**Intelligent Materials and Innovations for Eco-Friendly Concrete Construction**

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**Abstract:** This article provides an all-encompassing analysis of prevailing patterns and prospects within the realm of eco-conscious concrete construction. The focal point is on the imperative adoption of environmentally friendly methodologies to curtail the ecological repercussions associated with the construction industry. The exploration delves into sustainable materials and technologies like green concrete, supplementary cementitious materials, permeable concrete, cool concrete, and the utilization of locally sourced materials. Additionally, it probes into pioneering innovations such as self-repairing concrete, 3D-printed concrete, photocatalytic concrete, electrified machinery, and the principles of carbon capture, utilization, and storage, underscoring their potential in enhancing the sustainability of construction processes. The study also addresses the obstacles that arise in the execution of sustainable concrete construction practices, including technical, economic, and societal hindrances. It scrutinizes the roles played by governments, industry stakeholders, and academia in propelling sustainable concrete construction, underscoring the imperative for cross-disciplinary cooperation and dedicated research efforts. Lastly, the discourse identifies burgeoning trends and technologies, including digitalization, data-informed methodologies, and principles of circular economy, as pivotal agents in steering the trajectory toward sustainable concrete construction.

**Keywords:** Concrete construction, Sustainability, Smart materials, Green concrete, Permeable concrete, Self-healing concrete, Photocatalytic concrete, Phase change materials, Strategic management

**Introduction**

The history of concrete spans millennia, showcasing humanity's ingenuity and adaptability in shaping the built environment. Beginning with rudimentary mixtures used by ancient Egyptians and refined by Greeks and Romans, concrete evolved into a transformative technology during the Roman era, enabling colossal structures like the Colosseum and the Pantheon. The Dark Ages and Renaissance saw a resurgence of interest in classical architecture, which led to renewed experimentation. The Industrial Revolution brought about the invention of cement, paving the way for modern concrete, while the 20th century witnessed the rise of high-strength concrete and innovative techniques like pre-stressed concrete. Today, concrete continues to advance, addressing sustainability and aesthetic concerns, thus ensuring its enduring role in constructing the architectural marvels of the future.

Concrete is a versatile and durable construction material that has been used for centuries. It is the second most consumed substance in the world, after water. Concrete is made from cement, water, aggregates (such as sand and gravel), and admixtures (such as fly ash and slag).The production of cement is a major source of carbon dioxide emissions. The cement industry accounts for about 7-8% of global CO2 emissions. This is because the production of cement requires a lot of energy and heat.

The use of concrete also contributes to the depletion of natural resources, such as aggregates and water. Aggregates are mined from quarries, which can have a negative impact on the environment. Water is also a limited resource, and its use in concrete production can contribute to water scarcity.Despite its environmental impact, concrete can be a sustainable material. There are a number of ways to reduce the environmental impact of concrete production and use.

These include:

* Using low-carbon cements, such as blended cements and geopolymers.
* Using recycled materials, such as fly ash and slag.
* Reducing the amount of water used in concrete production.
* Designing concrete structures to be more energy-efficient.

The construction industry is committed to reducing the environmental impact of concrete. There is a growing trend towards the use of sustainable concrete, and the industry is developing new technologies to make concrete production more environmentally friendly.

The swift pace of urbanization and the expanding global population are driving the need for increased infrastructure and housing, intensifying the ecological repercussions of the construction sector. In the face of persistent challenges posed by climate change and limited resources, there arises a pressing imperative for the development of more environmentally sound approaches within concrete construction.

Addressing these challenges, the construction sector is actively exploring and integrating more sustainable methods and materials into concrete construction practices. This transition aims to mitigate the environmental impact of concrete production, extend the lifespan of structures, and minimize resource usage. Collaboration among researchers, industry experts, and policymakers is driving the development and promotion of inventive technologies, materials, and strategies that can significantly decrease carbon emissions, energy consumption, and waste generation associated with concrete construction. An instance of this effort is the introduction of a climate-neutral concrete roadmap in 2018 by the Swedish concrete industry through The Concrete Initiative—a network encompassing stakeholders across the concrete production and construction spectrum. Notable goals include achieving a 50% reduction in concrete's climate impact for housing construction by 2023 (compared to 1990 levels), introducing climate-neutral concrete to the Swedish market by 2030, and attaining overall climate neutrality in the concrete industry by 2045. Similarly, a parallel roadmap within the Swedish construction and civil engineering sector outlines objectives of reducing greenhouse gas emissions by 50% by 2030 (relative to 2015 levels) and achieving net-zero greenhouse gas emissions by 2045.

The significance of sustainability within concrete construction has been underscored by international pacts like the Paris Agreement and the United Nations' Sustainable Development Goals (SDGs). These agreements demand urgent actions to mitigate climate change and advance sustainable development.

In light of escalating apprehensions about climate change, dwindling resources, and waste accumulation, there has been a surge in the establishment of ecologically conscious methodologies. A pivotal facet of this transition involves incorporating sustainable components into concrete construction. Consequently, an array of inventive materials and technologies has emerged, all with the goal of diminishing the environmental impact of concrete construction, amplifying its resilience and efficacy, and ultimately augmenting the sustainability of the constructed landscape.

**Green concrete** refers to a spectrum of concrete mixtures that integrate recycled materials, waste by-products, and environmentally conscious elements. The intention behind these mixtures is to curtail the consumption of natural resources, decrease carbon emissions linked to cement production, and mitigate the environmental consequences of concrete construction. Instances of components utilized in green concrete include recycled aggregates, supplementary cementitious materials, and industrial residues like fly ash and slag. Another approach promoting sustainability involves the utilization of locally sourced materials, resulting in notable reductions in transportation-related emissions and energy consumption. Additionally, local materials frequently possess distinct characteristics that can bolster the strength and longevity of concrete structures. Illustrative examples encompass limestone calcined clay cement, which functions as a partial substitute for conventional cement, and the incorporation of natural fibers or aggregates, facilitating the development of more sustainable and cost-efficient concrete blends.

**Permeable concrete** is a specialized form of concrete engineered to facilitate the passage of water through its structure, effectively diminishing storm water runoff and promoting the replenishment of groundwater. This inventive material assumes a pivotal role in advancing sustainable urban development, offering solutions for mitigating urban heat island impacts, lowering flood risks, and enhancing water quality. Beyond its environmental merits, permeable concrete presents potential advantages such as reduced construction expenses and maintenance needs, potentially obviating conventional storm water management systems like gutters, drains, and retention ponds. Another eco-conscious material, cool concrete, is devised to curtail the environmental imprint of concrete construction. This variant incorporates reflective or light-toned constituents that aid in mitigating heat absorption and consequently lowering the surface temperature of concrete structures. This cooling attribute can effectively counteract urban heat island effects and contribute to curbing energy consumption for cooling buildings. Moreover, the implementation of cool concrete has the added advantage of augmenting the durability of concrete structures by mitigating thermal stress and resultant cracking stemming from temperature fluctuations.

**Ultra High Performance Concrete (UHPC)** is a meticulously engineered cementitious blend renowned for its remarkable mechanical attributes, elevated strength, improved fire resistance, and enduring durability. UHPC's exceptional performance not only allows for optimized material usage in projects, thereby lessening the ecological impact of concrete construction, but also brings about prolonged sustainability. The heightened durability inherent to UHPC contributes to an elongated lifespan for concrete structures, subsequently curbing the necessity for maintenance, repairs, and replacements. This material's potential benefits extend to enhanced energy efficiency and thermal qualities in buildings, stemming from its formidable strength and minimal permeability.

In conjunction with eco-friendly materials, the concrete construction sector has embarked on a quest for ground breaking technologies and methodologies to amplify the sustainability, functionality, and efficacy of structures. The assimilation of these emerging practices is pivotal in the industry's ongoing endeavours to curtail its ecological impact and bolster the resilience of constructed environments. A notable innovation is self-healing concrete, infused with substances or agents enabling autonomous repair upon damage. This advancement extends structural lifespan, diminishes upkeep demands, and curbs the requirement for resource-intensive repairs. Employing additive manufacturing techniques, 3D-printed concrete fabricates intricate structural elements with precision and efficiency, resulting in decreased material consumption and waste generation. It also facilitates the creation of intricate geometries that would prove formidable to achieve using conventional methods. Photocatalytic concrete introduces photocatalytic components that disintegrate pollutants and organic compounds on the concrete surface upon exposure to sunlight, enhancing air quality and fostering a cleaner milieu. By uniting the structural prowess of reinforced concrete with the energy efficiency of high-performance insulation materials, insulated concrete forms yield energy savings and elevated thermal comfort within buildings. The incorporation of waste-derived fuels like biomass or industrial refuse in cement production stands as a potential alternative to traditional fossil fuels, thereby reducing greenhouse gas emissions and the overall carbon footprint of concrete construction.

**2 Sustainable materials in concrete construction**

**2.1 Green concrete**

The term "green concrete" has become increasingly prominent in recent times, indicating environmentally enhanced materials utilized in concrete construction. This concept revolves around employing eco-friendly components and processes to diminish the environmental impact of concrete manufacturing and building activities. The production of green concrete entails diverse approaches, encompassing the utilization of recycled aggregates, industrial by-products, and alternative binders. These methods collectively contribute to a reduced carbon footprint and a more restrained consumption of natural resources. This type of concrete is alternatively known as ecological concrete or climate-improved concrete. It also encompasses practices like incorporating Supplementary Cementitious Materials (SCM), employing Geopolymer concrete, or utilizing Alkali-activated concrete.

**2.2 Permeable concrete**

Permeable concrete, alternatively referred to as pervious concrete, signifies an inventive technology and methodology in concrete construction that facilitates the passage of water through its structure. This approach advocates for natural drainage and concurrently curbs surface runoff. This concrete variant is distinguished by its heightened porosity, achieved through a minimal incorporation of fine aggregates or sand in the mixture, coupled with an increased proportion of coarse aggregates. The outcome yields interconnected voids within the concrete, enabling the unhindered flow of water. As a result, permeable concrete emerges as an ecologically conscientious choice for a range of construction applications.

Permeable concrete, exemplified by its ability to enable water infiltration through pavements and into the soil, plays a pivotal role in managing stormwater runoff. This characteristic aids in diminishing the potential for flooding, erosion, and water contamination. Additionally, this natural drainage mechanism contributes to replenishing groundwater reserves and lessening the necessity for extensive stormwater infrastructure. The permeable nature of such pavements also fosters the filtration of water, effectively sieving out pollutants like oil, heavy metals, and sediments. This action prevents their entry into water bodies and the subsequent exacerbation of water pollution.

The permeable concrete's porous composition serves as a mitigating factor against the urban heat island phenomenon. This is achieved by fostering evaporative cooling and diminishing the extent of heat absorption by paved surfaces. Furthermore, the porosity of permeable concrete aids in the prevention of water accumulation on its surface, thus reducing the likelihood of hydroplaning. Additionally, this characteristic enhances skid resistance, thereby enhancing safety for pedestrians and vehicles in wet weather conditions.

Permeable concrete demands notably less upkeep in contrast to conventional non-porous pavements, primarily due to its elimination of stormwater drainage systems like curbs, gutters, and storm drains. Consequently, property owners and municipalities can potentially enjoy diminished maintenance expenses and lowered long-term costs. Typically, routine cleaning activities such as vacuum sweeping or pressure washing are sufficient to uphold the infiltration capacity of permeable concrete pavements.

Not with standing its benefits, permeable concrete also presents challenges and limitations. Its heightened porosity and comparatively reduced strength when compared to conventional concrete render it less suitable for applications involving heavy loads or areas with substantial traffic flow. Nevertheless, it emerges as an optimal choice for low-traffic regions like parking lots, sidewalks, residential streets, and other areas with minimal stress. As time passes, sediment, debris, or organic matter can accumulate within the voids of permeable concrete, thus decreasing its infiltration capacity (Singh et al., 2020). To counteract this, consistent maintenance, including vacuum sweeping or pressure washing, is imperative to sustain the concrete's permeability and ensure enduring performance. In certain instances, the integration of geotextiles or filter layers beneath the permeable concrete can serve to deter clogging and preserve infiltration capacity.

In areas subjected to freeze-thaw cycles, the efficiency of permeable concrete can be influenced by the expansion and contraction of water within its interconnected voids. This dynamic can precipitate a decline in strength, durability, and overall performance. Nevertheless, meticulous mix design and the incorporation of air-entraining admixtures can ameliorate freeze-thaw resilience and prolong the operational life of permeable concrete structures. The installation expenses for permeable concrete might surpass those of conventional impermeable pavements due to the specialized mix formulation and installation techniques necessitated. However, this initial investment could potentially be balanced out by the diminished requirement for stormwater infrastructure and long-term maintenance cost savings.

**2.3 Cool concrete**

Cool concrete, also known as high-albedo or reflective concrete, represents a progressive technological and methodological approach in concrete construction. It endeavors to counteract the urban heat island (UHI) effect by integrating materials with elevated solar reflectance either within the concrete mixture or through surface coatings. Such concrete is characterized by its ability to redirect a greater proportion of solar radiation back into the atmosphere, resulting in a notably cooler surface temperature when compared to conventional concrete. In addressing the UHI effect, cool concrete makes valuable contributions toward fostering sustainable and comfortable urban surroundings, while concurrently aiding in the reduction of energy consumption related to building cooling requirements.

Cool concrete effectively counteracts the urban heat island (UHI) effect through its capacity to diminish the temperature of paved areas like sidewalks, parking lots, and roadways. This outcome yields more pleasant outdoor environments, enhanced air quality, and decreased thermal strain on urban ecosystems. By curtailing the heat absorption of paved surfaces, cool concrete substantially contributes to reducing cooling requirements for adjacent buildings, thereby generating energy savings and diminishing greenhouse gas emissions. The decreased surface temperatures attributed to cool concrete have the added benefit of extending pavement longevity by minimizing thermal stress and temperature-induced damages such as cracking or expansion. The cooler surface of pavements also plays a role in reducing the temperature of stormwater runoff, thus safeguarding aquatic ecosystems against thermal pollution and ameliorating the overall quality of urban water bodies.

However promising, cool concrete does encounter challenges and constraints. Integrating high-albedo materials or specific coatings in cool concrete might incur higher initial expenses in comparison to traditional concrete. Yet, the long-term gains of diminished energy consumption, heightened durability, and amplified environmental efficiency could potentially counterbalance these initial outlays. Over time, the surface of cool concrete can accumulate dirt, dust, and other pollutants, thereby diminishing its solar reflectance and subsequently its cooling efficacy. To uphold the high-albedo characteristics and ensure the continued performance of cool concrete, consistent cleaning and maintenance practices become essential.

However promising, the selection of materials with elevated solar reflectance can face constraints, as certain high-albedo substances might not deliver equivalent strength or durability as conventional concrete components. Additional exploration and advancement are necessary to pinpoint and develop appropriate high-albedo materials capable of satisfying the dual requirements of performance and sustainability in cool concrete applications. It's worth noting that cool concrete surfaces might exhibit a lighter color or divergent appearance in comparison to traditional concrete, which may not harmonize with all architectural aesthetics or urban surroundings. Consequently, incorporating cool concrete into specific projects necessitates an extra layer of consideration, factoring in aesthetic preferences and compatibility with design elements.

Cool concrete is anticipated to gain rising significance as a technology and methodology within concrete construction, ushering in fresh prospects for attenuating the urban heat island effect and fostering sustainable urban progress. By confronting the obstacles and constraints associated with cool concrete – encompassing aspects like initial expenditure, upkeep, material assortment, and aesthetic reflections – the construction sector can harness the complete potential of this inventive substance. Thereby, it can play a pivotal role in engendering more sustainable and agreeable urban surroundings.

**2.4 Ultra-high-performance concrete (UHPC)**

Ultra High Performance Concrete (UHPC) has surfaced as a compelling and eco-friendly option in concrete construction, boasting considerable advantages vis-à-vis conventional concrete. UHPC stands as a meticulously crafted, fiber-reinforced cementitious amalgam distinguished by its extraordinary mechanical attributes, heightened strength, and robust longevity. Such characteristics render UHPC a captivating material for a diverse array of construction applications. Be it bridges, buildings, or infrastructure undertakings, UHPC's capabilities prove particularly enticing where augmented performance and sustainability are the desired outcomes.

A standout advantage of UHPC lies in its exceptional strength and durability, a trait that can result in reduced material requirements for a given project (Meng et al., 2017). This reduction in material consumption offers a twofold benefit. Firstly, it contributes to a diminished overall environmental impact of concrete construction, as the demand for energy and resources in production, transportation, and installation is curtailed. Secondly, the heightened durability of UHPC contributes to prolonged service lifespans for concrete structures, thereby reducing the need for maintenance, repairs, and eventual replacements. This ripple effect contributes to a decrease in the consumption of raw materials, energy, and emissions linked to concrete construction in the long run.

Another notable advantage of UHPC rests in its potential to enhance the energy efficiency and thermal performance of buildings, alongside bolstering fire safety measures. Owing to its formidable strength and minimal permeability, UHPC can serve as an efficient insulator for buildings, effectively mitigating heat transfer and thereby diminishing energy consumption for heating and cooling systems. This in turn contributes to a reduction in the greenhouse gas emissions associated with building operations, thus aiding in the global fight against climate change. Moreover, UHPC's low permeability augments the resilience of concrete structures against environmental wear and tear, such as freeze-thaw cycles and chloride intrusion, subsequently enhancing their longevity while concurrently reducing the demand for maintenance.

UHPC's versatility and adaptability are integral to its role as a promising sustainable construction material. Its composition can be finely tuned to align with distinct applications and performance prerequisites, thereby facilitating the formulation of inventive and eco-friendly construction resolutions. UHPC seamlessly integrates with other materials, such as recycled aggregates, supplementary cementitious substances, and natural fibers, to generate hybrid materials that exhibit enriched characteristics and decreased ecological footprints. This adaptability underpins the creation of innovative, sustainable concrete solutions capable of satisfying the evolving needs of the construction sector.

While UHPC boasts numerous advantages, several obstacles and barriers necessitate overcoming to unlock its full potential as a sustainable construction material. Foremost among these challenges is the substantial cost of UHPC, particularly in comparison to traditional concrete, which poses a notable impediment to its extensive integration. This elevated cost is predominantly attributed to UHPC's intricate composition, encompassing specialized fibers, admixtures, and fine aggregates.

**2.5 Use of local materials**

Incorporating indigenous materials into concrete construction is a pivotal facet of sustainable progress, as it effectively diminishes environmental repercussions, curtails transportation expenses, and bolsters the local economy. The integration of locally accessible materials within concrete formulations presents an avenue to amplify the sustainability of construction endeavors, all while adhering to the stipulated performance and durability benchmarks. Various local material alternatives can be employed in concrete construction, encompassing natural aggregates, recycled aggregates, natural pozzolans, locally sourced fibers, and indigenous binders.

Aggregates form a fundamental component of concrete production. Acquiring these materials from nearby quarries and deposits yields a reduction in emissions from transportation and curtails energy consumption. By opting for locally accessible aggregates, the resulting concrete mix can be better aligned with the prevalent environmental conditions, encompassing factors like freeze-thaw cycles, salt exposure, or soil attributes. Incorporating recycled aggregates, such as crushed concrete, brick, or glass, serves to champion resource conservation and curtail waste. These recycled materials can be procured from local sources of construction and demolition waste, thereby repurposing them within fresh concrete blends, and ultimately curbing the demand for excessive aggregate extraction.

Certain regions possess inherent pozzolanic materials like volcanic ash or calcined clays, which can function as supplementary cementitious materials. These indigenous resources can substitute a portion of Portland cement in concrete compositions, thereby curtailing the environmental consequences and resource depletion linked to cement manufacturing. The utilization of locally procurable fibers, be they natural (such as sisal, coir, or jute) or derived from local industries (like steel fibers sourced from industrial waste), can heighten concrete performance and advance sustainability. These fibers can be integrated into concrete mixtures to fortify tensile strength, bolster crack resistance, enhance durability, and concurrently minimize dependence on synthetic fibers or imported inputs. In some geographic locales, alternative binders that either partially or entirely replace Portland cement might be accessible. Illustrative instances encompass locally produced lime, natural hydraulic limes, or indigenous geopolymers. Harnessing these region-specific binding agents translates to a reduction in the carbon footprint of concrete production and lends support to the local economy.

Limestone Calcined Clay Cement (LC3) represents a pioneering, environmentally conscious cementitious substance that has garnered attention as a viable alternative to traditional Portland cement within concrete construction. LC3 amalgamates clinker, calcined clay, limestone, and gypsum, culminating in diminished carbon emissions and reduced energy usage throughout its production in contrast to conventional cement. Adopting LC3 in concrete construction yields several advantages vis-à-vis conventional materials. Primarily, it harnesses locally available raw materials like limestone and clay, effectively mitigating transportation expenses and their ensuing emissions. Furthermore, the clay's calcination at lower temperatures than clinker production translates to lower energy consumption and carbon dioxide discharges. LC3 not only showcases comparable or even superior mechanical and durability characteristics in certain compositions compared to conventional Portland cement but also holds the potential to quell the escalating demand for cement by judiciously exploiting abundant clay resources, thus alleviating the stress on clinker production.

The utilization of local materials in concrete construction yields numerous benefits. Locally sourcing materials offers a pathway to curbing emissions tied to transportation, as well as reducing energy consumption and the overall carbon footprint inherent to construction endeavors. The incorporation of indigenous materials can foster resource preservation and waste reduction, given its propensity for encouraging the repurposing and reuse of locally abundant resources, which may include waste and by-products from neighboring industries. Championing local suppliers and industries serves to invigorate the regional economy, engender job creation, and stimulate the emergence of sustainable construction methodologies within the area. Local materials frequently align adeptly with regional environmental conditions, potentially leading to structures that boast heightened resilience and suitability in addressing the specific challenges and demands of the locale. It is paramount, however, to exercise caution that the integration of local materials does not compromise the quality and performance of the concrete. Rigorous testing, comprehensive characterization, and meticulous mix design are indispensable to guarantee that the sought-after attributes and durability prerequisites are upheld, all while harnessing the potential of locally available materials within concrete construction.

**3. Innovative technologies and practices**

**3.1 Self-Healing Concrete**

Self-healing concrete stands as a groundbreaking technology and methodology within concrete construction, holding the promise of bolstering the longevity, functionality, and sustainability of concrete structures. This innovation centers on the idea of empowering concrete to independently mend cracks and impairments, thereby elongating the operational lifespan of structures while concurrently curtailing the demand for maintenance and repairs.

The capacity of self-healing concrete to autonomously mend cracks and address damage plays a pivotal role in extending the operational longevity of structures, concurrently diminishing the vulnerability to corrosion and other modes of deterioration. As the requirement for manual inspections, upkeep, and repair interventions is lessened, self-healing concrete effectively ushers in noteworthy cost efficiencies throughout a structure's lifespan. The extension of concrete structures' service life, coupled with a decreased reliance on maintenance and repairs, significantly contributes to the mitigation of resource utilization, waste production, and the overarching environmental footprint.

Although presenting promising advantages, self-healing concrete technologies encounter certain challenges and constraints. These include the translation of successful laboratory outcomes to real-world scenarios, the endurance and dependability of self-healing mechanisms over extended periods, and the augmented initial expenses incurred during technology implementation. Overcoming these hurdles and fully harnessing the potential of self-healing concrete within the construction sector necessitates the imperative of intensified research and development efforts. Additionally, comprehensive full-scale trials and on-field demonstrations are essential to navigate these challenges and unlock the complete potential of self-healing concrete.

**3.2 3D Printed Concrete**

3D-printed concrete emerges as a pioneering technology and approach within concrete construction, characterized by the utilization of computer-controlled robotic systems to strategically layer concrete material according to a preconceived digital design. This process encompasses the creation of structural elements and, in some instances, entire edifices. Referred to as additive manufacturing or digital fabrication, this technology harbors the capacity to transform the construction sector by ushering in a myriad of advantages spanning efficiency, tailored design, and sustainability.

The potential of 3D printing to notably truncate construction timelines in contrast to conventional approaches is noteworthy. This technology facilitates the concurrent fabrication of multiple components or structures. Moreover, it curtails the requirement for manual labor and formwork, fostering heightened efficiency and diminished labor expenses. By embracing 3D printing, intricate and intricate geometries can be actualized, a feat often challenging or unattainable through traditional construction techniques. This unfetters design latitude, endowing customization and an avenue for pioneering architectural concepts that optimize both structural efficacy and material utilization.

3D printing holds the potential to curtail material wastage through targeted deposition of concrete solely in necessary areas, thereby mitigating raw material consumption and the production of construction debris. This innovation empowers the realization of optimized, lightweight structures, effectively curbing the overall material demand for achieving desired structural efficacy. The resultant reduction in material usage, waste production, and labor prerequisites linked with 3D-printed concrete significantly contributes to fostering a more sustainable construction sector. Furthermore, this technology could potentially facilitate the incorporation of recycled components or novel environmentally friendly materials into concrete mixtures, further elevating the ecological performance of the resulting structures.

The challenges and limitations associated with 3D-printed concrete predominantly revolve around technological and material dimensions. The ongoing refinement of 3D printing systems, materials, and processes for concrete construction remains a focal point. Advances in areas like robotic systems, printing speed, concrete mixture formulation, and curing methods are imperative for realizing the full scope of this technology. The assimilation of 3D-printed concrete within the construction sector necessitates the formulation of fresh codes, standards, and guidelines to guarantee the quality, safety, and durability of the structures produced. The transition toward digital fabrication and automation may additionally require the retraining and upskilling of the construction workforce to adeptly embrace novel technologies, tools, and methodologies. While the long-term prospects of 3D printing encompass reduced labor and material expenditures, the initial investment in equipment and technology can indeed be substantial.

With ongoing research and development, the trajectory of 3D-printed concrete is poised to ascend, becoming a progressively pivotal technology and methodology within concrete construction. This evolution is set to usher in novel prospects for heightened efficiency, tailored design, and sustainability.

**3.3 Photocatalytic Concrete**

Photocatalytic concrete constitutes an innovative technology and approach within concrete construction, encompassing the integration of photocatalytic substances, like titanium dioxide (TiO2), into the concrete mixture or surface coatings. When subjected to sunlight or ultraviolet (UV) radiation, these substances engender reactive oxygen species (ROS) capable of decomposing diverse pollutants like nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM). This intrinsic self-cleansing and air-purifying attribute of photocatalytic concrete possesses the potential to bolster air quality and foster enhanced sustainability within urban environments.

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Despite its benefits, photocatalytic concrete does come with certain challenges and limitations. The incorporation of photocatalytic materials like titanium dioxide can lead to higher initial expenses compared to conventional concrete. However, the enduring advantages of improved air quality, decreased maintenance, and heightened durability could potentially outweigh these initial costs. Photocatalytic reactions necessitate exposure to sunlight or ultraviolet radiation to trigger the generation of reactive oxygen species. The effectiveness of photocatalytic concrete might be diminished in shaded areas or periods of limited light, such as cloudy days or nighttime. This constraint could restrict the overall performance of photocatalytic concrete in specific settings or scenarios.

Selecting the appropriate photocatalytic materials and effectively integrating them into the concrete mix or surface coating can pose challenges. Aspects like particle size, distribution, and concentration can exert significant influence on the efficacy of photocatalytic concrete. There's a requirement for ongoing research and development to pinpoint and refine suitable photocatalytic materials and formulations that can simultaneously fulfill performance and sustainability criteria across diverse construction applications. While photocatalytic concrete holds potential for enhancing air quality, it's important to note that the reactive oxygen species generated during photocatalytic reactions could potentially generate secondary pollutants or inflict harm on adjacent materials or ecosystems. Further investigations are imperative to comprehensively comprehend and mitigate any potential environmental repercussions tied to photocatalytic concrete.

**3.4. Insulated concrete forms**

Insulated Concrete Forms (ICFs) stand as an innovative technology and practice in concrete construction. These involve the utilization of lightweight, interlocking foam forms to establish a continuous insulation layer around cast-in-place concrete walls, as depicted in Figure 5. Following the pouring and curing of concrete, the foam forms remain in position, endowing a structurally robust and energy-efficient building enclosure. ICFs have garnered substantial traction in both residential and commercial construction arenas due to their manifold advantages vis-à-vis conventional construction methods. The thermal insulation provided by ICF walls reaches high levels, culminating in marked reductions in heating and cooling loads within structures. As a consequence, energy consumption dips, greenhouse gas emissions are curbed, and occupants reap financial savings. The amalgamation of concrete and foam insulation engenders a robust, unified wall system capable of weathering harsh elements like hurricanes, tornadoes, and earthquakes, demonstrating commendable resilience.

ICF walls serve as an effective barrier against the propagation of outdoor noise, fostering a tranquil indoor ambiance and enhancing occupants' comfort. The installation of ICFs is relatively straightforward and swift, often resulting in expedited construction timelines and diminished labor expenses in contrast to conventional methods. The concrete core inherent to ICF walls offers robust fire resistance, thus minimizing the likelihood of fire propagation within rooms or across neighboring structures.

The initial expense of ICF construction can surpass that of conventional methods due to the costs associated with foam forms and specialized installation procedures. However, the enduring advantages of decreased energy usage and lowered maintenance expenditures could potentially counterbalance these initial outlays. While ICF construction can accommodate various architectural designs, intricate or unconventional shapes may prove more challenging or costly to achieve compared to traditional techniques. This might necessitate extra coordination and planning between the design and construction teams to ensure that the desired architectural aspects align with ICF feasibility. Specialized training and skills are prerequisites for proper ICF installation, a resource that might not be universally available in all regions or markets. This scarcity of skilled contractors can result in elevated labor expenses or restricted access to proficient professionals.

Insulated concrete forms (ICFs) hold the promise of evolving into a significantly vital technology and practice within concrete construction, opening up fresh avenues for energy-efficient and robust building design. Ongoing developments in material science, manufacturing methodologies, and construction approaches have the potential to elevate the effectiveness, cost-efficiency, and adaptability of ICF systems. Furthermore, the fusion of ICF construction with other sustainable strategies, like incorporating recycled materials or utilizing renewable energy sources, can elevate the comprehensive environmental performance of concrete structures.

**3.5. Electrification**

The electrification of construction equipment and vehicles is an emerging and innovative technology within the construction industry. It strives to curtail greenhouse gas emissions, enhance energy efficiency, and mitigate the overall environmental footprint. Embracing electric-powered construction equipment and vehicles plays a pivotal role in advancing sustainable construction methodologies, aligning harmoniously with international endeavors to address climate change and transition to more environmentally friendly energy alternatives.

Nonetheless, the electrification of equipment and vehicles in concrete construction is not without its challenges. The initial investment for electric alternatives can often surpass that of their diesel counterparts, potentially creating financial barriers for smaller construction firms and projects operating within limited budgets. Furthermore, the availability of charging infrastructure, particularly in remote construction sites, may be insufficient, hindering the effective implementation of electrification. Electric equipment and vehicles also tend to possess shorter operational ranges and longer charging times compared to their diesel counterparts, which could impact productivity and scheduling on construction sites. Given the novelty of electric options in the concrete construction industry, concerns regarding their reliability, performance, and durability may also arise in comparison to the more established diesel choices.

To address these obstacles, ongoing research, development, and investment in electric equipment and vehicles are essential. Advances in battery technology and charging infrastructure must be pursued to enhance the practicality of electrification. Governments and industry stakeholders can contribute to this transition by providing incentives, subsidies, and regulatory frameworks that promote the adoption of electric equipment and vehicles in concrete construction. This comprehensive approach can help overcome challenges and facilitate the sustainable integration of electrification in the industry.

**3.6. Waste-derived fuels**

Waste-derived fuels (WDFs) represent an innovative approach within concrete construction. This method entails employing alternative fuels derived from diverse waste sources to replace conventional fossil fuels in the cement production process. These alternative fuels can originate from a broad spectrum of waste materials, including municipal solid waste, agricultural residues, industrial by-products, and discarded tires. The integration of WDFs in cement manufacturing holds the potential to foster more sustainable construction practices. This is achieved by diminishing dependence on fossil fuels, thereby curbing greenhouse gas emissions, and simultaneously advocating for effective waste management strategies.

The substitution of conventional fossil fuels with waste-derived fuels (WDFs) carries the potential to significantly curtail the carbon dioxide emissions linked to cement production. By doing so, it can make a substantial contribution to the broader endeavor of mitigating climate change while aiding the concrete industry in achieving its sustainability objectives. The utilization of waste materials as substitute fuels serves a dual purpose: diverting these materials away from landfills and incineration, thus fostering a circular economy and optimizing resource utilization. WDFs offer a valuable energy source for the cement manufacturing process, thereby diminishing the sector's dependency on non-renewable fossil fuels and enhancing energy security. In specific instances, the incorporation of WDFs can even lead to reduced fuel expenses compared to conventional fossil fuels, presenting economic advantages for cement producers. This becomes particularly evident when waste materials are readily accessible, and the costs associated with their disposal can be circumvented or minimized.

Indeed, while the utilization of waste-derived fuels (WDFs) in cement production presents notable benefits, it is not without its challenges and constraints. Incorporating WDFs may necessitate adjustments to existing kiln systems, process controls, and specialized handling and storage solutions for waste materials. These technical adaptations can introduce initial investment costs and operational complexities for cement manufacturers. Additionally, the incorporation of WDFs can be subject to a range of environmental regulations and permitting stipulations, which can differ across various jurisdictions. Cement manufacturers must adeptly navigate these regulatory landscapes to ensure adherence to standards and avoid potential fines or penalties.

Absolutely, the adoption of waste-derived fuels (WDFs) in cement production should be approached with careful consideration due to potential air quality concerns. While WDFs can aid in greenhouse gas emissions reduction, it's critical to recognize that the combustion of certain waste materials might give rise to other air pollutants, including nitrogen oxides (NOx), sulfur oxides (SOx), and heavy metals. Hence, thorough material selection and processing are imperative to prevent the unintended compromise of air quality standards. Public perception and community concerns are also factors to address when implementing WDFs. If worries arise regarding potential air quality deterioration, public health impacts, or environmental harm, it's vital for cement manufacturers to engage in open and transparent communication with stakeholders. Such efforts can help alleviate skepticism and build public trust in the responsible utilization of WDFs. The heterogeneous composition of waste materials adds another layer of complexity. Given the variability of waste, ensuring consistent and appropriate fuel quality becomes crucial. This necessitates investments in advanced technologies and quality control measures to ascertain that WDFs meet the necessary specifications, allowing for their effective and safe integration into cement production processes.

Effective collaboration among researchers, industry experts, policymakers, and relevant stakeholders plays a crucial role in advancing the utilization of fuels derived from waste in the production of cement. This entails the creation and application of optimal approaches for the selection, treatment, and incineration of waste materials. It also involves the establishment of strong monitoring and quality assurance systems to guarantee the secure and efficient utilization of waste-derived fuels. Additionally, integrating waste-derived fuel technology with other eco-friendly strategies and innovations in concrete construction, like the incorporation of supplementary cementitious materials, carbon capture and utilization, and energy-efficient architectural design, has the potential to enhance the overall environmental impact of the industry. By promoting interdisciplinary research, sharing of knowledge, and the creation of inventive solutions, the construction sector can strive towards the successful adoption of waste-derived fuels and other sustainable methodologies, ultimately making a significant contribution to the development of a more resilient and sustainable built environment.

**4. Challenges and barriers**

The implementation of sustainable approaches in concrete construction introduces a range of technical, economic, and societal obstacles. It's essential to confront these challenges and overcome potential resistance to adoption in order to facilitate the broad incorporation of sustainable methodologies throughout the construction sector.

**4.1 Technical Challenges**

Enhancing the sustainability of concrete construction comes with a set of technical challenges, which encompass:

* Material Behavior: The utilization of novel materials like supplementary cementitious materials (SCMs) and alternative binders may yield distinct performance traits compared to conventional concrete. This may entail additional research, development efforts, and adjustments to construction methodologies to ensure optimal durability and performance.
* Emerging Technologies: Innovations such as self-healing concrete, carbon capture techniques, and 3D printing demand further refinement and thorough testing to establish their long-term reliability, efficiency, and overall efficacy.
* System Integration: Sustainable construction methods frequently necessitate the harmonious integration of various systems, including energy efficiency, renewable energy generation, and water management. This can call for intricate design and engineering solutions to ensure flawless operation and to reap the maximum benefits.

**4.2. Economic challenges**

Challenges on the economic front for enhancing sustainability in concrete construction comprise:

* Initial Expenditure: Embracing sustainable concrete construction methods can involve greater upfront expenses due to the utilization of progressive materials and technologies. This aspect might serve as a hindrance to adoption, especially in markets sensitive to costs or for smaller ventures with constrained budgets.
* Market Reception: The construction sector tends to be traditional in its approach and slow to adopt novel methodologies. Convincing stakeholders such as developers, contractors, and clients about the lasting advantages of sustainable concrete construction can be arduous, particularly when confronted with heightened initial expenditures.
* Return on Investment: Sustainable construction practices frequently demand a more extended perspective on return on investment. Stakeholders might exhibit reluctance to invest in sustainable methods if the financial benefits aren't immediately evident or if they perceive the associated risks as substantial.

**4.3. Social challenges**

Social challenges in advancing sustainability in concrete construction encompass:

* Awareness and Education: A deficiency in understanding or awareness of the advantages tied to sustainable concrete construction could be prevalent among both industry professionals and the general public. This dearth of knowledge may impede the adoption of fresh practices, as stakeholders might not fully comprehend their significance or their potential for long-term savings and environmental gains.
* Workforce Proficiency: Embracing sustainable concrete construction necessitates a workforce well-versed in novel materials, technologies, and methodologies. The sector might grapple with a scarcity of proficient labor, thereby decelerating the widespread implementation of sustainable practices.
* Regulatory Hurdles: Prevailing building codes, regulations, and standards might not comprehensively support or accommodate sustainable concrete construction approaches. This situation could pose challenges for projects aspiring to integrate innovative materials and technologies, potentially leading to regulatory hindrances or project delays.

**4.4. Potential ways to overcome challenges**

Potential strategies for tackling these challenges and barriers encompass:

* Research and Development: Continued investment in research and development can enhance the performance, reliability, and cost-effectiveness of sustainable materials and technologies, rendering them more appealing to the construction sector.
* Education and Training: Elevating awareness about the merits of sustainable concrete construction among industry experts and the general populace, coupled with offering training and educational avenues for the workforce, can bridge skill gaps and stimulate the adoption of novel practices.
* Policy Support and Incentives: Governments and regulatory bodies possess the ability to play a pivotal role in advocating for sustainable concrete construction. This can involve updating building codes and standards, granting incentives for the adoption of sustainable methods, and supporting the evolution of innovative materials and technologies.
* Collaboration and Knowledge Sharing: Nurturing collaboration and knowledge exchange among industry stakeholders—ranging from architects and engineers to contractors, material suppliers, and researchers—can effectively address technical hurdles and foster a heightened comprehension of the advantages associated with sustainable concrete construction. This collaboration can also expedite the formulation of best practices and inventive solutions that can be widely adopted.
* Demonstration Projects and Case Studies: Illuminating successful instances of sustainable concrete construction projects can surmount challenges tied to market acceptance by offering tangible illustrations of the benefits and viability of integrating sustainable practices (Goh et al., 2020). These projects can serve as valuable learning opportunities and yield insights into surmounting technical, economic, and social challenges.
* Life-Cycle Assessment and Cost Analysis: Conducting thorough life-cycle assessments and cost analyses can effectively underscore the enduring environmental and economic gains linked with sustainable concrete construction. This approach can inform decision-making processes and inspire stakeholders to invest in sustainable practices, even when initial expenses are higher.

Surmounting the obstacles and hurdles associated with the adoption of sustainable concrete construction practices necessitates a united endeavor involving various stakeholders such as industry experts, governmental bodies, researchers, and the general populace. Through initiatives like research and development investments, educational campaigns and training, policy and regulation updates, fostering collaborative interactions and knowledge dissemination, highlighting exemplar projects, and conducting comprehensive life-cycle assessments and cost analyses, the construction sector can stride toward a future characterized by greater sustainability—ultimately benefiting both humanity and the environment.

**5. Strategies and policies for promoting sustainable concrete construction**

The promotion of sustainable concrete construction relies heavily on the active participation of governments, industry players, and academic institutions. It is imperative that these stakeholders collaborate closely to stimulate innovation and ensure the broad implementation of sustainable methodologies across the construction sector.

**5.1. Government strategies**

Governments wield a crucial role in advancing sustainable concrete construction due to their capacity to shape public policy, implement incentives, and establish regulations that significantly impact the construction industry (Goh et al., 2020). Governments have the capacity to:

* Formulate and enforce building codes and regulations that endorse sustainable concrete construction practices, encompassing the utilization of low-carbon materials, energy-efficient design approaches, and strategies for minimizing waste.
* Offer financial incentives, such as tax incentives, grants, or subsidies, to motivate developers, contractors, and property owners to embrace sustainable construction methods.
* Allocate resources to the research and development of sustainable concrete technologies, supporting collaborations between academic institutions and industry stakeholders to expedite innovation.
* Foster the establishment of public-private partnerships to execute sustainable construction projects, thereby demonstrating the viability and advantages of sustainable practices.

**5.2. Industry strategies**

The construction sector possesses a pivotal role in actualizing sustainable concrete construction practices by way of industry benchmarks, certifications, and voluntary endeavors. Key industry stakeholders can:

* Embrace and champion industry standards and certifications focused on sustainable construction, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Green Globes. These certifications function to establish optimum practices, set benchmarks, and offer a competitive edge to companies that prioritize sustainability.
* Engage in voluntary initiatives and collaborative efforts within the industry aimed at enhancing 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 objectives, including commitments to curbing greenhouse gas emissions, ethically sourcing materials, and augmenting the utilization of recycled and renewable resources.
* Disseminate insights, exemplary practices, and lessons garnered throughout the industry, fostering innovation and lending support to the uptake of sustainable construction methodologies.

**5.3. Academic strategies**

Academic institutions assume a pivotal role in propelling research, development, and ingenuity within the realm of sustainable concrete technologies and methodologies. Academic entities can:

* Spearhead research initiatives into sustainable materials, technologies, and construction methodologies. This involves pursuits like exploring alternative binders, the creation of self-healing concrete, and the advancement of carbon capture technologies.
* Forge collaborations with industry collaborators to assess and validate novel sustainable concrete technologies and practices, ensuring their feasibility, effectiveness, and potential for scalability in real-world scenarios.
* Offer educational programs and training courses that center on sustainable construction, catering to both students and professionals. This endeavor helps bridge the existing knowledge and skills gap within the industry and fosters a workforce proficient in executing sustainable practices.
* Arrange conferences, workshops, and seminars aimed at facilitating knowledge exchange and networking among researchers, industry experts, and policymakers. This serves to stimulate the exchange of ideas and promote collaboration within the sphere of sustainable concrete construction.

The collaboration of governments, industry, and academia is imperative in the promotion of sustainable concrete construction practices. Governments can facilitate these endeavors through the implementation of public policy, incentives, and regulations. Meanwhile, the industry can actively contribute by adopting and advocating for standards, certifications, and voluntary initiatives. Academic institutions hold a pivotal position in propelling research, development, and innovation in sustainable concrete technologies and methodologies. By synergizing and endorsing each other's initiatives, these stakeholders can expedite the transformation towards a construction industry that is more sustainable and environmentally conscious.

**6. Future trends and opportunities**

Emerging developments in trends, technologies, and materials offer promising opportunities to enhance the sustainability of concrete construction.

The optimization of concrete construction processes is heavily influenced by digitalization and data-driven strategies. These mechanisms foster enhanced communication, collaboration, and decision-making across stakeholders, resulting in resource efficiency and reduced environmental impact. Moreover, they aid in identifying avenues for refining construction methods, material choices, and project management, ultimately culminating in more sustainable project outcomes.

The integration of circular economy principles and the concept of 'design for disassembly' holds substantial promise in augmenting the sustainability of concrete construction. By crafting structures with consideration for their end-of-life phase, the streamlined dismantling and recycling of materials become feasible, leading to diminished waste generation and amplified resource preservation. Additionally, adopting a circular economy mindset propels the utilization of waste-derived materials and products in concrete production, further mitigating the ecological footprint of the construction sector.

Promising trends, technologies, and materials, encompassing digitalization, data-driven methodologies, nanotechnology, smart concrete, and circular economy principles, present remarkable potential for elevating the sustainability of concrete construction. The fostering of interdisciplinary cooperation and knowledge exchange among stakeholders remains pivotal for fostering innovation and widespread adoption of these practices. By embracing novel technologies, materials, and design concepts, the construction industry can embark on a path towards a more sustainable future.

**7. Conclusion**

This study has delved into a range of trends, technologies, and materials with the primary objective of enhancing the sustainability of concrete construction. Notable discoveries and perspectives encompass the prospects presented by green concrete, the diverse utilization of supplementary cementitious materials (SCMs), permeable concrete, cool concrete, and the incorporation of local resources. Furthermore, innovative technologies and methodologies were explored, including self-healing concrete, 3D-printed concrete, photocatalytic concrete, insulated concrete forms (ICF), the utilization of waste-derived fuels, and the implementation of carbon capture, utilization, and storage (CCUS) solutions.

The significance of adopting sustainable concrete construction practices cannot be emphasized enough, given their direct influence on both the industry's future and the environment. Considering the construction sector's substantial role in global greenhouse gas emissions and resource utilization, the shift towards sustainable methodologies becomes imperative in combating climate change and safeguarding natural resources.

Certainly, here are some recommendations for future research, policy, and industry actions to expedite the transition to sustainable concrete construction:

* Research and Development Investment: Sustain investments in research and development focusing on sustainable materials, technologies, and practices. Encourage cross-disciplinary collaboration and the exchange of knowledge between academia, industry, and policymakers.
* Supportive Policies and Incentives: Implement policies, incentives, and regulations that incentivize the adoption of sustainable concrete construction practices among developers, contractors, and property owners.
* Standardization and Certifications: Advocate for the adoption and promotion of industry standards, certifications, and voluntary initiatives that pertain to sustainable construction. This will encourage adherence to best practices and provide competitive advantages for companies prioritizing sustainability.
* Academia-Industry Collaboration: Strengthen collaborations between academia and industry to facilitate the testing and validation of emerging sustainable concrete technologies and practices. Ensure their applicability, efficiency, and scalability for real-world scenarios.
* Education and Training Programs: Promote the development of education and training programs tailored to sustainable construction for both students and professionals. Cultivate a skilled workforce capable of effectively implementing sustainable practices.
* Circular Economy Integration: Advocate for the integration of circular economy principles and 'design for disassembly' concepts in concrete construction. This approach minimizes waste, enhances resource efficiency, and extends the lifecycle of materials.
* Digitalization and Data-Driven Approaches: Support the adoption of digitalization and data-driven strategies in the construction sector. Utilize technologies like Building Information Modeling (BIM), Artificial Intelligence (AI), and the Internet of Things (IoT) to optimize resource utilization, reduce waste, and enhance project management.

By adhering to these recommendations, collaboration between research, policy, and industry efforts can drive forward the transition to sustainable concrete construction, fostering an environmentally responsible and resilient construction landscape.

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