to prevent failures and ensure structural integrity. Additionally, incorporating fail-safe mechanisms and safety protocols further enhance the reliability of the TES system, reducing the risk of malfunctions and protecting both the system and the surrounding infrastructure. By optimising control strategies, TES systems can operate efficiently, reliably and safely, maximising their overall performance.

Integration with Building Management Systems (BMS) and advanced monitoring and control technologies is crucial for optimising the performance of TES systems [68,198]. By connecting the TES system to a BMS, real-time monitoring of system parameters, such as energy storage levels, temperature differentials and energy demand, becomes possible. This enables proactive management, allowing operators to closely monitor the system's performance and detect any abnormalities or deviations from optimal operation. With advanced control technologies, adjustments and optimisations can be made in real-time, ensuring efficient energy storage and release. In the event of system malfunctions or anomalies, timely intervention can be implemented to resolve issues and prevent further complications, optimising the overall performance of the TES system.

Advanced modelling and simulation techniques play a crucial role in optimising the design and configuration of TES systems. By creating detailed computational models, engineers can simulate the behaviour of the system under different operating conditions and configurations. These models take into account factors such as storage medium characteristics, insulation materials, heat transfer mechanisms and control strategies [16,119,142]. Through extensive simulations, engineers can analyse the impact of these design parameters on the overall system performance, including energy storage and release efficiency, thermal losses and response time. This enables them to make informed design decisions, optimise the system's performance and identify the most effective configuration for a given application or set of requirements.

Optimisation and control strategies for TES systems are dynamic processes that require ongoing monitoring and adjustment. Regular assessment of system performance is essential to identify areas for improvement and ensure optimal operation. This involves analysing data on energy demand, weather conditions and system performance to identify potential optimisations and adjust control algorithms accordingly. By continuously monitoring and analysing system behaviour, engineers can make informed decisions to optimise charging and discharging cycles, adjust control parameters and fine-tune operational strategies. This iterative approach allows for the adaptation of the TES system to changing conditions, ensuring efficient energy storage and release while maximising system performance and overall effectiveness.

5.3. Integration with smart grids and energy management systems

Integration with smart grids and energy management systems enables TES systems to leverage real-time data on electricity pricing, energy demand and grid conditions to optimise their charging and discharging schedules. By intelligently adjusting energy usage based on grid signals, TES systems can store energy during off-peak hours and release it during periods of high demand, reducing energy costs and supporting grid stability (Zhang et al., 2007; Arteconi et al., 2012). Furthermore, integration with energy management systems provides centralised control and monitoring capabilities, allowing operators to dynamically manage the TES system in coordination with other energy-consuming systems. This integration promotes efficient energy usage, load balancing and the integration of renewable energy sources, contributing to a more sustainable and resilient energy infrastructure.

Integration with smart grids and energy management systems allows TES systems to actively participate in demand response programs and provide ancillary services to the grid. Through bidirectional communication and coordination with the grid operator, the TES system can respond to signals and adjust its operation to support grid stability and reliability [195,199]. This includes shifting energy consumption to times when renewable energy generation is high, reducing the need for fossil fuel-based power plants. The integration also enables TES systems to benefit from incentives and tariff structures that reward flexible and responsive energy consumption, further enhancing their economic feasibility and contribution to a more sustainable energy system.

Integration with energy management systems provides centralised control and monitoring capabilities for TES systems. Energy management systems collect data from various sources, such as smart meters, weather forecasts and building energy management systems, to optimise energy usage and distribution within a facility [200,201]. By incorporating TES systems into the energy management system, operators can dynamically adjust the operation of the TES system based on real-time energy demand and grid conditions. This ensures that the TES system operates in coordination with other energy-consuming systems within the facility, such as HVAC and lighting, to achieve maximum energy efficiency and cost savings.

Integration with smart grids and energy management systems empowers TES systems with advanced monitoring and data analytics capabilities. Real-time data on energy consumption, storage levels and system performance can be collected and analysed to gain insights into system behaviour and optimise operation. This data-driven approach enables proactive maintenance, identification of potential issues and predictive modelling for system performance optimisation [202–204]. By leveraging these capabilities, stakeholders can make informed decisions to enhance the efficiency, reliability and cost-effectiveness of TES systems. Additionally, the integration facilitates remote monitoring and control, allowing for efficient management of multiple TES systems and the ability to respond quickly to changing grid conditions or energy demand.

The integration of TES systems with smart grids and energy management systems also supports the transition to a more sustainable and resilient energy infrastructure. By enabling load shifting, demand response and effective utilisation of renewable energy sources, TES systems can contribute to the integration of intermittent renewable energy generation into the grid, reducing reliance on fossil fuel-based power plants and enhancing grid stability. TES systems can store excess renewable energy during periods of high generation and release it when demand is high or renewable generation is low ([205]; Amtouche et al., 2016; Li & Zheng, 2016). This helps to balance the grid, reduce curtailment of renewable energy and optimise the use of clean energy resources. Additionally, TES systems can provide backup power and enhance grid resilience by offering stored energy during power outages or emergencies.

In summary, integration with smart grids and energy management systems provides TES systems with advanced capabilities for optimising energy usage, maximising cost savings and contributing to grid stability. The seamless coordination and data exchange between the TES system and the larger energy infrastructure enable efficient energy management, demand response and enhanced operational control, making TES systems an integral part of the smart grid ecosystem and energy-efficient buildings. This integration allows for real-time monitoring, analysis and optimisation of energy storage and release, ensuring that TES systems operate at their highest efficiency levels. By leveraging the benefits of smart grids and energy management systems, TESsystems can effectively support the transition to a more sustainable and resilient energy future.

5.4. Research and development opportunities

Research and development opportunities in thermal energy storage (TES) in concrete offer great potential for advancing technology, improving performance and expanding applications in the field. Some key areas of research and development in this domain include:

1. Concrete Mix Design: Investigating the composition and properties of concrete mixes to optimise thermal conductivity, heat storage capacity and long-term stability is crucial. Research can focus on exploring alternative cementitious materials, such as fly ash, slag, or calcined clays, that can reduce the carbon footprint and enhance the thermal properties of concrete.
2. Composite Materials: Exploring the incorporation of advanced composite materials, such as carbon fibres or nanoparticles, into concrete can improve its thermal properties and increase energy storage efficiency. Research can investigate the effects of different additives and reinforcements on thermal conductivity, heat transfer and mechanical properties of concrete.
3. Integration of Phase Change Materials (PCMs): Investigating the integration of PCMs into concrete can enhance its thermal energy storage capabilities. Research can focus on developing new PCM-concrete composites or exploring the use of microencapsulated PCMs to enhance the latent heat storage capacity of concrete.
4. Structural Design and Heat Transfer Optimisation: Research can explore innovative design approaches to enhance heat transfer between the storage medium and the concrete matrix. This includes optimising the shape and arrangement of storage elements within the concrete structure to maximise heat transfer efficiency and minimise thermal losses.
5. Durability and Structural Integrity: Investigating the long-term durability and structural integrity of concrete structures with integrated TES systems is essential. Research can focus on addressing issues such as material degradation, thermal stresses and potential cracking or damage due to thermal expansion and contraction, ensuring the long-term reliability and performance of the TES system.
6. Modelling and Simulation: Developing advanced modelling and simulation tools can enable accurate prediction of TES system performance in concrete structures. Research can focus on refining numerical models, incorporating multi-physics and multi-scale approaches and integrating real-time data for dynamic system simulation.
7. Energy and Economic Analysis: Assessing the energy performance and economic viability of TES systems in concrete is crucial. Research can focus on conducting comprehensive energy and economic analyses, considering factors such as energy savings, payback periods, return on investment and life cycle cost analysis to evaluate the feasibility and potential benefits of implementing TES in concrete applications.
8. Field Testing and Demonstration Projects: Conducting field testing and demonstration projects in real-world settings can provide valuable insights into the performance, reliability and practical challenges of TES systems in concrete. Research can focus on monitoring system performance, collecting data and evaluating the real-world benefits and limitations of implementing TES in different concrete structures and applications.

By conducting research and development in thermal energy storage in concrete, experts can drive innovation and improve the efficiency, sustainability and economic viability of energy management in the built environment. Exploring areas such as concrete mix design, composite materials, integration of phase change materials, structural design optimisation, durability considerations, modelling and simulation, energy and economic analysis and field testing can lead to significant advancements in the field. These advancements have the potential to revolutionise energy storage and utilisation, reduce carbon emissions, enhance building performance and contribute to a more sustainable and resilient built environment. By addressing these opportunities, researchers and professionals can pave the way for a future with efficient and sustainable thermal energy storage in concrete.

6. Concluding remarks

The advancements in thermal energy storage (TES) in concrete have opened up new possibilities for efficient energy management in the built environment. The applications of TES in concrete are wide-ranging and offer significant benefits, including load shifting, demand response and integration of renewable energy sources. By effectively storing and releasing thermal energy, TES systems in concrete contribute to reduced energy consumption, cost savings and environmental sustainability. The advancements in materials, design and control strategies have greatly improved the performance and efficiency of TES systems. The utilisation of alternative cementitious materials, advanced insulation techniques and optimised system designs have resulted in higher energy storage capacities and improved heat transfer capabilities. Integration with smart grids and energy management systems has enhanced the operation and control of TES systems, enabling real-time monitoring, data analysis and optimisation.

The applications of TES in concrete offer significant opportunities for energy optimisation and efficiency in various sectors. In residential buildings, TES systems can provide thermal comfort by storing excess heat during off-peak hours for later use during peak demand periods. In commercial buildings, TES systems can help reduce energy costs by shifting cooling loads to off-peak hours and utilising stored thermal energy during peak demand. Industrial applications can benefit from TES systems by storing waste heat from industrial processes and using it for heating or other thermal applications. Moreover, integrating TES systems in concrete into district heating and cooling networks can enhance energy efficiency and contribute to sustainable urban development.

However, further research and development are needed to address challenges and optimise TES systems in concrete. This includes investigating new materials with enhanced thermal properties, such as phase change materials or advanced composite materials, to improve energy storage and release efficiency. Exploring innovative designs and construction techniques can maximise heat transfer and minimise thermal losses in TES systems. Additionally, improving control strategies and integrating advanced monitoring and control technologies can enhance system performance and ensure reliable operation. It is also crucial to evaluate the long-term durability and structural integrity of TES systems in concrete to ensure their sustainable and reliable operation over their lifespan. Collaboration among researchers, engineers, manufacturers and policymakers is essential to drive advancements, share knowledge and overcome existing limitations in TES systems in concrete.

Overall, the advancements and applications of TES in concrete offer significant potential for improving energy efficiency, reducing costs and promoting environmental sustainability in the built environment. TES systems provide a reliable and efficient means of storing and utilising thermal energy, enabling the integration of renewable energy sources, load shifting and demand response capabilities. By effectively managing energy consumption and optimising the use of resources, TES in concrete can contribute to the reduction of greenhouse gas emissions and the overall sustainability of buildings and communities. Continued research, innovation and collaboration among researchers, industry professionals and policymakers are crucial to further unlocking the benefits of TES in concrete and realising a more energy-efficient and sustainable future.

CRediT authorship contribution statement

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