A Review of Sustainable Concrete Construction: Strategies, Advancements, and Future Directions

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Abstract:
The construction industry significantly impacts the environment. This review article explores various strategies and advancements in sustainable concrete construction, focusing on environmentally friendly concrete constituents, novel construction approaches, and sustainable material selection practices. The article discusses the benefits and potential of green concrete, permeable concrete, cool concrete, Ultra-High-Performance Concrete (UHPC), and the integration of local aggregates. Novel approaches like Insulated Concrete Forms (ICFs), photocatalytic concrete, 3D-printed concrete, and self-healing concrete are examined for their potential to revolutionize construction practices. Furthermore, the article explores the utilization of low-carbon concrete mixes with supplementary cementitious materials (SCMs). Challenges and considerations associated with sustainable concrete construction are also addressed, including the need for continued research, complex design considerations, economic barriers, and the importance of awareness within the industry. Finally, the article provides recommendations for future advancements, including research and development efforts, standardized practices, economic incentives, and collaborative initiatives to overcome regulatory hurdles. By implementing these recommendations, the construction industry can leverage the full potential of sustainable concrete construction for a more environmentally friendly and resilient future.

Keywords: Sustainable concrete construction, Low-carbon concrete, Supplementary cementitious materials, Life cycle assessment.

Introduction

Concrete stands as the world's second most utilized material following water, owing to its adaptability and enduring qualities, facilitating the construction of enduring edifices (Monteiro, Miller, & Horvath, 2017). Global cement output in 2021 surged to an impressive 4.1 billion tons (Statista, 2023), equating to approximately 28.7 billion tons of concrete annually. Nonetheless, this widespread application exacts an environmental toll. Portland cement, fundamental to concrete, emerges as a substantial contributor to the environmental impact (EI) of the construction sector, potentially accounting for 7-8% of global CO₂ emissions (Lehne & Preston, 2018).
A noteworthy instance of this movement is Sweden's concrete industry "Roadmap for Climate Neutral Concrete" initiated in 2018 (Mörk, 2021). This roadmap, formulated by The Concrete Initiative, delineates ambitious targets for attaining climate neutrality. These include a 50% reduction in the carbon footprint of housebuilding concrete by 2023 (relative to 1990) and complete climate neutrality across the entire Swedish industry by 2045. This initiative dovetails with Sweden's broader aspiration of achieving net-zero emissions in construction and civil engineering by 2045 (Karlsson et al., 2020). The exigency to combat climate change, resource exhaustion, and waste generation necessitates a robust emphasis on sustainable construction practices. A pivotal facet of this metamorphosis is the advancement and deployment of environmentally sound concrete substitutes and sustainable construction materials (Duxson, Provis, Lukey, & van Deventer, 2007).

This paper delves into diverse environmentally friendly alternatives and sustainable construction materials that harbor immense potential to substantially diminish the environmental footprint of concrete production and usage.

Environmentally friendly concrete constituents

Green Concrete (GC)

The concept of GC has become synonymous with environmentally conscious advancements in concrete technology (Sivakrishna, Adesina, Awoyera, & Rajesh Kumar, 2020). This overarching term encompasses a range of eco-friendly materials and methods aimed at mitigating the EI of concrete production and construction. Several strategies contribute to this goal, such as utilizing recycled aggregates, industrial byproducts, and alternative cementitious materials (binders). These approaches collectively target a reduction in the use of virgin resources and a decrease in carbon dioxide emissions. Green concrete is also known as "ecological concrete" (Kothari, Habermehl-Cwirzen, Hedlund, & Cwirzen, 2020) or "climate-improved concrete" (Hofgård & Sundkvist, 2020).

Permeable Concrete

Porous concrete, referred to as pervious concrete (Elizondo-Martínez, Andrés-Valeri, Jato-Espino, & Rodriguez-Hernandez, 2020; Li, Feng, Zhu, Chu, & Kwan, 2021), represents an innovative and environmentally favorable construction material. This technology achieves high porosity through a unique mix design featuring minimal fine particles and increased coarse aggregate content (Xie, Akin, & Shi, 2019). The resulting interconnected void network enables water to permeate the concrete structure, facilitating natural drainage and decreasing surface runoff.

Permeable concrete provides numerous advantages for stormwater management. By promoting water infiltration into the ground (Kuruppu, Rahman, & Rahman, 2019), it mitigates the risks associated with flooding, erosion, and water pollution. This natural drainage process also replenishes groundwater stores and alleviates stress on stormwater systems. Additionally, the porous structure acts as a natural filter, capturing pollutants before they reach water bodies (Kuruppu et al., 2019). Moreover, permeable pavements help mitigate the urban heat island effect by encouraging evaporative cooling and reducing heat absorption by paved surfaces (Chen et al., 2019). The inherent porosity also enhances safety for pedestrians and vehicles during wet weather by minimizing water accumulation and improving skid resistance.

Cool Concrete

Cool concrete also referred to as high-albedo (Sanjuán, Morales, & Zaragoza, 2022) or reflective concrete (Qin et al., 2019), represents an innovative approach in urban construction aimed at mitigating the urban heat island (UHI) effect. This technology incorporates highly reflective materials directly into concrete mixes or applies specialized surface coatings to achieve its thermal benefits (Anupam, Sahoo, Chandrappa, & Rath, 2021). Addressing the UHI effect through cool concrete offers
numerous advantages for creating more sustainable and comfortable urban environments. This technology effectively moderates the temperature of paved surfaces (Anupam et al., 2021; Sanjuán et al., 2022), resulting in cooler outdoor spaces, improved air quality due to reduced heat-related pollutant formation, and less thermal stress on urban ecosystems.

**Ultra-High-Performance Concrete (UHPC)**

UHPC represents a significant advancement in sustainable construction materials, offering substantial advantages over conventional concrete (Azmee & Shafiq, 2018). This meticulously engineered cementitious composite, reinforced with fibers, exhibits exceptional mechanical properties, particularly high strength, and outstanding durability (Hisseine, Soliman, Tolnai, & Tagnit-Hamou, 2020). These attributes render UHPC appealing for applications requiring superior performance and sustainability, such as bridges, buildings, and infrastructure projects. A notable benefit of UHPC lies in its remarkable strength and durability, resulting in a noteworthy reduction in material usage for specific projects (Meng, Valipour, & Khayat, 2016). By requiring less material, UHPC contributes to a decreased EI associated with concrete construction. This advantage is achieved through reduced energy and resource consumption during production, transportation, and installation (Meng et al., 2016).

**Integration of local aggregates in concrete production**

Incorporating local materials into concrete construction is a core principle of sustainable development (Adesina, 2020; Muteb & Hasan, 2020). This approach offers numerous environmental and economic advantages. By integrating locally accessible resources into concrete formulations, construction projects can achieve enhanced sustainability without compromising performance or durability. A variety of local materials offer advantages. Commonly used are natural aggregates sourced from nearby quarries to minimize emissions and energy consumption related to transportation (Muteb & Hasan, 2020). Recycled aggregates from construction and demolition waste can be employed, supporting resource conservation and waste reduction (Muteb & Hasan, 2020). These materials can be incorporated into new concrete mixes, reducing the necessity for virgin aggregate extraction. Some areas also have natural pozzolans (Tayeh, Hamada, Almeshal, & Bakar, 2022) that function as SCMs.

**Novel approaches to sustainable concrete manufacturing**

**Self-Healing Concrete**

Self-healing concrete signifies a transformative progression in construction technology with the capability to redefine the durability, performance, and sustainability of concrete structures. This pioneering material exhibits the capacity to autonomously mend cracks and damage, effectively "healing" itself. This capability extends the service life of structures significantly and diminishes the necessity for external maintenance and repairs, ultimately fostering a more sustainable built environment. The concept of self-healing concrete can be further classified into two primary mechanisms.

**Autogenous Healing**

Autogenous healing is an innate process observed in cementitious materials like concrete, where cracks can partially or completely close over time. This phenomenon plays an important role in restoring the material's original durability and mechanical strength. The impressive longevity of certain ancient concrete structures is attributed in part to autogenous healing within these cement-based composites (Ghosh, 2009). Over the past century, extensive research efforts, encompassing both theoretical and experimental studies, have been devoted to elucidating this phenomenon (De Rooij, Van Tittelboom, De Belie, & Schlangen, 2013). These investigations have revealed that autogenous healing results from a complex interplay of physical, mechanical, and chemical mechanisms within the concrete matrix (De Rooij et al., 2013). Figure 1 (insert a brief description of the figure) illustrates the mechanisms believed to contribute
to autogenous healing upon crack formation and exposure to water.

![Figure 1 Main Mechanisms Producing Autogenous Self-Healing of Cementitious Materials](image)

**Figure 1 Main Mechanisms Producing Autogenous Self-Healing of Cementitious Materials**

**Source:** De Rooij et al., 2013

**Stimulated Autogenous Healing (Nonencapsulated)**

Our comprehension of autogenous healing suggests that narrower cracks exhibit more effective healing. The presence of readily available water within the concrete matrix is also essential for this process. Moreover, stimulating continuous hydration or crystallization reactions within the cementitious matrix can enhance autogenous healing further. Approaches aimed at achieving these objectives, such as reducing crack width, ensuring water availability, or promoting hydration/crystallization reactions, can be categorized as methods for stimulated or enhanced autogenous healing.

**3D Printing: A Transformative Technology for Construction**

3D-printed concrete, also referred to as additive manufacturing or digital fabrication, has emerged as a transformative technology poised to revolutionize the construction industry (Tenório Filho et al., 2021). This innovative method employs computer-controlled robotic systems to construct structures layer-by-layer according to digital models. 3D-printed concrete presents an innovative technology poised to transform the construction industry through enhanced efficiency, expanded design capabilities, and improved sustainability. Nonetheless, overcoming technological hurdles, establishing fresh standards, and preparing the workforce are imperative steps for its widespread integration and acceptance.

**Photocatalytic Concrete: A Breath of Fresh Air for Urban Environments**

Photocatalytic concrete is an advanced construction technology that involves incorporating photocatalytic materials such as titanium dioxide (TiO$_2$) into the concrete mix or applying them as surface treatments (Y. Chen, Zhang, Xie, Zhang, & Banthia, 2022). Upon exposure to sunlight or ultraviolet (UV) radiation, these materials initiate chemical reactions that generate reactive oxygen species (ROS). These ROS can break down various air pollutants, including nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM). This inherent self-cleaning and air-purifying characteristic of photocatalytic concrete contributes to the enhancement of air quality in urban environments. Photocatalytic concrete represents a promising technology for achieving cleaner urban environments through the active reduction of air pollutants and promotion of self-cleaning capabilities. Nonetheless, overcoming challenges associated with cost, reliance on light, material optimization, and potential environmental impacts is essential to facilitate its widespread adoption.

**Insulated Concrete Forms (ICFs): A Path Towards Sustainable and Resilient Buildings**

ICFs are a pioneering technology in concrete construction that employs lightweight, interlocking foam forms to establish a continuous insulation layer for cast-in-place concrete walls (citations can be provided). These foam forms are retained in position post-curing of the concrete, yielding a building envelope characterized by high energy efficiency and durability. The myriad benefits associated with ICFs have driven their widespread adoption in residential and commercial construction projects, offering a compelling alternative to conventional methods.
ICFs offer substantial potential as a forefront technology for sustainable and resilient building design within concrete construction. Progress in material science, manufacturing methods, and construction techniques can augment the effectiveness, cost-efficiency, and adaptability of ICF systems.

Materials for sustainable concrete mixtures

Fly Ash: A Sustainable and Functional Material for Concrete

Fly ash (FA) has developed as a critical material in civil engineering due to its economic and environmental advantages. The effectiveness of FA as a partial replacement for Portland cement depends on the inherent free lime content within the fly ash itself (Matković et al., 1990). Beyond this chemical characteristic, factors such as the ash’s phase composition, glassy content, burning temperature, and specific surface area (SSA) all significantly influence its reactivity (Matković et al., 1990). Standardized by ASTM, two main classes of fly ash exist for concrete applications: Class F and C. Class F, derived from the combustion of bituminous coal, is high in iron, silica, and alumina but remains low in calcium. This glassy material requires activation by either cement or lime to achieve its cementitious potential. Conversely, Class C FA, originating from sub-bituminous coal and lignite combustion, possesses a higher calcium content compared to Class F. Concrete containing Class C FA exhibits faster strength development than its Class F counterpart (McCarthy & Dyer, 2019).

Ground Granulated Blast-Furnace Slag (GGBS): A Sustainable and Functional Material for Concrete

GGBS is a significant byproduct generated during high-temperature steel and iron production (approximately 1500°C) (Sharma & Sivapullaiah, 2016). Blast furnaces process a carefully controlled mixture of limestone, iron ore, and coke, resulting in molten iron and slag. Rapid quenching with water jets transforms the molten slag into GGBS, a fine, glassy material with advantageous properties (Aydın & Baradan, 2014). Despite a global production of roughly 530 million tonnes, only around 65% of GGBS is utilized in construction (Sharma & Sivapullaiah, 2016). Primarily composed of calcium silicates and aluminosilicates, GGBS is routinely removed from blast furnaces during iron production (Aydın & Baradan, 2014). This high content of amorphous calcium, silica, and alumina makes it an ideal binder in cement concrete production (Aydın & Baradan, 2014).

Advantages of GGBS in Construction:

- **Sustainable Byproduct:** GGBS offers a sustainable solution by utilizing a waste product from steel production as a cementitious material in concrete. This reduces the demand for virgin raw materials and promotes environmental responsibility.

- **Enhanced Concrete Performance:** GGBS acts as a binding agent, improving concrete strength and reducing its permeability by filling voids between aggregate particles (Wang & Lee, 2010).

- **Reduced Greenhouse Gas Emissions:** Replacing Ordinary Portland Cement (OPC) with GGBS in concrete production lowers energy consumption and greenhouse gas emissions associated with cement manufacturing (Naik Tarun, 2008).

- **Comparable Strength and Durability:** GGBS offers strength and durability characteristics comparable to traditional cement, making it a viable alternative with environmental benefits.

- **Potential for Geopolymer Concrete:** Researchers are exploring GGBS-based geopolymer concrete as a promising alternative binding material for even more sustainable concrete production (Sumajouw, Hardjito, Wallah, & Rangan, 2007).

Optimizing GGBS Use in Concrete

While studies have shown that GGBS particle size variations have minimal impact on its chemical composition or shape, these variations do significantly influence water requirements during concrete mixing (Zhang, Yu, Wei, Zhang,
& Li, 2011). Optimizing the water content is crucial for achieving desired concrete properties.

**High-Performance Concrete Applications**

- **Ground Nano-Slag (NS):** Studies on High-Strength Concrete (HSC) incorporating finely ground nano-slag (NS) revealed excellent strength and durability properties when the replacement ratio reached 10% (Sharmila & Dhinakaran, 2016). Lower NS content resulted in uneven distribution and insufficient improvement, while a high NS proportion hindered performance due to excess ultrafine particles.

- **Ultra-Fine Slag (UFS):** Experimental evaluation demonstrated that Ultra-Fine Slag (UFS)-incorporated concrete exhibited higher early compressive strength, lower permeability, and enhanced durability compared to conventional concrete after three days of curing (Teng, Lim, & Sabet Divsholi, 2013).

In conclusion, GGBS presents a valuable and sustainable material for concrete production. Its cementitious properties, combined with its role in reducing environmental impact, make it a promising alternative to traditional binders. Ongoing research on optimizing particle size and exploring applications in high-performance concretes like HSC and UFS paves the way for even greater utilization of GGBS in sustainable construction practices.

**Silica Fume: Enhancing Concrete Performance with Exceptional Fineness**

Silica fume (SF), also known by various terms like micro silica, condensed silica fume, or volatilized silica, is a byproduct generated during the production of silicon and ferrosilicon alloys (Aïtcin, 1998). This material appears as a fine, vitreous powder, either white or grey, and consists of exceptionally small glassy particles (Aïtcin, 1998). The remarkable characteristic of silica fume lies in its immense surface area, ranging from 13,000 to 30,000 m²/kg. This translates to particles roughly 100 times smaller than the average cement particle (Aïtcin, 1998). This extreme fineness, combined with its high silica content, equips silica fume with highly effective pozzolanic properties.

In the realm of concrete applications, silica fume plays a crucial role in enhancing various performance aspects. Additionally, it reduces the overall permeability of concrete, offering superior protection for embedded reinforcing steel against corrosion (Aïtcin, 1998).

**Challenges and Considerations for Widespread Adoption of Sustainable Concrete Construction**

Despite the promise of sustainable concrete construction for the future, several key hurdles and considerations must be addressed to achieve mainstream adoption:

- **Performance of Novel Materials:** Introducing novel materials can result in concrete exhibiting unique performance characteristics in comparison to conventional concrete. (Yang et al., 2022).

- **Long-Term Evaluation Necessary:** Sophisticated technologies require continuous improvement and thorough evaluation to determine their durability, efficiency, and effectiveness in real-world construction applications (Ali, 2020).

- **Cost Considerations:** Sustainable construction practices may involve increased upfront expenses because of the use of innovative materials and technologies. This can pose a significant obstacle, especially in markets emphasizing cost efficiency or for smaller projects with limited budgets.

**Conclusion**

Sustainable concrete construction presents a multifaceted approach for minimizing the environmental impact of the construction industry while promoting resource efficiency and durability of structures. This review article has explored various strategies and advancements across concrete constituents, manufacturing processes, and material selection. The incorporation of environmentally friendly concrete constituents, including green concrete, permeable concrete, and cool concrete, offers
solutions for reducing embodied energy and mitigating the urban heat island effect. Additionally, novel approaches like 3D-printed concrete and self-healing concrete have the potential to revolutionize construction practices, promoting efficiency and potentially reducing waste. Furthermore, the integration of local aggregates and the utilization of low-carbon concrete mixes with SCMs can significantly decrease the environmental footprint of concrete production.

However, challenges and considerations remain that require further attention. The performance characteristics of new materials and technologies necessitate continuous research and development to ensure optimal performance and long-term durability. Integrating sustainable practices often demands complex design solutions to ensure the seamless operation of various systems. Additionally, overcoming economic barriers of higher initial costs, promoting awareness within the industry, and addressing potential regulatory hurdles are crucial for widespread adoption.

**Recommendations**

By addressing these recommendations, the construction industry can leverage the full potential of sustainable concrete and contribute significantly towards a more environmentally responsible and resilient built environment.

1. Continued research and development efforts focused on optimizing the performance and long-term durability of environmentally friendly concrete constituents and novel construction technologies.

2. Development of comprehensive design guidelines and standardized practices for integrating sustainable concrete construction methods into various project types.

3. Establishment of economic incentives and policy frameworks to encourage the adoption of sustainable concrete construction practices.

4. Increased educational programs and knowledge-sharing initiatives to raise awareness of the benefits and long-term value proposition of sustainable concrete construction among industry professionals and the general public.

5. Active collaboration between researchers, construction stakeholders, and policymakers to address potential regulatory hurdles and ensure the smooth integration of sustainable solutions into building codes and standards.

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Consent to Publish
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Reference


