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Smart materials and technologies for sustainable concrete construction

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ABSTRACT

This paper presents a comprehensive review of current trends and opportunities for sustainable concrete construction, emphasizing the importance of adopting eco-friendly practices to mitigate the industry's environmental impact. Green concrete, supplementary cementitious materials, permeable concrete, cool concrete, and the use of local materials are explored as sustainable materials and technologies. Innovations like self-healing concrete, 3D-printed concrete, photocatalytic concrete, electrified machineries, and carbon capture, utilization, and storage principles are also discussed, highlighting their potential to improve the sustainability of construction practices. Challenges faced in implementing sustainable concrete construction practices, such as technical, economic, and social barriers, are also addressed. The roles of governments, industry, and academia in promoting sustainable concrete construction are examined, stressing the need for interdisciplinary collaboration and research. Lastly, emerging trends and technologies, including digitalization, data-driven approaches, and circular economy principles, are identified as critical factors in driving the transition towards sustainable concrete construction.

1. Introduction

Concrete is a sustainable and versatile construction material which can produce structures that last for thousands of years. Due to the many areas of application, concrete is the second most consumed material on Earth, only after water, with a global production of around 4.1 billion tons of cement in 2021 (Statista, 2023), and an annual concrete consumption about 7 times higher (Monteiro et al., 2017). The importance of sustainability in concrete construction arises from the high environmental impact of the construction industry, particularly due to the extensive use of concrete as a primary building material. The production of Portland cement, a primary component of concrete, is responsible for approximately 7–8% of global CO_2 emissions (Lehne and Preston, 2018). This significant carbon footprint, coupled with the depletion of natural resources like aggregates and water (Grebenkov, 2022; Wada et al., 2010), has led to growing concerns about the sustainability of concrete construction and initiated a global transformation to climate neutrality.

Rapid urbanization (Ritchie and Roser, 2018) and population growth (Roser et al., 2013) are factors increasing the demand for new infrastructure and housing, further exacerbating the environmental impact of the construction industry. As climate change and resource scarcity continue to pose major challenges, there is an urgent need for more sustainable solutions in concrete construction.

In response to these challenges, the construction industry is actively exploring and implementing more sustainable practices and materials in concrete construction. This shift aims to reduce the environmental impact of concrete production, extend the service life of structures, and minimize resource consumption. Researchers, industry professionals, and policymakers are collaborating to develop and promote innovative technologies, materials, and strategies that can significantly reduce the carbon footprint, energy use, and waste generation associated with concrete construction. A roadmap for climate neutral concrete was for example introduced by the Swedish concrete industry in 2018. The roadmap was designed by The Concrete Initiative, a trade network of actors along the entire value chain of concrete production and -construction. The main milestones include a 50% reduction in the climate impact of concrete for house building by 2023, compared to the levels of 1990, introducing climate neutral concrete on the Swedish market by 2030, and climate neutrality in the entire concrete industry by 2045 (Fossil Free Sweden, 2018a). A corresponding roadmap for the Swedish construction and civil engineering sector proclaims 50% reduction in greenhouse gas emissions by 2030, compared to the levels of 2015, and net-zero greenhouse gas emissions by 2045 (Fossil Free Sweden, 2018b).

The importance of sustainability in concrete construction has been further emphasized by international agreements such as the Paris Agreement (United Nations, 2015; Schleussner et al., 2016) and the United Nations' Sustainable Development Goals (SDGs) (Cf, 2015; Colglazier, 2015), which call for urgent actions to mitigate climate change

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and promote sustainable development.

The construction industry is increasingly focusing on sustainability and the development of environmentally friendly practices, in response to the growing concerns about climate change, resource depletion, and waste generation. One crucial aspect of this shift is the adoption of sustainable materials in concrete construction. Various innovative materials and technologies have therefore emerged, aiming to reduce the environmental footprint of concrete construction, enhance its durability and performance, and contribute to the overall sustainability of the built environment (Duxson et al., 2007).

Green concrete is a term used to describe a range of concrete formulations that incorporate recycled materials, waste products, and environmentally friendly components (Qaidi et al., 2021, 2022a, 2022b, 2022c, 2022d; Agwa et al., 2022a). These formulations aim to reduce the consumption of natural resources, lower the carbon emissions associated with cement production, and minimize the environmental impact of concrete construction. The use of recycled aggregates, supplementary cementitious materials, and industrial by-products, such as fly ash and slag, are examples of green concrete components that contribute to a more sustainable concrete mix (Qaidi et al., 2022e, 2022f; Kaze et al., 2022; Tayeh et al., 2022a). The use of local materials in concrete construction is another sustainable approach that can contribute to a reduced environmental impact (de Azevedo et al., 2022; Hamada et al., 2020a, 2020b; Tayeh et al., 2019). By sourcing materials locally, transportation-related emissions and energy consumption can be significantly decreased. Moreover, local materials often have unique properties that can enhance the performance and durability of concrete structures (Agwa et al., 2022b). Examples of local materials include limestone calcined clay cement, which can partially replace conventional cement, and natural fibers or aggregates, which can be used to create more sustainable and cost-effective concrete mixes (Zhou et al., 2022a; Guo et al., 2022; Zunino and Scrivener, 2022).

Permeable concrete is a type of concrete designed to allow water to pass through its structure (Aravind and Abdulrehman, 2022), thereby reducing stormwater runoff and promoting groundwater recharge. This innovative material can play a crucial role in sustainable urban development by mitigating the effects of urban heat islands, reducing the risk of flooding, and improving water quality (Luo et al., 2022). Permeable concrete also offers potential benefits in terms of reduced construction costs and maintenance requirements, as it can eliminate the need for conventional stormwater management systems, such as gutters, drains, and retention ponds. Cool concrete is another sustainable material designed to reduce the environmental impact of concrete construction (Anupam et al., 2022). This type of concrete incorporates reflective or light-colored components that can help minimize heat absorption and lower the surface temperature of concrete structures. By doing so, cool concrete can contribute to the mitigation of urban heat island effects and reduce the energy consumption of buildings for cooling purposes (Wardeh et al., 2022). Additionally, the use of cool concrete can enhance the durability of concrete structures by minimizing the thermal stress and subsequent cracking caused by temperature fluctuations (Qin, 2015).

Ultra High Performance Concrete (UHPC) is a highly engineered cementitious composite that offers exceptional mechanical properties, high strength, enhanced fire properties and durability (Wen et al., 2022; Hamada et al., 2022; Qaidi et al., 2022g; Akeed et al., 2022; Divya et al., 2022; Almeshal et al., 2022). The superior performance of UHPC allows for a reduction in the amount of material needed for a given project, decreasing the overall environmental footprint of concrete construction (Qaidi et al., 2022g). Additionally, UHPC's increased durability can extend the service life of concrete structures, reducing the need for maintenance, repair, and replacement (Wen et al., 2022). This material also offers potential improvements in energy efficiency and thermal performance of buildings due to its high strength and low permeability.

In addition to sustainable materials, the concrete construction industry has been exploring innovative technologies and practices to improve the sustainability, performance, and efficiency of structures. The adoption of these emerging techniques is critical for the industry's ongoing efforts to reduce its environmental impact and enhance the resilience of the built environment. One such innovation is self-healing concrete, which incorporates materials or agents that enable the concrete to repair itself when damaged (Amran et al., 2022a; Hossain et al., 2022). This technology increases the lifespan of structures, reduces maintenance requirements, and minimizes the need for resource-intensive repairs (Sohail et al., 2022). 3D-printed concrete employs additive manufacturing techniques to create complex structural components with precision and efficiency, resulting in reduced material usage and waste generation (Mohan et al., 2022). It also enables the construction of unique geometries that would be challenging to achieve with traditional methods (Wu et al., 2022). Photocatalytic concrete incorporates photocatalytic materials that break down pollutants and organic compounds on the concrete surface when exposed to sunlight, improving air quality and contributing to a cleaner environment (Khannyra et al., 2022). Insulated concrete forms combine the structural strength of reinforced concrete with the energy efficiency of high-performance insulation materials, resulting in energy savings and enhanced thermal comfort in buildings (Hemalatha et al., 2022). Waste-derived fuels, such as biomass or industrial waste, can be used to replace traditional fossil fuels in the production of cement, reducing greenhouse gas emissions and the overall carbon footprint of concrete construction (Vershinina et al., 2022).

The electrification of equipment and vehicles in concrete construction helps decrease the reliance on fossil fuels, reducing emissions and noise pollution (Trinh et al., 2022). This transition is facilitated by advancements in battery technologies, electric motors, and charging infrastructure (Zhang et al., 2022). Phase change materials (PCMs) can be incorporated into concrete to store and release thermal energy, enhancing the thermal performance of structures and reducing energy consumption for heating and cooling (Asadi et al., 2022; Sharma et al., 2022). Carbon capture, utilization, and storage (CCUS) technologies have the potential to significantly reduce the carbon emissions associated with cement and concrete production (Statista, 2023; Monteiro et al., 2017; Lehne and Preston, 2018). By capturing CO2 emitted during the manufacturing process and either utilizing it in the production of new materials or permanently storing it in geological formations, CCUS technologies can help mitigate the climate impact of the concrete industry (Bahman et al., 2023).

The aim of this paper is to provide a comprehensive overview of the current trends and opportunities for sustainable concrete construction, focusing on innovative materials, technologies, and practices that have the potential to significantly reduce the environmental impact of concrete production and use. The scope of the review encompasses recent advancements in sustainable materials, such as green concrete and supplementary cementitious materials, as well as emerging technologies and practices, including self-healing concrete, 3D-printed concrete, and carbon capture, utilization and storage principles. In addition, the paper will discuss the role of policies, incentives, and research in promoting sustainable concrete construction.

The importance of this study lies in identifying and analyzing sustainable materials, innovative technologies, and practices in concrete construction. As the construction industry faces growing concerns regarding climate change, resource depletion, and waste generation, this research contributes to a holistic understanding of how to minimize environmental impact and enhance performance in the built environment. By evaluating emerging trends and providing insights, this study aims to guide the industry, academia, and policymakers in adopting more sustainable approaches, ultimately facilitating the transition towards a more resilient and environmentally responsible construction sector.

2. Sustainable materials in concrete construction

2.1. Green concrete

Green concrete is a common term for environmentally enhanced materials in concrete construction that has gained increasing attention in recent years (Obla, 2009; Baikerikar, 2014; Liew et al., 2017; Sivakrishna et al., 2020; Suhendro, 2014; Glavind and Munch-Petersen, 2000; Garg and Jain, 2014; Al-Mansour et al., 2019; Błaszczyński and Król, 2015). The term "green concrete" refers to concrete made using eco-friendly materials and processes, with the aim of reducing the environmental impact of concrete production and construction. Green concrete can be produced using a variety of methods, including the use of recycled aggregates, industrial by-products, and alternative binders, all of which contribute to a lower carbon footprint and reduced consumption of natural resources as described in Tables 1–3. Green concrete can also be referred to as Ecological concrete (Kothari et al., 2020; Higuchi et al., 2014; Vieira et al., 2016; Yoshioka et al., 2013), or Climate improved concrete (Fossil Free Sweden, 2018a; Hofgård and Sundkvist, 2020; Cementa, 2009), including the use of Supplementary Cementitious Materials (SCM) (Lothenbach et al., 2011; Snellings et al., 2012; Juenger and Siddique, 2015; Juenger et al., 2019; Aprianti et al., 2015; Skibsted and Snellings, 2019), Geopolymer concrete (Almutairi et al., 2021; Singh et al., 2015; Aleem and Arumairaj, 2012; Rangan, 2014; Raijiwala and Patil, 2010), or Alkali activated concrete (Ding et al., 2016; Yang et al., 2013; Amer et al., 2021; Provis, 2018; Wang et al., 1995).

2.2. Permeable concrete

Permeable concrete (Xie et al., 2019), also known as pervious (Li et al., 2021) or porous concrete (Elizondo-Martinez et al., 2020), is an innovative technology and practice in concrete construction that allows water to pass through its structure, as seen in Fig. 1, promoting natural drainage and reducing surface runoff. This type of concrete is characterized by a high porosity, achieved by using a minimal amount of fine aggregates or sand in the mix and a higher proportion of coarse aggregates. The resulting interconnected voids within the concrete allow water to flow through it, making it an environmentally friendly solution for various construction applications.

Permeable concrete can for example help manage stormwater runoff by allowing water to infiltrate through the pavement and into the ground, thereby reducing the risk of flooding, erosion, and water pollution (Kuruppu et al., 2019). This natural drainage process can also help replenish groundwater resources and reduce the demand for stormwater infrastructure. By facilitating the infiltration of water through the concrete, permeable pavements can help filter out

Table 1
Recycled aggregates in green concrete construction.

Recycled aggregates
Recycled aggregates are an essential component of green concrete, as they help to reduce the environmental impact of concrete production by utilizing waste materials and reducing the demand for natural resources (Levy and Helene, 2004; Chen et al., 2003; Hansen, 1986; Evangelista and De Brito, 2014; Wang et al., 2021a; Tam et al., 2018). The use of recycled aggregates in concrete construction contributes to the principles of sustainable development and circular economy, promoting resource efficiency and waste minimization. Recycled aggregates can be sourced from various waste materials, such as construction and demolition (C&D) waste, which includes demolished concrete, bricks, and masonry, as well as waste materials like glass and plastics. These waste materials are processed and crushed into different sizes to replace natural aggregates in concrete mixtures partially or entirely.
By substituting natural aggregates with recycled aggregates, the extraction of raw materials such as sand, gravel, and limestone is reduced, leading to lower environmental impact, and preserving natural resources for future generations. Utilizing waste materials like C&D waste as a source of recycled aggregates diverts them from landfills, reducing the overall waste generated and associated environmental impacts. Processing and transporting recycled aggregates usually require less energy compared to the extraction and transportation of natural aggregates, resulting in lower energy consumption and greenhouse gas emissions. In some cases, the use of recycled aggregates can result in cost savings, as they may be more readily available and less expensive than natural aggregates.
There are also some challenges associated with using recycled aggregates in concrete construction, such as the variability in their quality and properties, potential contamination, and the need for proper quality control and processing techniques (Levy and Helene, 2004; Chen et al., 2003; Tam et al., 2018). Additionally, the performance of concrete made with recycled aggregates may vary depending on the type and proportion of recycled materials used. To address these challenges, further research, standardization, and development of guidelines for the use of recycled aggregates in concrete construction are needed. Incorporating recycled aggregates into green concrete is an effective way to improve the sustainability of concrete construction by reducing the consumption of natural resources, minimizing waste generation, and lowering the environmental impact.

Table 2
Industrial by-products in green concrete construction.

Industrial by-products
Industrial by-products are valuable components of green concrete, as they enable the utilization of waste materials from various industries and reduce the environmental impact associated with concrete production (Al-Mansour et al., 2019; Siddique, 2014; Part et al., 2015; Gupta et al., 2021; Corinaldesi and Moriconi, 2011; Mehta, 1989). The use of industrial by-products in concrete construction aligns with the principles of sustainable development and circular economy, encouraging resource efficiency and waste minimization. Some common industrial by-products used in green concrete include Fly ash, Silica fume, Blast furnace slag, and Rice husk ash, which can all be used as supplementary cementitious materials (SCMs) and thereby reduce the need for traditional cement. The following paragraphs give an overview of SCMs, and a more detailed description is given in the next chapter.
Fly ash is a by-product of coal combustion in thermal power plants and has the potential to partially replace cement in concrete mixtures, reducing the need for cement production and associated CO2 emissions (Gupta et al., 2021). Fly ash can in some applications improve the concrete's workability, durability, and resistance to chemical attacks and research has shown that it can potentially enhance the long-term strength. Silica fume is a by-product of silicon and ferrosilicon alloy production, which can be used as a SCM in concrete (Khan and Ali, 2019). It significantly improves concrete's mechanical properties and durability, including increased strength, reduced permeability, and enhanced resistance to chloride ingress and sulfate attack. Ground Granulated Blast Furnace Slag (GGBS) is a by-product of iron and steel production, which can be ground into a fine powder and used as a cementitious material in concrete mixtures (Ahmad et al., 2022). It may improve concrete's workability, strength, and durability, and can also reduce its heat of hydration, making it suitable for mass concrete applications. Rice husk ash is a by-product of rice milling, which is rich in silica and can also be used as SCM in concrete (Tayeh et al., 2021).
Using industrial by-products in concrete production may offer several benefits (Khan and Ali, 2019). By incorporating industrial by-products into concrete mixtures, the demand for virgin materials, such as cement, is reduced, conserving natural resources and decreasing the environmental impact of concrete production. Utilizing waste materials from various industries diverts them from landfills, reducing waste generation and the associated environmental impacts. The use of industrial by-products in concrete production often requires less energy compared to the production of traditional materials, resulting in lower energy consumption and greenhouse gas emissions. Partially replacing Portland cement with SCMs can result in cost savings, as many SCMs are by-products that are often less expensive than cement.
There are some challenges associated with using industrial by-products in green concrete, such as availability, variability in their properties, potential contamination, and the need for proper quality control and processing techniques (Khan and Ali, 2019). The availability of SCMs can be limited by regional factors, such as the presence of industries that produce these by-products. Additionally, the composition and quality of SCMs can vary depending on the source and production process, which may affect the performance and consistency of the resulting concrete. Some SCMs, such as fly ash and ground granulated blast-furnace slag, can cause a slower early-age strength gain in concrete compared to mixes with only Portland cement. This might be a concern in projects where rapid strength development is crucial. However, this drawback can be mitigated by optimizing the concrete mix design and using chemical admixtures to accelerate the strength development. In some regions, the use of certain SCMs may be subject to regulatory constraints, particularly when it comes to the use of waste materials or industrial by-products. Strict standards and guidelines may need to be met before these materials can be utilized in concrete construction. This can create additional challenges for construction projects, as it may require additional testing, documentation, and approvals from relevant authorities.

Table 3
Alternative binders in green concrete construction.

Alternative binders
Alternative binders are an essential aspect of green concrete, as they offer the potential to reduce the environmental impact of concrete production by replacing or supplementing traditional Portland cement. As cement production accounts for a significant portion of CO2 emissions in the construction sector, the use of alternative binders can contribute to more sustainable concrete construction practices. The alternative binders can be divided into different types based on their material composition and was partly discussed in the section of industrial by-products and SCM.
Geopolymer concrete (Almutairi et al., 2021; Singh et al., 2015; Aleem and Arumairaj, 2012; Rangan, 2014; Raijiwala and Patil, 2010), and alkali-activated concrete (Ding et al., 2016; Yang et al., 2013; Amer et al., 2021; Provis, 2018; Wang et al., 1995; Levy and Helene, 2004), are two eco-friendly alternatives to traditional concrete, utilizing industrial by-products such as fly ash and ground granulated blast furnace slag or other types of alternative binders, combined with an alkali activator. Geopolymers are based on alumina and silica, while alkali-activated cements have a higher content of calcium. CSA cement is for example a low- CO2 alternative to Portland cement that contains Calcium SulfoAluminate (CSA) as its primary constituent (Tao et al., 2022). CSA cement can be produced at lower temperatures than Portland cement, resulting in reduced CO2 emissions. It also has rapid setting and high early strength properties, making it suitable for various construction applications. Magnesium-based cements, such as magnesium phosphate cement (MPC) and magnesium oxide (MgO) cement, are alternative binders that offers the possibility to reduce CO2 emissions associated with cement production (Haque and Chen, 2019; Hay et al., 2021). Calcined clay cement is a promising alternative binder that combines calcined clay, limestone, and a reduced amount of clinker. This combination results in lower CO2 emissions and energy consumption compared to conventional Portland cement, while maintaining comparable performance characteristics (Sharma et al., 2021; Jaskulski et al., 2020; Zhang et al., 2020a).
Alternative binders typically have a lower carbon footprint than conventional Portland cement, as their production requires less energy and generates fewer greenhouse gas emissions. The production of Portland cement is associated with significant CO2 emissions, while some alternative binders rely on industrial by-products that does not require high-temperature kilns. As a result, the carbon footprint of alkali-activated concrete can be substantially lower than that of traditional cement-based concrete, contributing to global efforts to mitigate climate change. The use of alternative binders can help reduce the demand for natural resources, such as limestone, and minimize the environmental impact associated with cement production. Some alternative binders can offer improved mechanical properties, durability, and resistance to chemical attacks, making them suitable for various applications. Geopolymer concrete, for example, exhibits excellent resistance to various forms of chemical attacks, such as sulfate and chloride ingress, and has a low porosity, which can lead to increased durability and a longer service life for structures. This improved performance reduces the need for frequent repairs or replacements, further enhancing the sustainability of the material. However, there are some challenges associated with using alternative binders in green concrete, such as limited availability, variability in properties, and the need for proper quality control and processing techniques.

pollutants, such as oil, heavy metals, and sediments, preventing them from entering water bodies and contributing to water pollution.

The porous structure of permeable concrete can help reduce the urban heat island effect by promoting evaporative cooling and reducing the amount of heat absorbed by paved surfaces (Chen et al., 2019). The porous nature of permeable concrete also helps to reduce water accumulation on the surface, lowering the risk of hydroplaning and improving skid resistance, which can contribute to increased safety for pedestrians and vehicles during wet conditions.

Permeable concrete requires minimal maintenance compared to traditional impervious pavements, as it eliminates the need for stormwater drainage systems, such as curbs, gutters, and storm drains. This can result in reduced maintenance costs and lower long-term expenses for property owners and municipalities. Periodic cleaning, such as vacuum sweeping or pressure washing, is generally sufficient to maintain the infiltration capacity of permeable concrete pavements.

Despite its advantages, there are also challenges and limitations associated with permeable concrete. Due to its high porosity and reduced strength compared to conventional concrete, permeable concrete may not be suitable for heavy-load applications or areas with high traffic volumes. However, it is well-suited for low-traffic areas, such as parking lots, sidewalks, residential streets, and other low-stress applications. Over time, the voids in permeable concrete can become clogged with sediment, debris, or organic matter, reducing its infiltration capacity (Singh et al., 2020). Regular maintenance, such as vacuum sweeping or pressure washing, is essential to maintain the permeability of the concrete and ensure its long-term performance. In some cases, the use of geotextiles or filter layers beneath the permeable concrete can help prevent clogging and maintain infiltration capacity.

Fig. 1. Sample of pervious concrete (Khan et al., 2017).

In regions with freeze-thaw cycles, the performance of permeable concrete can be affected by the expansion and contraction of water within the interconnected voids (Wang et al., 2022a). This can lead to a reduction in strength, durability, and overall performance. However, proper mix design and the use of air-entraining admixtures can help improve freeze-thaw resistance and extend the service life of permeable concrete structures. The installation cost of permeable concrete can be higher than that of traditional impervious pavements due to the specialized mix design and installation techniques required. However, this initial investment may be offset by the reduced need for stormwater infrastructure and long-term maintenance savings.

2.3. Cool concrete

Cool concrete (Anupam et al., 2021), also known as high-albedo (Sanjuán et al., 2022) or reflective concrete (Qin et al., 2019), is an innovative technology and practice in concrete construction that aims to reduce the urban heat island (UHI) effect by incorporating materials with high solar reflectance into the concrete mix or surface coatings. This type of concrete reflects a larger portion of solar radiation back into the atmosphere, resulting in a cooler surface temperature compared to traditional concrete, as shown in Fig. 2. By mitigating the UHI effect, cool concrete can contribute to more sustainable and comfortable urban environments, as well as help reduce energy consumption associated with cooling buildings.

Cool concrete can help reduce the UHI effect by lowering the temperature of paved surfaces, such as sidewalks, parking lots, and roadways (Anupam et al., 2021; Sanjuán et al., 2022). This can result in more comfortable outdoor spaces, improved air quality, and reduced thermal

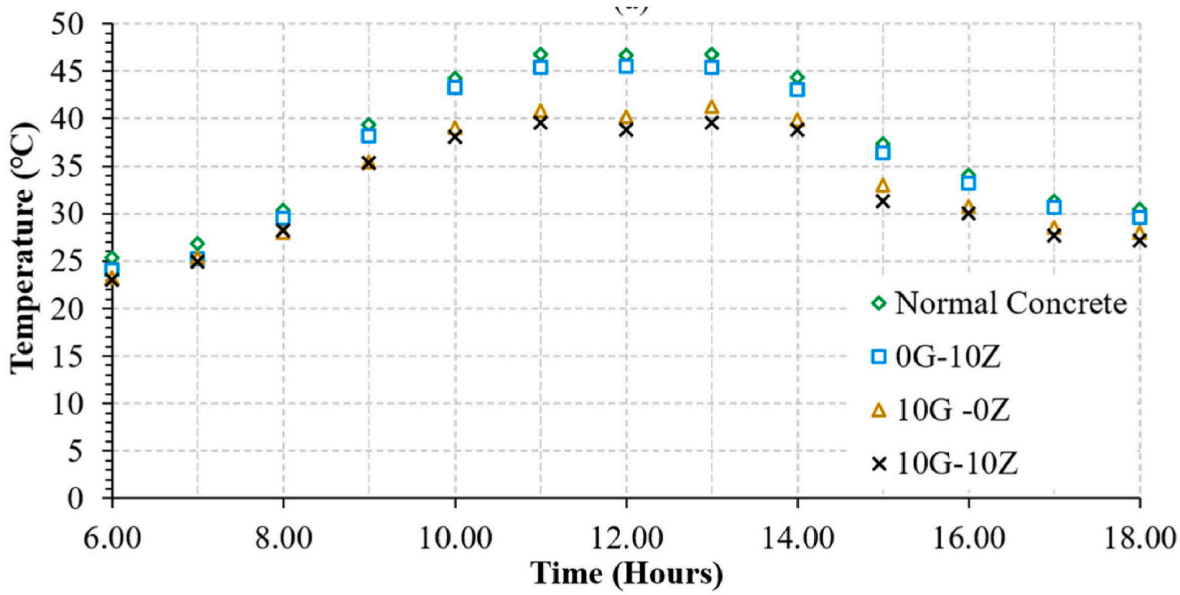

Fig. 2. Surface temperature for cool concrete with up to 10% of glass powder (G) as replacement of fine aggregates and up to 10% of zeolite (Z) as replacement of cement (Balan et al., 2021).

stress on urban ecosystems. By reducing the heat absorbed by paved surfaces, cool concrete can contribute to lower cooling demands for adjacent buildings, leading to energy savings and reduced greenhouse gas emissions. The reduced surface temperatures of cool concrete can help extend the service life of the pavement by minimizing thermal stress and temperature-induced damage, such as cracking or expansion. Cooler pavement surfaces can reduce the temperature of stormwater runoff, which can help protect aquatic ecosystems from thermal pollution and improve the overall quality of urban water bodies.

There are also challenges and limitations associated with cool concrete. The use of high-albedo materials or specialized coatings in cool concrete can result in higher initial costs compared to traditional concrete (Anupam et al., 2021). However, the long-term benefits of reduced energy consumption, improved durability, and enhanced environmental performance may offset these initial investments. Dirt, dust, and other contaminants can accumulate on the surface of cool concrete over time, reducing its solar reflectance and, consequently, its cooling effect. Regular cleaning and maintenance are necessary to preserve the high-albedo properties and maintain the performance of cool concrete.

The choice of materials with high solar reflectance can be limited, and some high-albedo materials may not provide the same strength or durability as traditional concrete materials (Cheela et al., 2021). Further research and development are needed to identify and develop suitable high-albedo materials that can meet both the performance and sustainability criteria for cool concrete applications. Cool concrete surfaces may have a lighter color or different appearance compared to traditional concrete, which may not be suitable for all architectural styles or urban settings. This may require additional consideration of aesthetic preferences and design compatibility when implementing cool concrete in specific projects.

Cool concrete is expected to become an increasingly important technology and practice in concrete construction, offering new opportunities for mitigating the urban heat island effect and promoting sustainable urban development. By addressing the challenges and limitations associated with cool concrete, such as initial cost, maintenance, material selection, and aesthetic considerations, the construction industry can unlock the full potential of this innovative material and contribute to more sustainable and comfortable urban environments.

2.4. Ultra-high-performance concrete (UHPC)

Ultra High Performance Concrete (UHPC) has emerged as a promising sustainable material in concrete construction, offering significant advantages over traditional concrete (Azmee and Shafiq, 2018). UHPC is a highly engineered, fiber-reinforced cementitious composite characterized by its exceptional mechanical properties, high strength, and durability (Hisseine et al., 2020). These properties make UHPC an attractive material for various construction applications, including bridges, buildings, and infrastructure projects, where enhanced performance and sustainability are desired.

One of the key benefits of UHPC is its superior strength and durability, which can lead to a reduction in the amount of material needed for a given project (Meng et al., 2017). By using less material, UHPC can help decrease the overall environmental footprint of concrete construction, as less energy and resources are required for its production, transportation, and installation. Additionally, UHPC's increased durability can help extend the service life of concrete structures, reducing the need for maintenance, repair, and eventual replacement (Zhou et al., 2018). This can contribute to a decrease in the consumption of raw materials, energy, and emissions associated with concrete construction over the long term.

Another advantage of UHPC is its potential to improve the energy efficiency and thermal performance of buildings, including the fire safety (Xue et al., 2022). Due to its high strength and low permeability, UHPC can effectively insulate buildings and minimize heat transfer, reducing energy consumption for heating and cooling purposes. This can contribute to a decrease in greenhouse gas emissions associated with building operations and help combat climate change. Furthermore, UHPC's low permeability can enhance the resilience of concrete structures to environmental degradation, such as freeze-thaw cycles and chloride ingress (Li et al., 2020), increasing their longevity and reducing maintenance requirements.

UHPC's versatility and adaptability also contribute to its potential as a sustainable construction material. The material can be tailored to suit specific applications and performance requirements (Jung et al., 2022), enabling the development of innovative and sustainable construction solutions. UHPC can be used in combination with other materials, such as recycled aggregates, supplementary cementitious materials, and natural fibers, to create hybrid materials with enhanced properties and reduced environmental impacts (Smarzewski and Barnat-Hunek, 2018). This versatility allows for the development of novel, sustainable concrete solutions that can meet the demands of an evolving construction industry.

Despite the many benefits of UHPC, several challenges and barriers must be overcome to fully realize its potential as a sustainable construction material. The high cost of UHPC, particularly in comparison to traditional concrete, can be a significant barrier to its widespread adoption. The cost of UHPC is primarily driven by its complex composition, which includes specialized fibers, admixtures, and fine aggregates (Shah et al., 2022).

2.5. Use of local materials

The use of local materials in concrete construction is an essential aspect of sustainable development, as it can help reduce the environmental impact, lower transportation costs, and support the local economy (Muteb and Hasan, 2020; Adesina, 2020). Incorporating locally available materials into concrete mixtures can improve the sustainability of construction projects while still meeting the required performance and durability criteria. Some examples of local materials that can be used in concrete construction include natural aggregates, recycled aggregates, natural pozzolans, locally sourced fibers, and local binders.

Sand, gravel, and crushed stone are commonly used natural aggregates in concrete production. Sourcing these materials from local quarries and deposits can reduce transportation-related emissions and energy consumption. The use of locally available aggregates can ensure that the concrete mix is better suited to the local environmental conditions, such as freeze-thaw cycles, salt exposure, or soil characteristics. Using recycled aggregates, such as crushed concrete, brick, or glass, can promote resource conservation and waste reduction. These materials can be sourced from local construction and demolition waste, repurposing them in new concrete mixes and reducing the demand for excessive aggregate extraction.

Some regions have natural pozzolanic materials (Tayeh et al., 2022b), such as volcanic ash or calcined clays, that can be used as supplementary cementitious materials. These local materials can partially replace Portland cement in concrete mixtures, reducing the environmental impact and resource consumption associated with cement production. The use of locally available fibers, such as natural fibers (e.g., sisal, coir, or jute) or waste materials from local industries (e.g., steel fibers from industrial waste), can enhance the performance of concrete and contribute to sustainability. These fibers can be incorporated into concrete mixtures to improve tensile strength, crack resistance, and durability, while also reducing the reliance on synthetic fibers or imported materials. Alternative binders that can partially or fully replace Portland cement may be available in some regions of the world. Examples include locally produced lime, natural hydraulic limes, or locally sourced geopolymers. Utilizing these local binders can contribute to reducing the carbon footprint of concrete production and support the local economy.

Limestone Calcined Clay Cement (LC3) is a novel, environmentally friendly cementitious material that has gained attention as an alternative to traditional Portland cement in concrete construction (Díaz et al., 2017). LC3 is a blend of clinker, calcined clay, limestone, and gypsum, which results in reduced carbon emissions and energy consumption during its production compared to conventional cement (Pillai et al., 2019). The use of LC3 in concrete construction offers several benefits compared to using more traditional materials. Firstly, it utilizes locally available raw materials, such as limestone and clay, which reduces transportation costs and associated emissions. Secondly, the calcination of clay at lower temperatures than clinker production results in lower energy consumption and carbon dioxide emissions (Scrivener et al., 2018). LC3 also exhibits similar or even better mechanical and durability properties for some mixes compared to traditional Portland cement (Dhandapani et al., 2018a). LC3 has the potential to address the growing demand for cement by utilizing abundant and underexploited clay resources, thereby reducing the pressure on clinker production.

There are several benefits that can be achieved by using local materials in concrete construction (Nodehi et al., 2022a). Sourcing materials locally can reduce transportation-related emissions, energy consumption, and overall carbon footprint of construction projects. The use of local materials may promote resource conservation and waste reduction, as it encourages the reuse and repurposing of locally available materials, including waste products and by-products from other industries. Supporting local suppliers and industries can help boost the local economy, create jobs, and encourage the development of sustainable construction practices in the region. Local materials are often well-, or even better suited to local environmental conditions, resulting in structures that are more resilient and better adapted to the specific challenges and needs of the region. It is, however, important to consider that the use of local materials should not compromise the quality and performance of the concrete. Proper testing, characterization, and mix design are essential to ensure that the desired properties and durability requirements are met while making use of locally available materials in concrete construction.

3. Innovative technologies and practices

3.1. Self-healing concrete

Self-healing concrete is an innovative technology and practice in concrete construction that has the potential to enhance the durability, performance, and sustainability of concrete structures. This technology is based on the concept of enabling concrete to autonomously repair cracks and damage, extending the service life of structures and reducing the need for maintenance and repairs.

There are several approaches to achieving self-healing capabilities in concrete as described in Table 4.

Self-healing concrete can prolong the service life of structures by autonomously repairing cracks and damage, reducing the risk of corrosion and other deterioration mechanisms. By minimizing the need for manual inspections, maintenance, and repair interventions, self-healing concrete can lead to significant cost savings over the life of a structure. Extending the service life of concrete structures and reducing the need for maintenance and repairs can contribute to a reduction in resource consumption, waste generation, and overall environmental impact.

Despite these promising benefits, there are still some challenges and limitations associated with self-healing concrete technologies, such as the scalability of laboratory successes to real-world applications, the long-term performance and reliability of self-healing mechanisms, and the increased initial costs of implementing these technologies. Further research and development, along with more full-scale and field demonstrations (https://doi.org/10.3389/fmats.2019.00048., 2019; Van Tittelboom et al., 2016) will be crucial to overcoming these challenges and realizing the full potential of self-healing concrete in the construction industry.

3.2. 3D-printed concrete

3D-printed concrete is an innovative technology and practice in concrete construction that involves the use of computer-controlled robotic systems to deposit layers of concrete material, following a predetermined digital design, to create structural components or even entire buildings, as illustrated in Fig. 3. This technology, also known as additive manufacturing or digital fabrication, has the potential to revolutionize the construction industry by offering numerous benefits in terms of efficiency, customization, and sustainability (Tenório Filho et al., 2021; Zhang et al., 2021; Nodehi et al., 2022b; Rahul et al., 2019).

3D printing has the potential to significantly reduce construction time compared to traditional methods, as it allows for the simultaneous

Table 4
Different approaches to self-healing concrete.

Self-healing approach	
Bacterial self-healing (Wang et al., 2021b):	This approach involves incorporating specific strains of bacteria and nutrients into the concrete mixture. When cracks form in the concrete, the bacteria become active in the presence of moisture and begin to produce calcium carbonate (limestone) as a byproduct of their metabolic processes. The calcium carbonate fills the cracks and restores the structural integrity of the concrete. This method has shown promising results in laboratory settings and has the potential to enhance the durability and sustainability of concrete structures.
Microencapsulated healing agents (Balzano et al., 2021):	In this approach, healing agents, such as polymeric materials or mineral-based compounds, are encapsulated in small capsules or tubes and incorporated into the concrete mix. When cracks form, the capsules rupture and release the healing agents, which then fill and seal the cracks. The healing agents can either harden through chemical reactions or solidify upon exposure to air, thus restoring the concrete's structural integrity.
Shape-memory polymers (Albuhairi and Di Sarno, 2022):	These are polymers that can return to their original shape after being deformed, typically upon exposure to heat or other external stimuli. By incorporating shape-memory polymers in the form of fibers or embedded reinforcements, concrete can be designed to "recover" from deformations or close small cracks that may form due to applied loads or environmental factors. This self-healing mechanism can help maintain the integrity and durability of concrete structures over time.
Intrinsic self-healing (Zhang et al., 2019a):	In this approach, the concrete mixture itself is designed to promote self-healing. This can be achieved by adjusting the mix proportions or using specific admixtures to create an environment that encourages the formation of calcium carbonate or other minerals that can fill and seal cracks naturally. This type of self-healing is often less effective than other approaches, but it can still contribute to improving the overall durability of concrete structures.
Superabsorbent polymers (Dhandapani et al., 2018b; Snoeck et al., 2014, 2016, 2020; Snoeck, 2022; Snoeck and De Belie, 2015, 2016, 2019; Wang et al., 2015)	Superabsorbent polymers (SAPs) are highly absorbent materials that can retain and release large amounts of water relative to their mass. SAPs are composed of cross-linked polymer networks, often derived from acrylic acid or other similar monomers. They have a wide range of applications in various industries, including agriculture, hygiene products, and construction. In the context of concrete construction, SAPs have gained attention due to their ability to improve the performance and durability of concrete. When added to the concrete mix, SAPs absorb water and swell, creating internal reservoirs of water within the concrete. These reservoirs help maintain the concrete's moisture content, mitigating problems such as shrinkage and cracking caused by excessive water loss during the curing process. SAPs can contribute to the self-healing properties of concrete by releasing the absorbed water in response to the formation of micro-cracks. The released water helps promote the hydration of unreacted cement particles, leading to the formation of calcium-silicate-hydrate (C–S–H) gels, which can partially or fully heal the cracks and restore the concrete's structural integrity.

fabrication of multiple components or structures (Zhang et al., 2019b). The technology also reduces the need for manual labor and formwork, contributing to increased productivity and reduced labor costs. 3D printing enables the creation of complex and intricate geometries that are difficult or impossible to achieve using conventional construction methods. This allows for greater design freedom, customization, and the potential for innovative architectural designs that optimize structural performance and material use.

3D printing can minimize material waste by depositing concrete only where it is needed, reducing the consumption of raw materials and the generation of construction waste (Amran et al., 2022b). This technology also enables the use of optimized, lightweight structures, which can reduce the overall amount of material required to achieve the desired structural performance. The reduced material consumption, waste generation, and labor requirements associated with 3D-printed concrete can contribute to a more sustainable construction industry. Moreover, this technology can potentially facilitate the integration of recycled materials or novel, eco-friendly materials into the concrete mixtures, further enhancing the environmental performance of the structures.

The challenges and limitations associated with 3D-printed concrete are typically associated with technological- and material aspects. The development and refinement of 3D printing systems, materials, and processes for concrete construction are ongoing (Kanyilmaz et al., 2022). Further advancements in areas such as robotic systems, print speed, concrete mix design, and curing processes are needed to fully realize the potential of this technology. The adoption of 3D-printed concrete in the construction industry will require the development of new codes, standards, and guidelines to ensure the quality, safety, and durability of the structures. The shift towards digital fabrication and automation may also require the retraining and upskilling of the construction workforce to adapt to new technologies, tools, and practices. While 3D printing has the potential to reduce labor and material costs in the long term, the initial investment in equipment and technology can be substantial.

As research and development continue, 3D-printed concrete is expected to become an increasingly important technology and practice in concrete construction, offering new opportunities for efficiency, customization, and sustainability.

3.3. Photocatalytic concrete

Photocatalytic concrete (Chen et al., 2022; Zhou et al., 2021, 2022b; Si et al., 2021; Singla et al., 2021) is an innovative technology and practice in concrete construction that incorporates photocatalytic materials, such as titanium dioxide (TiO_2), into the concrete mix or surface coatings. When exposed to sunlight or ultraviolet (UV) radiation, these materials generate reactive oxygen species (ROS) that can break down various pollutants, such as nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM). This self-cleaning and air-purifying property of photocatalytic concrete can contribute to improved air quality and more sustainable urban environments as

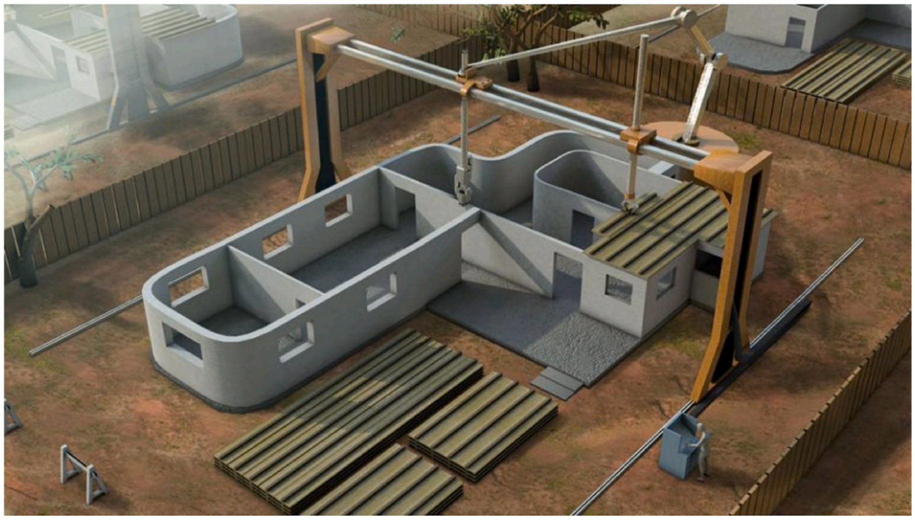

Fig. 3. Concept of 3D printed concrete (Yang et al., 2019).

demonstrated in Fig. 4.

Photocatalytic concrete can help improve urban air quality by reducing the concentration of airborne pollutants, such as NO_x, VOCs, and PM, which can be harmful to human health and the environment (Chen and Chu, 2011). This can result in cleaner air, reduced smog formation, and enhanced overall urban livability. The photocatalytic reactions can break down organic matter, such as algae, mold, and dirt, on the surface of the concrete. This self-cleaning property can help maintain the appearance and aesthetics of concrete structures, reducing the need for regular cleaning and maintenance.

The photocatalytic reactions can also help break down odor-causing compounds, such as ammonia and sulfides, leading to a reduction in unpleasant smells around concrete structures (Chouhan and Chandrappa, 2023). This can be particularly beneficial in urban areas, near waste treatment facilities, or in industrial settings where odors can negatively impact the quality of life for nearby residents. By breaking down pollutants and organic matter on the concrete surface, photocatalytic concrete can potentially increase the durability of the structure. This is because the pollutants and organic matter can contribute to the degradation and discoloration of concrete over time. By mitigating these factors, the overall service life of the structure can be extended.

Despite its advantages, there are also challenges and limitations associated with photocatalytic concrete. The use of photocatalytic materials, such as titanium dioxide, can result in higher initial costs compared to traditional concrete (Hamdany et al., 2022). However, the long-term benefits of improved air quality, reduced maintenance, and enhanced durability may offset these initial investments. Photocatalytic reactions require sunlight or ultraviolet radiation to generate reactive oxygen species. The effectiveness of photocatalytic concrete may be reduced in shaded areas or during periods of low light, such as cloudy days or nighttime. This can limit the overall performance of photocatalytic concrete in certain environments or applications.

The choice of photocatalytic materials and their optimal incorporation into the concrete mix or surface coating can be challenging. Factors such as particle size, distribution, and concentration can significantly impact the performance of photocatalytic concrete (Alcantara et al., 2023). Further research and development are needed to identify and optimize suitable photocatalytic materials and formulations that can meet both the performance and sustainability criteria for various construction applications. While photocatalytic concrete can contribute to improved air quality, the reactive oxygen species generated during the photocatalytic reactions can also produce secondary pollutants or cause

Fig. 4. Effect of a photocatalytic TiO2 coating on a concrete surface (right side), compared to an untreated concrete surface (left side) (Witkowski et al., 2019).

damage to surrounding materials or ecosystems. Further studies are needed to better understand and mitigate the potential environmental impacts of photocatalytic concrete.

3.4. Insulated concrete forms

Insulated Concrete Forms (ICFs) are an innovative technology and practice in concrete construction that involve the use of lightweight, interlocking foam forms to create a continuous insulation layer for cast-in-place concrete walls, as seen in Fig. 5. Once the concrete is poured and cured, the foam forms remain in place, providing a highly energy-efficient and durable building envelope. ICFs have gained popularity in residential and commercial construction due to their numerous advantages over traditional construction methods. ICF walls offer a high level of thermal insulation, which can significantly reduce heating and cooling loads in buildings (Liao and Yao, 2022). This can lead to lower energy consumption, reduced greenhouse gas emissions, and cost savings for building occupants. The combination of concrete and foam insulation creates a strong, monolithic wall system that can withstand severe weather conditions, including hurricanes and tornadoes, and resist damage from earthquakes.

Walls constructed with ICFs can effectively reduce the transmission of exterior noise, providing a quieter indoor environment and improved occupant comfort (Amer-Yahia and Majidzadeh, 2012). ICFs are relatively easy and quick to install, which can lead to shorter construction times and reduced labor costs compared to traditional construction methods. The concrete core of ICF walls provides excellent fire resistance, reducing the risk of fire spreading between rooms or adjacent buildings.

The upfront cost of ICF construction can be higher than traditional construction methods due to the expense of the foam forms and specialized installation techniques (Fediuk et al., 2021). However, the long-term benefits of reduced energy consumption and lower maintenance costs may offset these initial investments. While ICF construction can accommodate a variety of architectural styles, some complex designs or unconventional shapes may be more difficult or costly to achieve compared to traditional construction methods. This may require additional planning and coordination between the design team and construction team to ensure that the desired architectural features are compatible with ICF construction. ICF construction requires specialized training and skills for proper installation, which may not be readily available in all regions or markets. This can result in higher labor costs or limited access to qualified contractors.

Insulated concrete forms have the potential to become an increasingly important technology and practice in concrete construction, offering new opportunities for energy-efficient and resilient building design. Further advancements in material science, manufacturing processes, and construction techniques can lead to improved performance, cost-effectiveness, and versatility of ICF systems. In addition, the integration of ICF construction with other sustainable practices, such as the use of recycled materials or renewable energy sources, can enhance the overall environmental performance of concrete structures.

3.5. Electrification

Electrification of construction equipment and vehicles is an emerging innovative technology in the construction industry, aiming to reduce greenhouse gas emissions, improve energy efficiency, and lower the overall environmental impact. The adoption of electric-powered construction equipment and vehicles contributes to sustainable construction practices, aligning with global efforts to combat climate change and transition towards cleaner energy sources (Mantesi et al., 2019; Karlsson et al., 2020; Nadel, 2019). Some key aspects of electrification in concrete construction are discussed in Table 5.

However, there are some challenges associated with the electrification of equipment and vehicles in concrete construction. The upfront cost of electric equipment and vehicles can be higher than their diesel

Table 5
Key aspects of electrification in the construction industry.

Electrification aspect	
Electric construction equipment (Un-Noor et al., 2022):	The use of electric construction equipment, such as concrete mixers, pumps, and excavators, can significantly reduce emissions, noise, and vibration levels on construction sites. These electric-powered machines operate more quietly and efficiently compared to their diesel counterparts, providing a cleaner and more sustainable alternative.
Electric vehicles (Caldarelli et al., 2022):	Replacing conventional diesel-powered vehicles with electric trucks and vans for material transportation, on-site logistics, and personnel movement contributes to reduced emissions and improved air quality. Electric vehicles also benefit from lower operating costs due to reduced fuel consumption and maintenance requirements.
Battery technology advancements (Wang et al., 2022b):	The development of more efficient and longer-lasting batteries enables electric equipment and vehicles to operate for extended periods without recharging, improving their feasibility and productivity in concrete construction applications.
Renewable energy integration (See et al., 2022):	Pairing electric equipment and vehicles with renewable energy sources, such as solar or wind power, further enhances the sustainability of concrete construction practices by minimizing the reliance on fossil fuels and reducing the carbon footprint of construction activities.

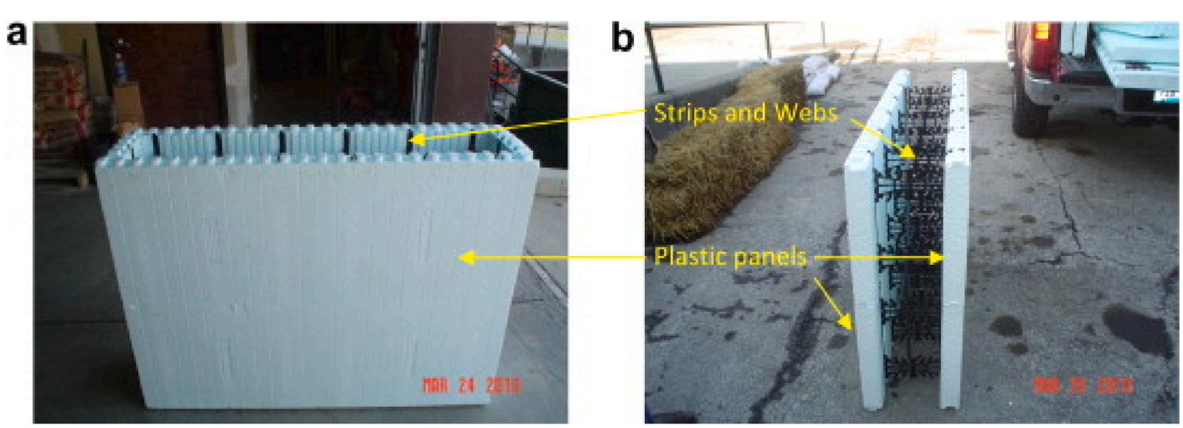

Fig. 5. Example of insulated concrete forms (Solomon and Hemalatha, 2020).

counterparts, which may pose a barrier for smaller construction companies and projects with limited budgets. The availability of charging infrastructure, particularly in remote construction sites, may be limited, making it challenging to implement electrification effectively (Osman et al., 2023). Electric equipment and vehicles typically have a shorter range and longer charging times compared to diesel-powered alternatives, which may affect productivity and work schedules on construction sites. As electric equipment and vehicles are relatively new in the concrete construction industry, there may be concerns about their reliability, performance, and durability compared to well-established diesel options. To overcome these challenges, continued research, development, and investment in electric equipment and vehicles, as well as improvements in battery technology and charging infrastructure, are crucial. Governments and industry stakeholders can also support the transition towards electrification by providing incentives, subsidies, and policy frameworks that encourage the adoption of electric equipment and vehicles in concrete construction.

3.6. Waste-derived fuels

Waste-derived fuels (WDFs) are an innovative technology and practice in concrete construction that involve the use of alternative fuels derived from various waste materials to replace traditional fossil fuels in the cement production process (Mutarraf et al., 2022; Hossain et al., 2019; Gerassimidou et al., 2021; Bień, 2021; Hashem et al., 2019). These alternative fuels can be sourced from a wide range of waste materials, such as municipal solid waste, agricultural residues, industrial by-products, and end-of-life tires. By utilizing WDFs in cement manufacturing, the concrete industry can contribute to more sustainable construction practices by reducing its reliance on fossil fuels, decreasing greenhouse gas emissions, and promoting waste management solutions.

Replacing traditional fossil fuels with WDFs can significantly reduce the carbon dioxide emissions associated with cement production. This can contribute to climate change mitigation efforts and help the concrete industry achieve its sustainability goals. Utilizing waste materials as alternative fuels can help divert them from landfills and incineration, promoting a more circular economy and efficient use of resources. Waste-derived fuels can provide a valuable source of energy for the cement production process, helping to reduce the industry's reliance on non-renewable fossil fuels and enhance its overall energy security. In some cases, the use of WDFs can even result in lower fuel costs compared to traditional fossil fuels, providing economic benefits for cement manufacturers. This is particularly true when waste materials are readily available, and their disposal costs can be avoided or minimized.

Despite the advantages of waste-derived fuels, there are also challenges and limitations associated with their use in concrete construction (Shehata et al., 2022a). The use of WDFs in cement production may require modifications to the existing kiln systems and process controls, as well as the development of specialized handling and storage solutions for waste materials. These technical challenges can pose initial investment and operational hurdles for cement manufacturers. The use of WDFs in cement manufacturing may also be subject to various environmental regulations and permitting requirements, which can vary across different jurisdictions. Cement manufacturers must navigate these regulatory frameworks to ensure compliance and avoid potential fines or penalties.

While WDFs can contribute to reducing greenhouse gas emissions, the combustion of some waste materials may generate other air pollutants, such as nitrogen oxides (NO_x), sulfur oxides (SO_x), or heavy metals (Samadi et al., 2022). It is essential to carefully select and process waste materials to ensure that the use of WDFs does not compromise air quality standards. The use of waste-derived fuels in cement production may face public opposition or skepticism, particularly if there are concerns about potential impacts on air quality, public health, or the environment. Cement manufacturers must engage in transparent communication and stakeholder engagement efforts to address these concerns and build public trust in the use of WDFs. The composition of waste materials can be highly variable, which may impact the quality and consistency of WDFs. This variability can pose challenges in terms of fuel preparation, handling, and combustion performance. Cement manufacturers may need to invest in advanced technologies and quality control measures to ensure that WDFs meet the required specifications for efficient and safe use in cement production.

Collaboration among researchers, industry professionals, policymakers, and stakeholders is essential to advance the use of waste-derived fuels in cement manufacturing. This includes developing and implementing best practices for waste material selection, processing, and combustion, as well as establishing robust monitoring and quality control systems to ensure the safety and efficiency of WDF utilization. Furthermore, the integration of waste-derived fuel technology with other sustainable practices and innovations in concrete construction, such as the use of supplementary cementitious materials, carbon capture and utilization, and energy-efficient building design, can enhance the overall environmental performance of the industry. By fostering interdisciplinary research, knowledge sharing, and the development of innovative solutions, the construction industry can work towards the successful implementation of waste-derived fuels and other sustainable practices, ultimately contributing to a more resilient and sustainable built environment.

3.7. Carbon capture, utilization, and storage (CCUS)

Carbon capture, utilization, and storage (CCUS) is an emerging technology that aims to mitigate climate change by capturing carbon dioxide (CO_2) emissions from industrial processes and power generation, utilizing the captured CO_2 for various applications, and storing the remaining CO_2 in secure geological formations to prevent its release into the atmosphere (https://doi.org/10.1016/j.resconrec.2022.106497., 1016; Narisetty et al., 2022; Nocito and Dibenedetto, 2020; Zhang et al., 2020b). The carbon capture process, as illustrated in Fig. 6, involves separation and capture of CO_2 from emission sources, such as power plants, cement factories, and other industrial facilities. Various technologies can be employed for carbon capture, including post-combustion capture, pre-combustion capture, and oxy-fuel combustion, each with its own advantages and limitations. The choice of technology depends on the specific application, source of emissions, and economic factors.

Captured CO_2 can be utilized in various applications, which not only reduces the volume of CO_2 that needs to be stored but also creates value-added products (Jiang and Ashworth, 2021). Some common uses of captured C CO_2 include the production of chemicals, plastics, and building materials, enhanced oil recovery, and the cultivation of algae for biofuels or other bioproducts. Another emerging application is the use of CO_2 to produce synthetic fuels through processes such as methanol synthesis. The remaining CO_2 that cannot be utilized may be stored in secure geological formations, such as deep saline aquifers, depleted oil and gas reservoirs, or un-mineable coal seams. These storage sites are carefully selected and monitored to ensure the long-term containment of CO_2 and to prevent leakage into the atmosphere.

By capturing and storing CO_2 emissions, CCUS can help reduce greenhouse gas emissions from industrial processes and power generation, contributing to global efforts to mitigate climate change and meet the goals set forth in international agreements, such as the Paris Agreement. CCUS can be integrated with enhanced oil recovery (EOR) processes, where the captured CO_2 is injected into depleted oil reservoirs to increase the recovery of oil (Hong, 2022). This not only helps utilize CO_2 emissions but also improves domestic energy production and security. The captured CO_2 can be utilized in the production of other valuable products, such as chemicals, building materials, and synthetic fuels. This may potentially create new economic opportunities and support the growth of a circular, low-carbon economy. CCUS can also act as a bridge technology, enabling industries and power plants to

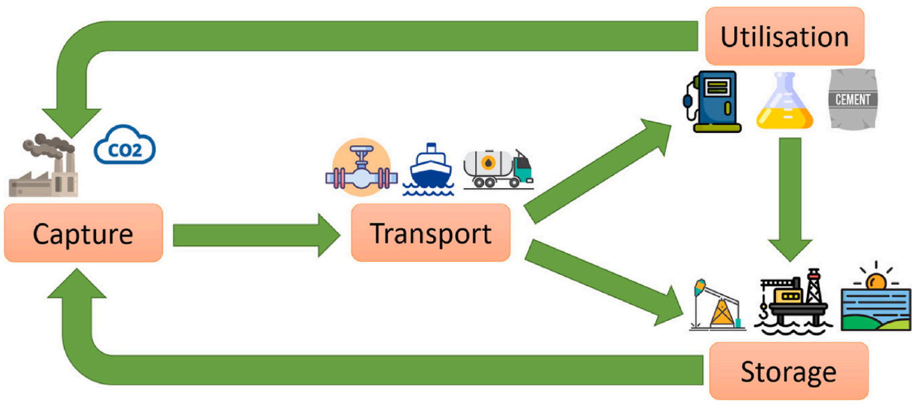

Fig. 6. Concept of carbon capture, utilization and storage (CCUS) (Hills et al., 2020).

reduce their carbon emissions while cleaner, renewable energy sources are being developed and scaled up.

Certain industries, such as cement production, steelmaking, and chemical manufacturing, are inherently carbon-intensive, and it is challenging to reduce emissions through process improvements alone. CCUS provides a viable solution for these industries to significantly reduce their carbon footprint. The challenges associated with CCUS, includes high costs, technological barriers, public perception, and regulatory issues.

3.8. *Phase change materials (PCMs)*

Phase Change Materials (PCMs) are substances capable of storing and releasing thermal energy during phase transitions, such as melting and solidification (Iyer et al., 2022). These materials have garnered significant interest in various sectors, including construction, due to their potential to improve thermal comfort, energy efficiency, and overall sustainability (Aliev et al., 2022). In concrete construction, the integration of PCMs can enhance the thermal performance of buildings, reducing energy consumption and associated emissions. PCMs have the potential to store and release thermal energy through phase transitions, which typically involve solid-liquid, liquid-gas, or solid-solid changes (https://doi.org/10.3390/pr10112306., 1011). The most common application of PCMs in construction is their solid-liquid transition, which offers a high storage density and minimal temperature fluctuations.

PCMs can be categorized into three main types based on their origins and compositions (Umair et al., 2019). Organic PCMs primarily consist of paraffin waxes and fatty acids. They are characterized by their high latent heat storage capacities, good thermal stability, and non-corrosive properties. However, their low thermal conductivity and flammability can limit their application in certain scenarios. Inorganic PCMs are predominantly composed of salt hydrates and metallic alloys. They offer high thermal storage capacities and thermal conductivities but may suffer from phase segregation, subcooling, and corrosion issues. Eutectic PCMs are mixtures of organic or inorganic substances that have a single melting point, combining the beneficial properties of both organic and inorganic PCMs. They exhibit good thermal stability, high latent heat capacities, and minimal phase segregation.

PCMs can be integrated into concrete construction in various forms and applications. PCMs can be encapsulated in porous lightweight aggregates, such as expanded perlite or expanded clay, and added to the concrete mix (da Cunha and de Aguiar, 2020). This allows for the even distribution of PCMs throughout the concrete structure, improving its overall thermal performance. Hollow structures, such as pipes or panels, can be filled with PCMs and incorporated into concrete slabs or walls (Gao et al., 2022). These structures enable the targeted placement of PCMs in areas with high thermal loads or where additional insulation is required. PCMs can be combined with conventional insulation materials, such as foams, fibers, or boards, to create hybrid insulation systems with improved thermal performance. PCMs can also be incorporated into cementitious composites, such as concrete or mortar, by direct mixing or encapsulation (Faraj et al., 2020). These composites can be used in various structural and non-structural applications, enhancing the thermal performance of the entire building envelope.

PCMs can help maintain stable indoor temperatures, reducing the need for heating and cooling systems and improving occupant comfort. By reducing temperature fluctuations and the demand for heating and cooling, PCMs can lower energy consumption and associated emissions in buildings (https://doi.org/10.3390/pr10112306., 1011). PCMs can store excess thermal energy during periods of high demand and release it when needed, helping to alleviate peak energy loads and reducing stress on electrical grids. PCMs can also provide passive temperature regulation without the need for additional mechanical systems, reducing both energy consumption and maintenance requirements. By stabilizing temperature fluctuations within a building, PCMs can reduce the effects of thermal cycling on the structure, potentially increasing its lifespan and reducing maintenance costs.

Despite the potential benefits of PCMs in concrete construction, several challenges and barriers hinder their widespread adoption. The high cost of PCMs, particularly in comparison to conventional insulation materials, can be a significant barrier to their adoption (Sukontasukkul et al., 2019). Further research and innovation are needed to develop more cost-effective PCM solutions for concrete construction. PCMs often have low thermal conductivity (Zhao et al., 2022), which can limit their effectiveness in transferring heat. The use of thermal conductivity enhancers or other innovative solutions is necessary to overcome this challenge. Ensuring compatibility between PCMs and other construction materials, such as concrete and insulation, is crucial to maintain the integrity and performance of the structure. Material compatibility issues may require additional research and development to address. The long-term performance and reliability of PCMs in concrete construction are not yet fully understood, as PCMs may degrade over time or lose their effectiveness due to repeated phase transitions. Further research and monitoring are required to evaluate the longevity of PCMs in real-world applications.

4. Challenges and barriers

Implementing sustainable concrete construction practices presents various technical, economic, and social challenges. These challenges, along with potential barriers to adoption, must be addressed to ensure the widespread integration of sustainable practices within the construction industry.

4.1. Technical challenges

Technical challenges for improved sustainability in concrete construction include:

Material performance: The use of new materials, such as supplementary cementitious materials (SCMs) and alternative binders, may result in different performance characteristics compared to traditional concrete (Yang et al., 2022). This can necessitate additional research and development, as well as adjustments to construction processes, to ensure optimal performance and durability.

New technologies: Innovative technologies, such as self-healing concrete, carbon capture, and 3D printing, require further development and testing to establish their long-term reliability, efficiency, and effectiveness (Ali, 2020).

Integration of systems: Sustainable construction practices often involve the integration of multiple systems, such as energy efficiency, renewable energy production, and water management (Wu et al., 2020). This can require complex design and engineering solutions to ensure seamless operation and maximum benefits.

4.2. Economic challenges

Economic challenges for improved sustainability in concrete construction include:

Initial costs: Sustainable concrete construction practices may involve higher initial costs due to the use of innovative materials and technologies (https://doi.org/10.1016/j.ensm.2019.10.010., 1016). This can be a barrier to adoption, particularly in cost-sensitive markets or for smaller projects with limited budgets.

Market acceptance: The construction industry can be conservative and slow to adopt new practices (Cassiani et al., 2021). Convincing stakeholders, such as developers, contractors, and clients, of the long-term benefits of sustainable concrete construction can be challenging, especially when faced with higher upfront costs.

Return on investment: Sustainable construction practices often require a longer-term perspective on return on investment (Althoey et al., 2023). Stakeholders may be hesitant to invest in sustainable practices if the financial benefits are not immediately apparent or if they perceive the risks to be too high.

4.3. Social challenges

Social challenges for improved sustainability in concrete construction include:

Awareness and education: There may be a lack of awareness or understanding of the benefits of sustainable concrete construction among industry professionals and the general public (Hossain et al., 2020). This can hinder the adoption of new practices, as stakeholders may not recognize their value or potential for long-term savings and environmental benefits.

Workforce skills: The adoption of sustainable concrete construction practices requires skilled workers who are familiar with new materials, technologies, and methods (Opoku et al., 2019). The industry may face a shortage of skilled labor, which can slow the widespread adoption of sustainable practices.

Regulatory barriers: Existing building codes, regulations, and standards may not fully support or accommodate sustainable concrete construction practices (Regona et al., 2022). This can create challenges for projects seeking to implement innovative materials and technologies, as they may face regulatory obstacles or delays.

4.4. Potential ways to overcome challenges

Potential solutions to address these challenges and barriers include:

Research and development: Continued investment in research and development can help advance the performance, reliability, and cost-effectiveness of sustainable materials and technologies, making them more attractive to the construction industry (Maraveas, 2020).

Education and training: Increasing awareness of the benefits of sustainable concrete construction among industry professionals and the public, as well as providing training and educational opportunities for the workforce, can help address skill gaps and promote the adoption of new practices (Oke et al., 2019).

Policy support *and incentives*: Governments and regulatory bodies can play a crucial role in promoting sustainable concrete construction by updating building codes and standards, providing incentives for the adoption of sustainable practices, and supporting the development of innovative materials and technologies (Pham et al., 2020).

Collaboration and knowledge sharing: Encouraging collaboration and knowledge sharing among industry stakeholders, including architects, engineers, contractors, material suppliers, and researchers, can help to address technical challenges and foster a greater understanding of the benefits of sustainable concrete construction. This can also promote the development of best practices and innovative solutions that can be widely adopted across the industry (Aghimien et al., 2019).

Demonstration projects and case studies: Showcasing successful sustainable concrete construction projects can help to overcome market acceptance challenges by providing tangible examples of the benefits and feasibility of implementing sustainable practices (Goh et al., 2020). These projects can serve as valuable learning experiences and offer insights into overcoming technical, economic, and social challenges.

Life-cycle assessment and cost analysis: Conducting comprehensive life-cycle assessments and cost analyses can help demonstrate the long-term environmental and economic benefits of sustainable concrete construction (Cebrián et al., 2020). This can support decision-making processes and encourage stakeholders to invest in sustainable practices, even if initial costs are higher.

Overcoming the challenges and barriers to implementing sustainable concrete construction practices requires a concerted effort from all stakeholders, including industry professionals, governments, researchers, and the public. By investing in research and development, promoting education and training, updating policies and regulations, encouraging collaboration and knowledge sharing, showcasing successful projects, and conducting life-cycle assessments and cost analyses, the construction industry can move towards a more sustainable future that benefits both people and the planet.

5. Strategies and policies for promoting sustainable concrete construction

Governments, industry, and academia each play a crucial role in promoting sustainable concrete construction. Collaboration among these stakeholders is essential for driving innovation and widespread adoption of sustainable practices throughout the construction industry.

5.1. Government strategies

The role of governments in promoting sustainable concrete construction is vital, as public policy, incentives, and regulations significantly influence the construction sector (Goh et al., 2020). Governments can.

- Develop and implement building codes and regulations that support sustainable concrete construction practices, such as the use of low-carbon materials, energy-efficient design, and waste reduction measures.
- Provide financial incentives, such as tax breaks, grants, or subsidies, to encourage developers, contractors, and property owners to adopt sustainable construction practices.
- Invest in research and development of sustainable concrete technologies, supporting partnerships between academia and industry to accelerate innovation.

- Facilitate the creation of public-private partnerships for sustainable construction projects, demonstrating the feasibility and benefits of sustainable practices.

5.2. Industry strategies

The construction industry plays a critical role in implementing sustainable concrete construction practices through industry standards, certifications, and voluntary initiatives (Stanitsas and Kirytopoulos, 2023). Industry stakeholders can.

- Adopt and promote industry standards and certifications that focus on sustainable construction, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Green Globes. These certifications help establish best practices, set benchmarks, and create a competitive advantage for companies that prioritize sustainability.
- Participate in voluntary initiatives and industry collaborations aimed at improving sustainability in concrete construction, such as the Global Cement and Concrete Association's Sustainability Charter, or the Concrete Sustainability Council.
- Develop and implement corporate sustainability policies and targets, including the reduction of greenhouse gas emissions, responsible sourcing of materials, and increased use of recycled and renewable resources.
- Share knowledge, best practices, and lessons learned across the industry, fostering innovation and supporting the adoption of sustainable construction practices.

5.3. Academic strategies

Academia plays a vital role in driving research, development, and innovation in sustainable concrete technologies and practices (Maraveas, 2020). Academic institutions can.

- Conduct research on sustainable materials, technologies, and construction methods, including the development of alternative binders, self-healing concrete, and carbon capture technologies.
- Collaborate with industry partners to test and validate new sustainable concrete technologies and practices, ensuring their practicality, effectiveness, and scalability for real-world applications.
- Provide education and training programs focused on sustainable construction for students and professionals, helping to bridge the knowledge and skills gap in the industry and fostering a workforce capable of implementing sustainable practices.
- Organize conferences, workshops, and seminars to facilitate knowledge sharing and networking among researchers, industry professionals, and policymakers, promoting the exchange of ideas and collaboration in sustainable concrete construction.

Governments, industry, and academia must work together to promote sustainable concrete construction practices. Governments can support these efforts through public policy, incentives, and regulations, while industry can contribute by adopting and promoting standards, certifications, and voluntary initiatives. Academia plays a critical role in driving research, development, and innovation in sustainable concrete technologies and practices. By collaborating and supporting each other's efforts, these stakeholders can accelerate the transition towards a more sustainable and environmentally responsible construction industry.

6. Future trends and opportunities

Emerging trends, technologies, and materials with the potential to improve the sustainability of concrete construction.

- Advanced digitalization and data-driven approaches: Building Information Modeling (BIM) (Li et al., 2019; Ogunmakinde et al., 2022; Göswein et al., 2020; Cordero et al., 2019), Artificial Intelligence (AI) (Sheikhkhoshkar et al., 2019; Najjar et al., 2022; Ashtiani Araghi and Vosoughifar, 2023; Xue et al., 2021), and the Internet of Things (IoT) (Yang et al., 2023; Ahmed et al., 2022; Kar et al., 2022; Amin et al., 2022) are technologies that can optimize concrete construction processes by improving resource efficiency, reducing waste, and enhancing project management. These technologies can also enable better collaboration among stakeholders and facilitate data-driven decision-making.
- Nanotechnology: The incorporation of nanomaterials, such as carbon nanotubes (Singh et al., 2021; Oke and Arowoiya, 2021; Ismail, 2022) and nano-silica (Turner et al., 2021; Zhang et al., 2023; Siahkouhi et al., 2021), can improve the mechanical properties, durability, and environmental performance of concrete, resulting in more sustainable construction materials.
- Smart concrete: The integration of sensors and smart materials into concrete structures can enable real-time monitoring of structural health, enhancing maintenance efficiency and prolonging the service life of structures (Onaizi et al., 2021; Singh et al., 2013; Dawood and Mahmood, 2021; Shahbazpanahi et al., 2021).
- Circular economy principles and 'design for disassembly': Implementing circular economy principles in concrete construction can help minimize waste, promote resource efficiency, and extend the life cycle of materials (Makul, 2020; Li et al., 2022; Ali and Kharofa, 2021). This includes designing structures for easy disassembly and recycling, encouraging the reuse and recycling of construction materials, and using waste-derived products in concrete production (Bahrami et al., 2022; Al-Hamrani et al., 2021; Shehata et al., 2022b).

Digitalization and data-driven approaches play a significant role in optimizing concrete construction processes. They facilitate better communication, collaboration, and decision-making among stakeholders, allowing for more efficient use of resources and reduced environmental impact. These technologies can also help identify potential improvements in construction methods, material selection, and project management, ultimately leading to more sustainable outcomes.

The circular economy principles and the concept of 'design for disassembly' have the potential to significantly improve the sustainability of concrete construction. By designing structures with the end-of-life phase in mind, it becomes possible to dismantle and recycle materials more efficiently, reducing waste and promoting resource conservation. Additionally, adopting a circular economy approach encourages the use of waste-derived materials and products in concrete production, further reducing the environmental impact of the construction industry.

Emerging trends, technologies, and materials, such as digitalization, data-driven approaches, nanotechnology, smart concrete, and circular economy principles, offer significant potential for improving the sustainability of concrete construction. Interdisciplinary collaboration and knowledge sharing among stakeholders are vital for driving innovation and widespread adoption of these practices. By embracing new technologies, materials, and design principles, the construction industry can work towards a more sustainable future.

7. Conclusion

This paper has explored various trends, technologies, and materials aimed at improving the sustainability of concrete construction. Key findings and insights include the potential of green concrete, using different types of supplementary cementitious materials (SCMs), permeable concrete, cool concrete, and the use of local materials. Innovative technologies and practices, such as self-healing concrete, 3D-printed concrete, photocatalytic concrete, insulated concrete forms (ICF), waste-derived fuels, and carbon capture, utilization, and storage

(CCUS), were also discussed.

The importance of embracing sustainable concrete construction practices cannot be overstated, as it directly impacts the future of the industry and the environment. With the construction sector being a significant contributor to global greenhouse gas emissions and resource consumption, transitioning to sustainable practices is essential for addressing climate change and preserving natural resources.

Recommendations for future research, policy, and industry actions to accelerate the transition to sustainable concrete construction include.

- Continued investment in research and development of sustainable materials, technologies, and practices, with a focus on interdisciplinary collaboration and knowledge sharing among academia, industry, and policymakers.
- Implementation of supportive public policies, incentives, and regulations to encourage the adoption of sustainable concrete construction practices by developers, contractors, and property owners.
- Adoption and promotion of industry standards, certifications, and voluntary initiatives related to sustainable construction, fostering best practices and creating a competitive advantage for companies that prioritize sustainability.
- Strengthening partnerships between academia and industry to facilitate the testing and validation of new sustainable concrete technologies and practices, ensuring their practicality, effectiveness, and scalability for real-world applications.
- Encouraging the development of education and training programs focused on sustainable construction for students and professionals, fostering a skilled workforce capable of implementing sustainable practices.
- Promoting the implementation of circular economy principles and 'design for disassembly' concepts in concrete construction, helping minimize waste, promote resource efficiency, and extend the life cycle of materials.
- Supporting digitalization and data-driven approaches in the construction industry, optimizing resource use, reducing waste, and enhancing project management through the application of technologies such as Building Information Modeling (BIM), Artificial Intelligence (AI), and the Internet of Things (IoT).

By acting on these recommendations, stakeholders in the construction industry can work collectively towards a more sustainable and environmentally responsible future. Embracing sustainable concrete construction practices is not only beneficial for the environment but also presents significant opportunities for economic growth, innovation, and improved quality of life.

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

No data was used for the research described in the article.

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