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Review Article

Sustainable concrete solutions for green infrastructure development: A review

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ABSTRACT

This review paper explores the utilization of sustainable concrete materials in the development of green infrastructure. The primary objective is to investigate various concrete solutions that enhance environmental performance while maintaining structural integrity. The study integrates concrete with green infrastructure elements such as permeable concrete, green roofs, vegetated systems, bioswales, and vegetated channels. These elements are essential for managing stormwater, reducing urban heat islands, and promoting biodiversity in urban areas. The paper also examines optimized concrete mixtures designed to improve durability and reduce carbon emissions by incorporating alternative materials like recycled aggregates and supplementary cementitious materials. Additionally, innovative formwork and construction practices are analyzed to assess their contribution to minimizing resource consumption and waste. By aligning concrete design with green infrastructure objectives, the study highlights the potential of these solutions to mitigate environmental impacts, including reduced energy consumption and lower greenhouse gas emissions. The findings offer valuable insights into the role of sustainable concrete in future urban planning, emphasizing its capacity to support resilient, eco-friendly infrastructure while meeting the growing demands of urbanization. The research ultimately contributes to the broader discourse on green construction practices, offering practical guidelines for engineers and urban planners.

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1. INTRODUCTION

1.1. Background and Context

The construction industry's environmental impact, specifically concrete production, has become a growing concern recently [1]. Concrete is a durable and adaptable building material. After water, it is the material that is used the most extensively worldwide. In 2021, global cement production was estimated to have reached 4.1 billion tons, with annual concrete consumption seven times higher [2]. The world's population growth drives construction demand, necessitating more natural materials. However, this surge in construction also brings environmental challenges, including increased fossil fuel consumption and resource depletion. Achieving sustainability requires careful consideration of ecological, social, and economic factors. The construction industry mainly focuses on greenhouse gas emissions, notably carbon dioxide (CO_2) [3]. Concrete formulations containing cement, such as Ordinary Portland Cement (OPC), which are widely utilized in buildings across the globe, significantly increase atmospheric greenhouse gas emissions [4]. Portland cement is made by burn-

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ing a mixture of limestone (CaCO3) at temperatures usually above 1450°C. Of all anthropogenic emissions, Portland cement manufacture is responsible for 5–8% of greenhouse gas (GHG) emissions [5].

Cement production has a yearly growth rate of 2.5%. The most commonly used material in the world, after water, production has climbed from 2.3 gigatons (Gt) in 2005 to 3.5 Gt in 2020, with an anticipated reach of 3.7–4 Gt. Unfortunately, cement production leads to significant emissions of greenhouse gases, primarily carbon dioxide (CO_2), which is one of the main contributors to global warming. The manufacture of cement alone produces an estimated 1.35 billion tons of greenhouse gases annually [6]. The cement sector emits a significant amount of CO_2, mainly due to the kiln chamber's raw material processing, combustion of fossil fuels, and mineral grinding. These activities have long-term environmental effects and contribute to global warming, as demonstrated by melting glaciers in different parts of the world. Despite the known adverse effects, the international construction industry continues to increase its use of cement in building projects worldwide. The leading cause of variations in cement output is the availability of resources and materials. Several nations rely on their resources to produce cement for building, while others have to import ingredients to meet their needs. The United States Geological Survey recently analyzed global trends in cement output. Figure 1 shows global cement production in 2018 [7].

1.2. Importance of Green Infrastructure

The world's rapid urbanization is putting pressure on the population, natural resources, and available space. By 2050, around 70% of the world's people will live in cities. Consequently, the urban environment will increasingly influence human well-being [8]. This increase is stressing ecosystems; thus, careful planning of mitigation measures is essential for preventing disaster. Several challenges affect city people, such as noise pollution, air pollution, ecological issues, and a growing alienation from nature due to rapid urbanization [9].

A number of environmental risks, including drought, frequent flooding, water scarcity, landslides, pollution, and ecosystem degradation, can affect informal settlements. It is critical to address these challenges to protect the inhabitants' safety and well-being [10]. Over the last thirty years, several theories have proposed different solutions to the problem of sustainability and sustainable development [11].

Numerous issues, objectives, advantages, features, and components are linked to and encompassed by green infrastructure. As such, defining the concept of green infrastructure into a single, broad term is challenging. There are now many definitions of "green infrastructure," which encourages the phrase to be used in various contexts [12].

Given the ongoing tension between socioeconomic advancement and ecological preservation, sustainable development, circular economy, and smart growth have emerged as focal points in contemporary environmental discourse. One of the key methods to achieving sustainable development is the implementation of green infrastructure, which is an efficient way to combine social, economic, and environmental growth. Furthermore, "green infrastructure" promotes actively constructing, renovating, repairing, and reconstructing green networks.

Green infrastructure is crucial for mitigating the effects of climate change, increasing stormwater management capabilities, minimizing the heat island effect, and lowering pollutant levels in the environment [13]. With climate change threatening our planet, we must take immediate, decisive action to mitigate its disastrous effects through policy. Natural ecosystems and human societies are at risk from climate change, which increases the likelihood of natural disasters such as heat waves, floods, droughts, and biodiversity loss [14].

Urban green areas are central to integrated environmental planning systems, forming the foundation of the "green infrastructure" concept since 2000. Gaining global recognition, green infrastructure highlights the multifunctional roles of regional, peri-urban, and urban green spaces in enhancing their quantity, quality, and connectivity and emphasizing the importance of linking habitats. It delivers ecosystem services that promote healthier environments and improve physical and mental well-being for nearby residents. Comprising a network of interconnected areas such as forests, farms, wetlands, parks, greenways, wildlife habitats, and wilderness areas, its objectives include preserving air and water resources, supporting biodiversity, maintaining natural ecological processes, and enhancing community health and well-being [11].

The classification of green infrastructure has mostly been done from a functional and configurational perspective. 'Multi-functional network and connectivity' is the classification approach that has become widely accepted. It includes various elements, including the placement and distribution of functions, ecological, cultural, social, political, and economic values and significance, land-use kinds, purpose, connection, spatial hierarchy, configuration, catchment area, and accessibility [15].

1.3. Role of Concrete in Green Infrastructure Development

Concrete ranks as one of the most extensively utilized materials in built-environment applications due to its superior durability, strength, widespread availability, design adaptability, fire resistance, and cost-effectiveness [16]. Concrete and cement-based materials are among the most often used artificial materials in both civic and industrial constructions worldwide because of their high mechanical strength and low porosity [17]. One of the most widely used materials is concrete, which can consume up to 13 billion tons annually [16]. It is composed of cement, fine and coarse aggregates, and water. Typically, concrete production includes 60 to 75% coarse aggregate. In 2017, the global consumption of natural aggregates for concrete production was approximately 45 billion tons, with projections indicating a rise to 66 billion tons by 2025. Approximately 1.1–1.3 billion tons of concrete debris are generated yearly,

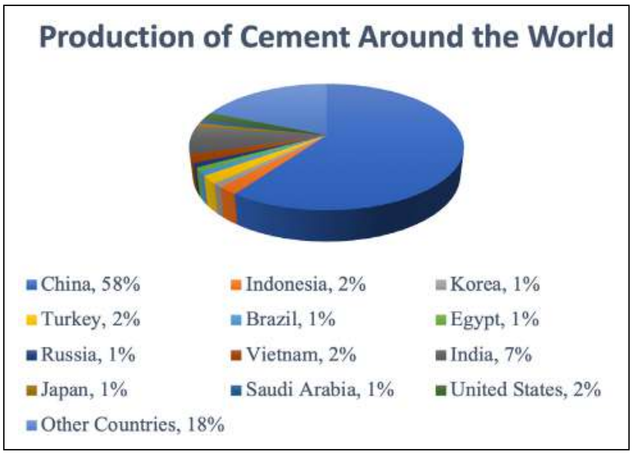

Figure 1. Production of cement in 2018.

making up around 50% of the waste in landfills [18]. Due to urbanization and industrialization, Portland cement concrete has been the second most consumed material in the world for many years. It is a composite material of fine and coarse aggregate, Portland cement, water, and additional additives mixed in a precise ratio. Fine aggregate is crucial, constituting approximately 30% of the total volume. With a well-graded particle size distribution, fine aggregate fills the gaps between coarse aggregate and cement, facilitating the even distribution of cement slurry and coarse aggregate, thus enhancing the uniformity of concrete.

Traditionally, river sand has been the primary source of fine aggregate. However, excessive excavation of river sand has led to environmental issues in river ecosystems, irreversible land erosion, and alterations in riverbeds and landscapes [19]. The growth in concrete production has significantly increased the demand for finite natural resources such as water and river sand. Cement concrete is still widely used in construction because it meets strength criteria effectively [20].

The average cement consumption per capita is predicted to climb in the upcoming years due to the global upsurge in construction activity, driven by an increase in buildings and infrastructure projects. The increased use of raw materials in traditional concrete components such as aggregates, water, and cement has made green concrete materials more visible as a sustainable substitute. Green concrete (GC), containing recycled materials or manufactured through environmentally friendly processes, offers substantial opportunities to improve residential developments' environmental, economic, and social aspects in their early design stages. By using recycled resources such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume as optimal substitutes for cementitious ingredients, green concrete lowers carbon emissions while enhancing strength and durability. These materials contribute to the pozzolanic reaction, refining concrete microstructure by reducing porosity and increasing density. For example, incorporating fly ash improves compressive strength and reduces permeability over time, while GGBS enhances long-term strength and resistance to chemical attacks. By improving these properties, GC holds the potential to align with the core principles of the circular economy and contribute to achieving environmental and economic sustainability goals [21].

1.4. Objectives of the Research Paper

This research paper aims to explore using sustainable concrete materials in green infrastructure development comprehensively. It seeks to investigate various aspects of different concrete solutions' properties, design considerations, and environmental benefits. The study investigates the integration of concrete with green infrastructure elements, such as permeable pavements, green roofs, vegetated systems, bioswales, and vegetated channels. It also analyses optimized concrete mixtures, innovative formwork, and construction practices that aim to reduce environmental impact.

2. SUSTAINABLE CONCRETE MATERIALS FOR GREEN INFRASTRUCTURE

2.1. Permeable Concrete

PCPs, or permeable concrete pavements, are often used as a low-impact development (LID) method to help reduce the negative environmental effects of infrastructure building and operation [22]. In addition to facilitating water drainage and groundwater replenishment, pervious concrete offers several other advantages, including enhanced quality of infiltrated stormwater, noise mitigation, improved thermal comfort, and mitigation of urban heat island effects [23–25].

2.1.1. Properties and Characteristics

Porous concrete, available in various configurations, such as highly pore-filled, permeable, and particle-free concrete, can create permeable pavement [26]. With the help of this innovative substance, runoff water can be managed and guided in desired directions when applied to pavement surfaces, recharging groundwater reservoirs in the process [27]. The holes, voids, and pores that makeup permeability concrete are usually between 2 and 8 mm in size. This allows for adequate drainage. Additionally, the porosity and void content of permeable concrete varies between 15% and 35%, while the compressive strength of pervious concrete falls between 2.8 and 28 MPa. To achieve optimal production, it's advised to maintain a water-to-cement ratio between 0.26 and 0.45 [28]. The desired porosity can be achieved using aggregates with a consistent size or ones with a diameter between 19 and 9.5 mm [29]. The aggregates' granulation in porous concrete differs from typical concrete since it contains little to no fine-grained material [30].

2.1.2. Mechanical and Physical Properties

Like regular concrete, previous concrete has unique qualities and attributes. Different from ordinary concrete, though, workability and compressive strength are not the only considerations. The intricate network of linked pores in pervious concrete is intended to balance permeability and compressive strength. Figure 2 [31], a harmonic relationship between hydrological and mechanical qualities is

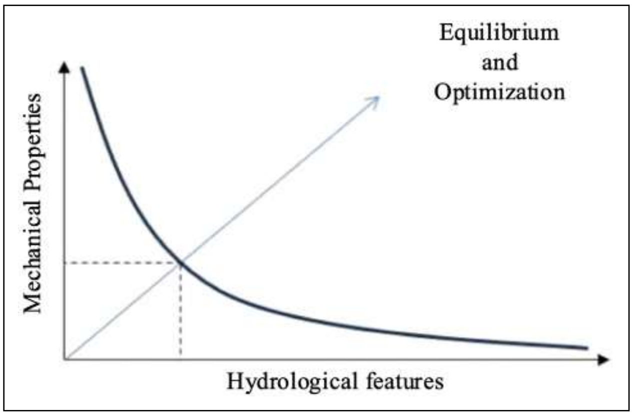

Figure 2. The correlation between permeability and compressive strength.

necessary to achieve this balance. According to Figure 2, previous concrete qualities are interdependent and tightly related to one enough. This interconnectedness can be an ideal mix that excels in hydra performance and mechanical strength.

2.1.3. Compressive Strength

Compared to regular concrete, pervious concrete typically exhibits a significantly lower compressive strength, usually between 2.8 and 28 MPa [32]. This reduction is attributed to compressive strength influenced by the strength-porosity relationship, where reduced porosity leads to higher strength. Therefore, it is essential to examine the factors affecting porosity to optimize strength [33]. Key variables include the type of cement, aggregate size and type, water-to-cement ratio, additives, and compaction techniques. Adjusting the water-to-cement ratio, additives, and mixing times all impact the properties of the cement material [34]. Different types of cement, such as Portland pozzolana cement, ordinary Portland cement, and geopolymer cement based on fly ash, can be used in previous concrete. Unlike traditional concrete, the water-to-cement ratio has a different effect on the compressive strength of pervious concrete. Higher water-to-cement ratios increase fluidity, fill pores, and reduce porosity. As a result, the water-to-cement ratio must be maintained within an optimal range, typically between 0.26 and 0.45 [35]. Numerous studies have examined the relationship between porosity and strength, as shown in Figure 3 [36] illustrates, and the findings consistently point to a negative correlation: higher porosity corresponds to lower compressive strength. Therefore, both elements must be assessed considering the project's needs. Density and compressive strength are directly correlated; increased density results in greater strength, as shown in Figure 4 [37]. However, density isn't the only consideration in compressive strength optimization; density also decreases porosity and permeability [38]. The ASTM C39 standard uses a cylindrical sample and increasing load until it cracks or breaks in a Universal Testing Machine (UTM) to assess the compressive strength of previous concrete [39]. The compressive strength test that the UTM performed is shown in Figure 5 [40].

2.1.4. Flexural Strength

Tension in concrete can be measured using flexural strength, albeit it is not a completely independent measure. By exerting pressure on an unreinforced concrete beam until it fractures while it is bent, this test aims to determine the tension in the beams. Flexural strength is then computed based on the force needed to cause the crack [41]. Notably, if the sample is uniform, bending and tensile strength align. However, heterogeneity in the sample leads to differing resistances. Typically, flexural strength slightly surpasses tensile strength because, unlike in the tensile strength test, all sample components must break during the flexural strength test [42]. Because of its porosity and permeability, pervious concrete typically has a flexural strength range of 1.5 to 3.2 MPa, significantly lower than ordinary concrete [43]. Flexural strength is related to the factors that affect compressive strength because it is categorized under mechanical characteristics. According to Ahmad et al. [44]

equations (1) and (2) show the empirical relationships between compressive and flexural strength.

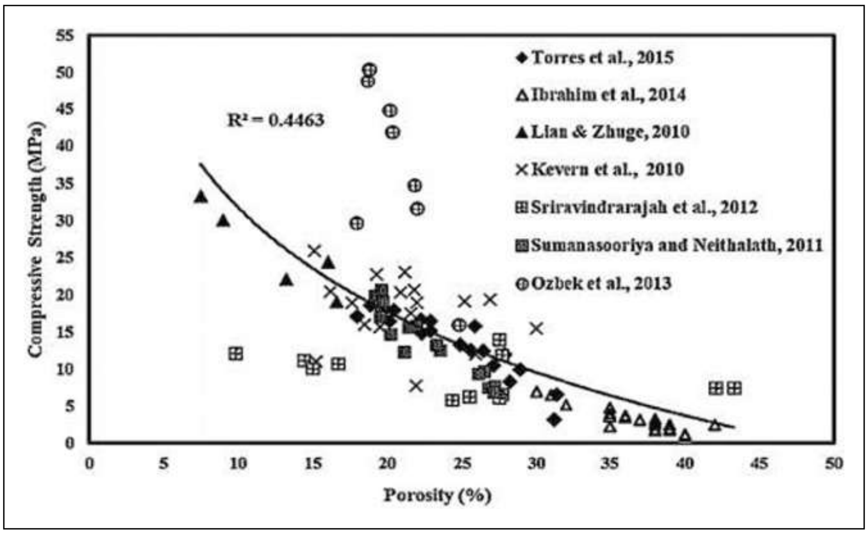

Figure 3. The relationship between pervious concrete's porosity and compressive strength.

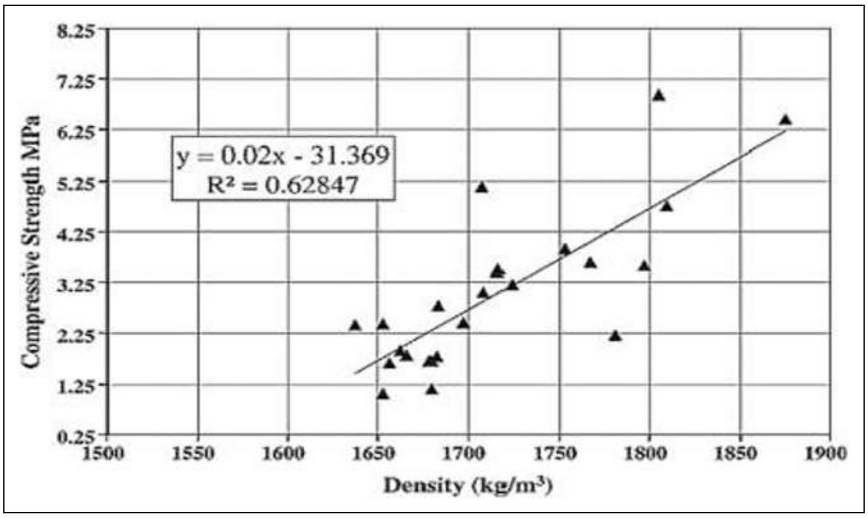

Figure 4. The relationship between previous concrete's density and compressive strength.

Figure 5. As per ASTM C39, the compressive strength test.

$$f_r = 0.083 f_c^{2/3} \text{ (SI)} \quad (1)$$

$$f_r = 2.3 f_c^{2/3} \text{ (in. lb)} \quad (2)$$

The equations above show that the compressive strength of pervious concrete is represented by fc, likewise in MPa or N/mm2, and the flexural strength is indicated by fr, measured in MPa or N/mm2. Experimental equations (1) and (2) directly link compressive and flexural strength. Anything that increases compressive strength usually increases flexural strength as well. The link between compressive and flexural strength is clearly shown in Figure 6 [37].

The clear relationship between compressive strength and flexural strength is demonstrated in Figure 6. Porosity essentially has an adverse effect on flexural and compressive strength. Figure 7 [45], from a prior study, illustrates the impact of porosity on these two types of strength. It's observed that porosity adversely affects compressive and flexural strength to a certain degree. However, it's crucial to recognize that the extent of this trend depends on environmental conditions and mixture design.

Evaluating flexural strength provides a dependable means to assess the tensile strength of pervious concrete indirectly. To conduct this assessment, either ASTM C78 or ASTM C293 standards can be employed, differing only in the loading method. Once the sample is prepared and has undergone a twenty-eight-day curing period, force is applied following the specified standards. The maximum applied load is then determined by examining any resulting cracks, facilitating the calculation of the previous concrete's flexural strength. Figure 8 [46] illustrates the procedure for flexural strength testing.

2.1.5. Tensile Strength

Concrete is prone to cracking and exhibits a low resistance to tension, as was noted in previous sections. This intrinsic inflexibility of ordinary concrete also presents impervious concrete. Tensile strength is directly related to compressive and flexural strength, making it an essential mechanical attribute for pervious concrete. Thus, the tensile strength of concrete is directly influenced by the same elements that determine its compressive strength [47].

Tensile strength will, therefore, be affected in proportion to any increase or decrease in compressive strength. It's crucial to remember that these variations are not constant and are dependent on several variables. Despite this, little is known about porous concrete's tensile strength. Based on available data, a typical range is suggested to be 1.24 to 2.75 MPa, while another study found a range of 1.2 to 1.8 MPa [48]. The Brazilian stress test may evaluate the tensile strength of pervious concrete in a manner akin to that of conventional concrete. In this test, a sample is

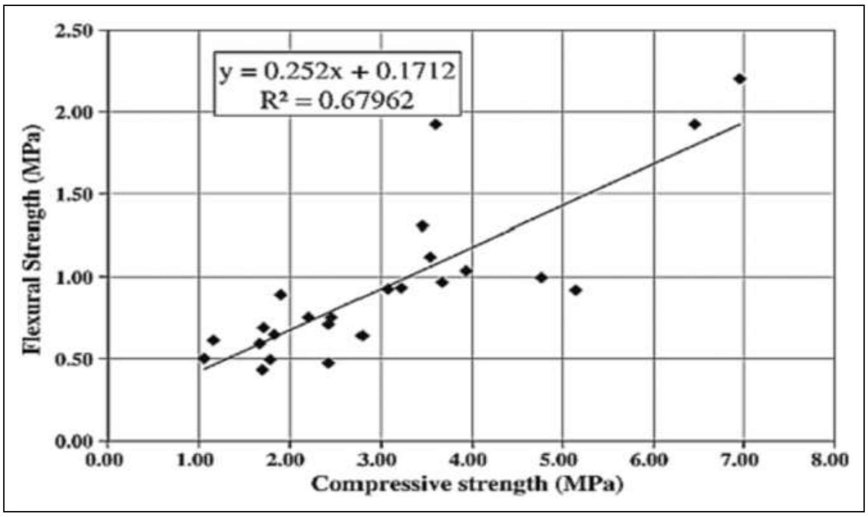

Figure 6. Relationship between flexural and compressive strengths of pervious concrete.

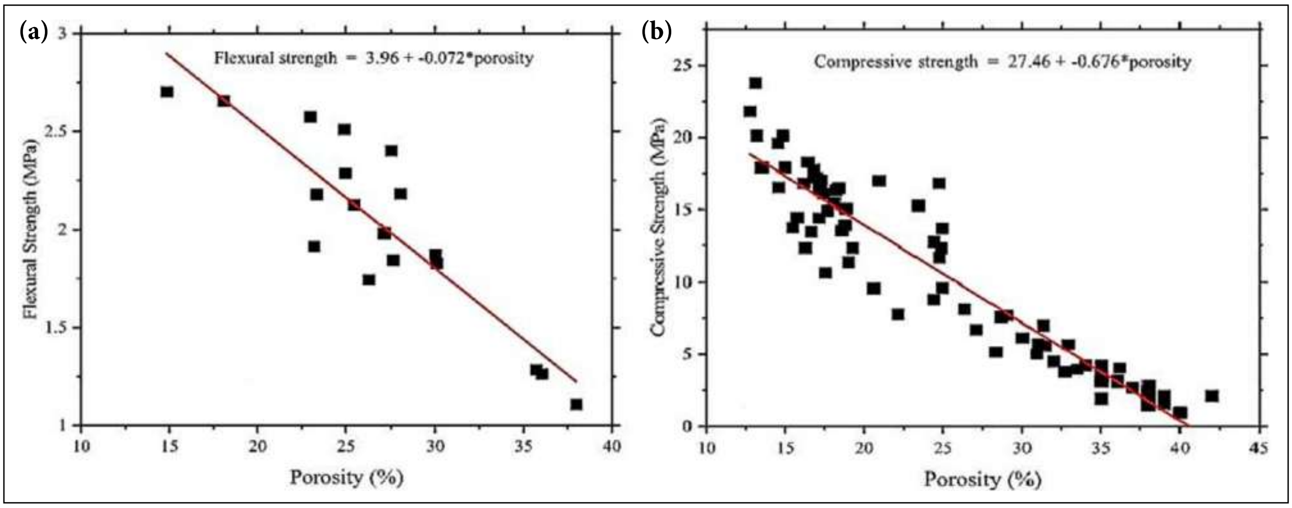

Figure 7. Porosity's impact on flexural strength (a) and compressive strength (b).

Figure 8. Flexural strength testing following the ASTM C78 standard.

inserted horizontally into a UTM device, and force is applied following ASTM C-496-96 until the concrete splits or cracks [49]. The indirect tensile strength of the porous concrete can then be determined using the highest load that was achieved. The Brazilian experiment's technique is shown in Figure 9 [50].

Figure 9. Tensile strength determination using the Brazilian approach.

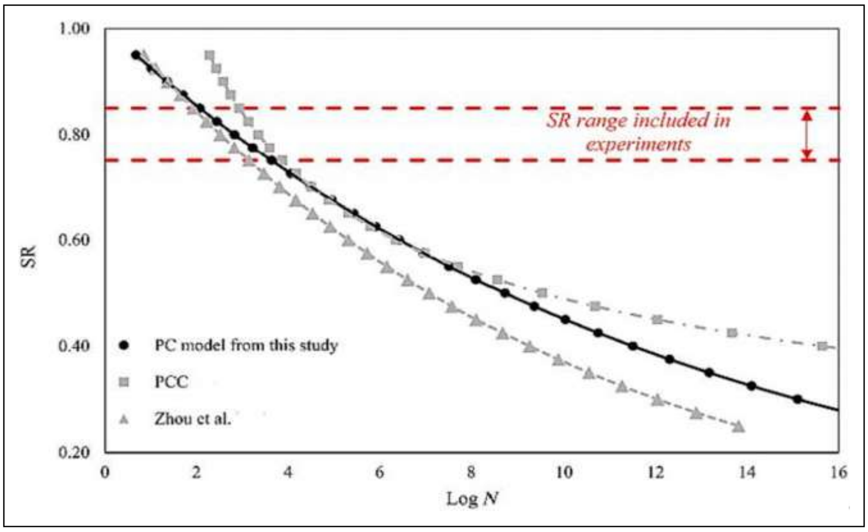

Figure 10. Fatigue performance of different mix designs.

2.1.6. Fatigue Performance

Fatigue performance refers to an object's ability to withstand loading and unloading cycles without succumbing to damage [51]. While traditional concrete typically demonstrates satisfactory fatigue performance due to its high hardness and density, pervious concrete shows poor performance in this aspect due to its inherent characteristics [52]. To explore the correlation between stress-resistance ratio (SR) and fatigue performance across three different scenarios, AlShareedah et al. [53] conducted research and depicted their findings in Figure 10. As the SR increases, fatigue rapidly deteriorates, making concrete susceptible to cracking and eventual destruction. Conversely, concrete exhibits a higher capacity to endure fatigue in the low SR range.

2.1.7. Environmental Benefits

Permeable concrete pavements (PCPs) are recognized for several environmental benefits, including reducing run-off, improving rainwater infiltration, and improving pavement skid resistance and groundwater quality. They also minimize aquaplaning, heat island effect, and traffic noise. These benefits can potentially enhance the resilience, environmental sustainability, and road safety of local transport systems or communities. Government agencies in many countries support green infrastructure strategies as a practical approach to meeting water regulations and requirements. In this context, PCPs are a promising tool for integrating simulated natural processes, such as infiltration, into the built environment. Figure 11 illustrates the interconnected factors influencing the performance of pervious concrete.

2.2. Green Roofs and Vegetated Concrete Systems

The implementation of innovative urban development approaches like rain green roofs, rain gardens, green walls, and bioretention systems serves to alleviate the negative impacts of urbanization and enhance the environmental quality of a region. The term "green roof" refers to a style of roofing covered in different kinds of vegetation

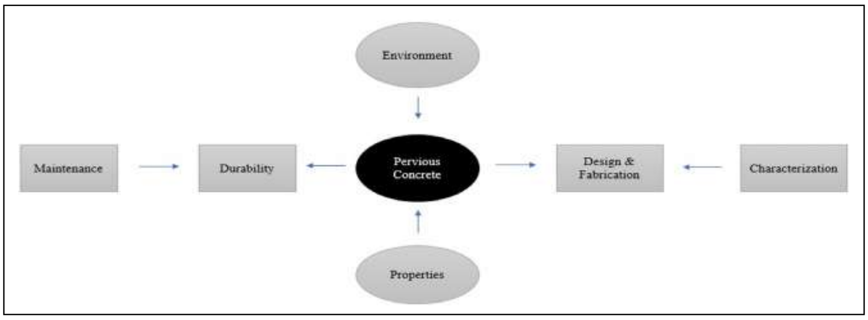

Figure 11. Factors influencing the performance of pervious concrete.

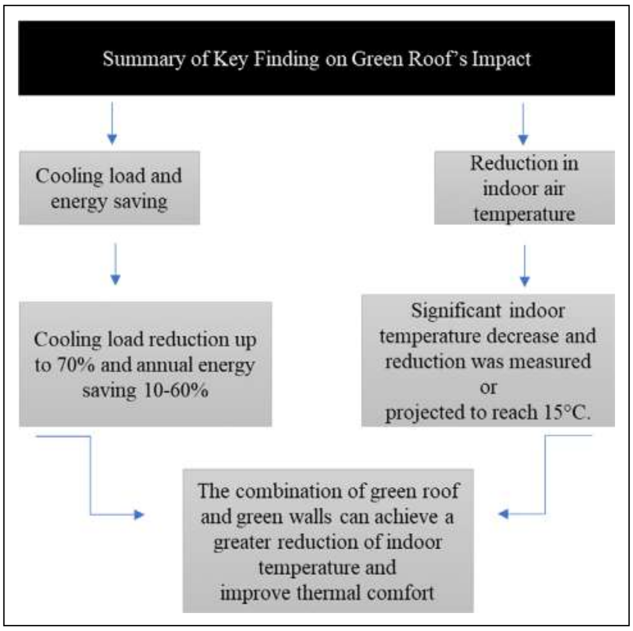

Figure 12. Summary of key findings on green roof impact.

or plants growing on a growing media, sometimes called a cool roof, vegetated roof, eco-roof, or living roof due to its ecological benefits. Several social, economic, and environmental advantages are intended by this idea, which was developed to encourage the growth of flora on building rooftops [54]. A summary of key findings on green roof impact has been given in Figure 12.

2.2.1. Thermal and Environmental Benefits

Many researchers have conducted thorough studies on the environmental benefits of green roofs. This section explores the essential elements of green roofs' environmental effectiveness. These include reductions in ambient noise, impact on indoor environmental conditions, substantial control over runoff water volume that lessens pluvial floods, and improvements in air quality. Air quality and runoff water quality are two advantages for the environment. Improvements in air quality also include pollution deposition, sequestration of carbon, and indoor air quality [55].

Certain plant species are remarkably effective at reducing emissions and air pollution. First, they actively remove air pollutants from the atmosphere, including O_3, NO_2, and SO_2, while utilizing deposition processes to trap dust and other particles through leaf stomata [56]. Second, they can reduce surface temperatures by evapotranspiration or shade, which naturally cools the surface and lessens photochemical reactions that cause air pollution. This also helps save energy for cooling and lowers CO_2 emissions [57]. Finally, through photosynthesis, plants are essential to the sequestration of carbon.

2.2.2. Vegetated Concrete Mixture

Vegetation concrete (VC) has many pores, a unique pore structure, improved water permeability, the ability to dissipate heat, and the ability to absorb sound. These characteristics are essential to implementing sponge cities because they reduce urban waterlogging, reduce noise pollution in urban areas, and promote ecological growth in urban areas. However, regular Portland cement is typically utilized in practical engineering, which causes VC to produce a sizable amount of the hydration product Ca(OH)2. This produces an alkaline environment that is detrimental to the growth of flora [58]. Li et al. [59] found that the ideal circumstances for vegetation development were provided by a water-to-cement ratio of 0.26 and a goal porosity of 26%, at which point the soil's pH and the concrete's porosity reached their lowest points. Cao et al. [60] prepared VC using an aggregate size of 5 to 13 mm, a water-to-cement ratio of 0.42, and an SR-3 admixture. Performance testing revealed a porosity of 18.3%, fulfilling the requirements for a conducive environment for plant root growth. Using various cement and greening additive compositions, several tests were performed on VC. It was shown that the internal pH of VC continuously stayed between 8.4 and 8.7, providing the ideal circumstances for plant growth, with a cement concentration of 6% and a greening additive ranging from 50% to 75%. Certain studies examined the performance trends of VC at different fly ash replacement rates. They found that the porosity of VC achieved its ideal level of 21.9% at a fly ash replacement rate of 40%. Peng et al. [61] compared the porosity in concrete containing fly ash and silica fume. They observed that incorporating fly ash or silica fume decreased porosity while enhancing concrete strength. Consequently, determining the appropriate amount of fly ash or silica fume during VC preparation should align with specific performance criteria. Kim et al. [62] conducted a study to assess the vegetation-growing capabilities of porous VC blocks made from blast furnace slag cement. Upon field placement of the test blocks, plant growth was monitored, and seeds germinated within a week of sowing. By the sixth week, plant lengths

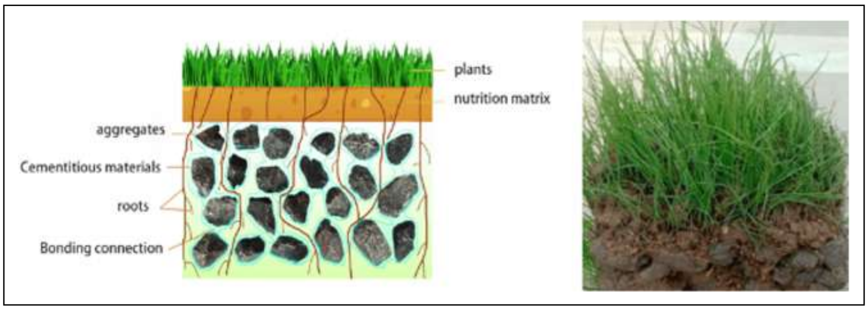

Figure 13. Depiction of vegetated concrete mixture.

Figure 14. (a) Bioswale (left) and (b)Vegetated Concrete Channel (right).

exceeded 300 mm, with an average coverage rate reaching 90%. These results highlight the applicability of VC made from blast furnace slag cement for environmental restoration projects and highlight the significant influence of cement replacements and aggregate on the vegetation-growing capabilities of VC. The biochar content was one of the parameters the researcher used to assess VC performance. It was shown that the porosity of VC rose to 25% when the biochar content hit 5 kg/m³, promoting plant growth. The study also made VC with iron tailings and evaluated its vegetation compatibility. The available nutrient content and pH value significantly decreased after 30 days, according to the results, before stabilizing. This suggests that iron tailings for VC preparation enhance VC's vegetation-growing capabilities. Furthermore, various concentrations of NH_4HCO_3, KH_2PO_4, and $NH_4H_2PO_4$ alkali-reducing solutions were employed. The results showed that the pH of the internal pores of VC could be quickly lowered to about 7 with a 3% composite alkali-reducing solution prepared with equal amounts of the three solutions while ensuring a gradual recovery rate to support vegetation growth. Wang et al. [63] found that the pH of internal pores in concrete can be lowered to about eight by immersing it in ferrous sulfate solution for six days, oxalic acid solution for ten days, and water for twenty-six days. This suggests that alkali-reducing solutions can quickly lower alkali levels without significantly altering the VC's other characteristics.

The review of research papers reveals that alkali reduction processes within VC pores primarily focus on changing mix proportions, alkali reduction solutions, and additives, among other characteristics. To explore the changing rules of VC properties under different cement types, researchers have chosen specific cement types as research variables. This has revealed the mechanism by which different cement types influence VC properties and provided a theoretical framework for meeting the performance requirements of VC in real-world engineering applications. This strategy seeks to broaden the scope of VC's applications in engineering practice. As shown in Figure 13, this mixture illustrates how vegetation can be effectively embedded within concrete structures. This integration supports biodiversity, helps manage stormwater, and reduces the urban heat island effect, making it a vital component of green infrastructure.

2.3. Bioswales and Vegetated Concrete Channels

Green infrastructure can encompass a variety of approaches, such as bioswales, constructed wetlands, or integrated systems like a blend of ponds and landscaped areas to preserve water quality. Bioswales (Fig. 14 (a)), essentially stormwater infiltration systems, stand out as one of the most compelling examples of green infrastructure. These systems are designed to capture the rainwater runoff that accumulates on surfaces [64]. Another notable example is vegetated concrete channels (Fig. 14 (b)), which combine concrete's durability with vegetation's environmental benefits. These channels are designed to manage stormwater while reducing runoff, improving water quality, and promoting biodiversity through the growth of plants along the channel's surface.

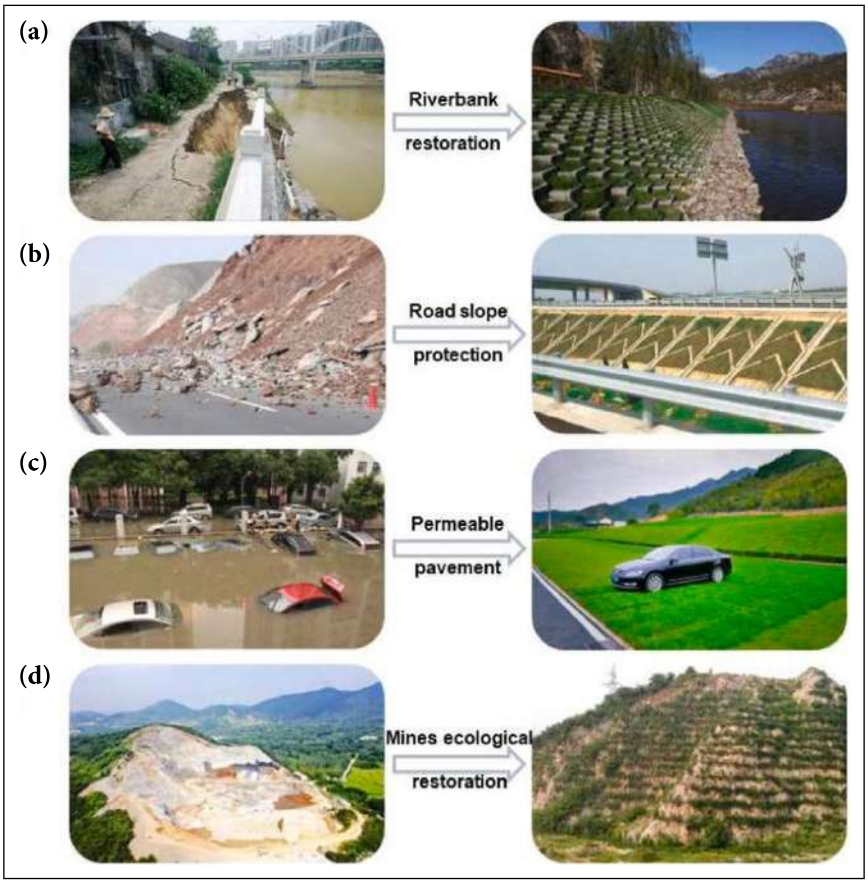

Figure 15. Common applications of porous eco-concretes (PVECs).

Unfortunately, stormwater runoff isn't always pristine. It can carry a mix of contaminants, including heavy metals like copper, lead, and nickel, as well as agricultural residues like fertilizer nutrients and pesticides. Bacteria and suspended solids can also be present, all of which threaten the health of natural water resources [65]. Bioswales are a natural filter, allowing stormwater runoff to soak into the ground. This helps lessen the negative consequences of runoff on delicate ecosystems [66].

Bioswales are shallow, open ditches with plant life that filter stormwater runoff as it flows through [67]. Bioswales are designed to divert urban runoff from built environments and mimic natural water drainage processes, helping reintegrate rainwater into the hydrological cycle. Bioswales face more pressure due to high impermeable surface ratios, so they are engineered with soil that allows rapid water infiltration and adequate filtration. This soil must resist compaction and hold enough water and nutrients to support plant life, helping to alleviate urban runoff issues through added greenery [64]. As demonstrated in Figure 14, these green infrastructure elements use plant life to enhance filtration and provide structural stability, optimizing ecological functionality in densely populated areas.

2.3.1. Design Principles and Hydraulic Performance

Porous vegetation eco-concrete, or green concrete, is a special type of firm, eco-friendly concrete. Made by mixing coarse rocks, water, and cement (often with additional ingredients), it has a honeycomb-like structure with lots of tiny holes (20–30%). This lets water pass through while still strong enough to handle everyday use (5–20 MPa compressive strength at 28 days). Typical applications of porous eco-concretes (PVECs) are shown in Figure 15.

PVEC boasts clear environmental benefits compared to regular concrete, as shown in Table 1. Its lower carbon emissions and reduced environmental impact make it a compelling choice. Further, Table 1 highlights the main differences between regular dense concrete and porous plant eco-concrete regarding carbon emissions and environmental impact [68].

Figure 16 shows conventional PVEC, which is a composite material made up of several key components. These include coarse aggregates, cementitious materials to bind everything together, admixtures for specific properties, prefilled soil to create porosity, and even plant seeds for establishing vegetation [68]. Selecting the right types and mix ratios for these raw materials is crucial to ensure the PVEC performs as needed for various engineering applications.

3. DESIGN AND CONSTRUCTION TECHNIQUES

The rapid growth of the construction industry significantly increases the consumption of natural materials, leading to the depletion of essential resources like river sand, crushed stone, and coarse aggregates such as dolomite and gravel. This scarcity escalates the cost of these materials and adversely affects the economy and the environment [69]. As a result, in recent decades, the demand

Table 1. Comparison of regular dense concrete vs. porous eco-concrete

Aspect	Ordinary dense concrete	Porous vegetation eco-concrete
CO_2 emissions	High (makes up about 8% of yearly world CO_2 emissions)	Lower (plants may absorb CO_2, and the cement dosage is typically 50–70% of regular concrete)
Energy use	High (the calcination of cement clinker uses between 3,000 and 4,000 kcal/kg of energy).	Reduced (possibility of using less energy-intensive materials and procedures)
Sustainability	Low but notable loss of resources and the environment	High (incorporates renewable and uses renewable materials)
Carbon sequestration	Not much (naturally occurring concrete slowly carbonates; around 40–70 g/m^3 of CO_2 is consumed annually.	Significant (mature herbaceous plants require 4–20 kg/m2 of CO_2 per year)
Environmental benefits	Restricted	Enhanced (minimizes heat island effect, enhances urban air quality, supports water management.
Application scope	Broad (used extensively in building)	Particular (fit for specific purposes, such as urban landscaping, eco-friendly projects, etc.)

for sustainable natural resource tenders has increased, particularly in concrete manufacturing.

Concrete, a composite material formed by fine particles bonded with a binder like cement, has been the focus of extensive research to substitute natural resources with by-product materials in its production. For example, by-products from steel manufacturing have been used as alternatives to traditional fine (silica sand) and coarse aggregates (crushed stones) due to their numerous advantages [70]. Manufacturing iron and steel yields byproducts, including mill scale and steel slag.

Mill scale, a waste by-product of steel production, forms during the hot-rolling stage as molten steel oxidizes to create a layer of iron oxides like hematite and magnetite, commonly known as rust. Notably, the mill scale has a high specific gravity, ranging from 5.2 to 5.5 [71].

Researchers are growing interested in using steel slag and mill scale for concrete production. The idea is to see if these industrial byproducts can create concrete with properties comparable to those of traditional concrete made with natural materials. Steel slag was investigated in a 2015 study by Ravikumar et al. [72] as a potential coarse aggregate replacement in concrete. They experimented with various concrete grades and slag replacement percentages. Interestingly, the most significant strength gains happened at the 60% replacement level of all the concrete grades they looked at. In a 2016 study, Qurishee et al. [73] contrasted the mechanical characteristics of concrete formed using conventional stone chips vs concrete prepared with steel slag as a coarse aggregate. They tested three different water-to-cement ratios and replacement percentages of steel slag in concrete. According to the researchers ' observations, the best compressive and tensile strength was found in concrete mixes with stone chips and steel slag, replacing 40% of the coarse aggregate.

3.1. Innovative Formwork and Fabrication Methods

The use of precast concrete in bridge construction has increased significantly in recent years because of its many benefits, which include less labor required, faster construction, better quality control, and less disruption to traffic. The advancement of digital fabrication technologies has led to improved prefabrication through 3D-printed concrete formwork. This method creates complex geometries more quickly and eliminates the need for temporary formwork, which can add up to 35–60% to the total construction cost. Moreover, 3D-printed concrete formwork can

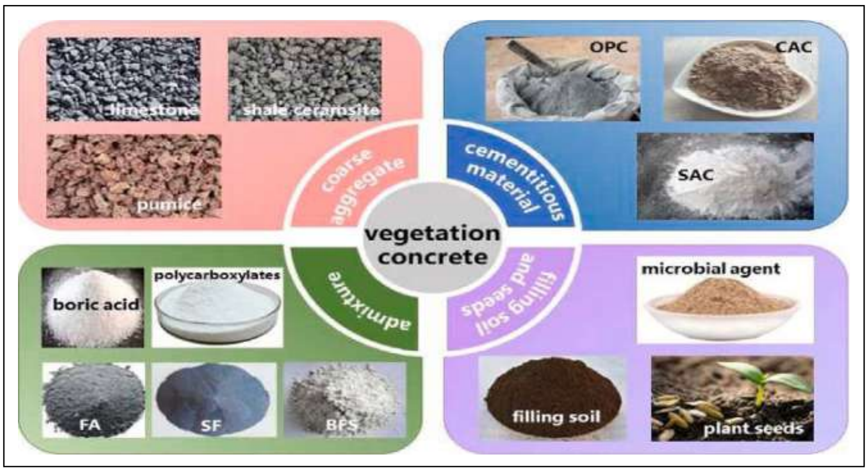

Figure 16. Examining porous vegetation eco-concrete (PVEC) technology: From material design to technical specifications.

drastically reduce construction waste compared to conventional timber formwork, yielding up to 30% of all trash generated during construction.

3.2. 3D Printing Techniques

Using a computer to control the layering of materials to create items is known as three-dimensional (3D) printing. This technique makes it possible to produce lightweight designs, complex constructions, and customized items. In addition, it offers advantages, including accessibility, flexibility, speed, sustainability, and lower risk [74].

3D printing in construction, often associated with advanced fabrication methods, holds significant potential for enhancing green building practices. This technology aligns with using green building materials by enabling more precise material usage, reducing waste during the building process, and incorporating innovative, sustainable materials like recycled plastics or geopolymers. For instance, 3D printing allows for the structural and functional integration of building components with minimal material waste, optimizing the use of resources and promoting sustainability. Moreover, 3D printing can facilitate the creation of complex geometries that improve the energy efficiency of buildings. Features such as organic architectural forms and optimized structural elements can be fabricated directly to enhance thermal insulation and natural climate control, directly contributing to a building's environmental performance. This capacity to integrate seamlessly with green technology, such as embedding energy-generating photovoltaic cells in building facades or optimizing structures for natural ventilation, exemplifies how 3D printing technologies are pivotal in advancing green building initiatives. By leveraging these advanced manufacturing techniques, the construction industry can significantly reduce its environmental footprint while enhancing the performance and sustainability of the built environment. Therefore, understanding the synergy between 3D printing and green building materials is crucial for appreciating its relevance to innovative, environmentally conscious construction practices.

Simple techniques like fused deposition modeling can print small amounts at a reasonable cost. However, the high prices still prevent mass production, mainly when using more sophisticated printing techniques. A narrow variety of appropriate materials, print faults, and the limited ability to construct big structures prevent 3D printing from being widely adopted [75].

Depending on where they come from, 3D printing production techniques differ. Any of these methods can be selected, depending on the components used.

The powder-based system is one of the 3D printing production methods that uses standard inkjet print heads to fabricate components. The four primary types of this system are Electron Beam Melting (EBM), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), and Laser Metal Deposition (LMD).

3.2.1. Laser Metal Deposition (LMD)

In Laser Metal Deposition (LMD) 3D printing, a laser beam melts a metal substrate, forming a molten pool where metal powder is injected through a gas stream, as depicted in Figure 17. This method repairs metallic parts like tools and valves. The laser creates a puddle that melts the injected powder, allowing different metals and ceramics to mix and form enhanced composites. The laser head and nozzle follow a set path to layer the substrate, with each new layer remelting the previous one for bonding. Designs begin with CAD software [76].

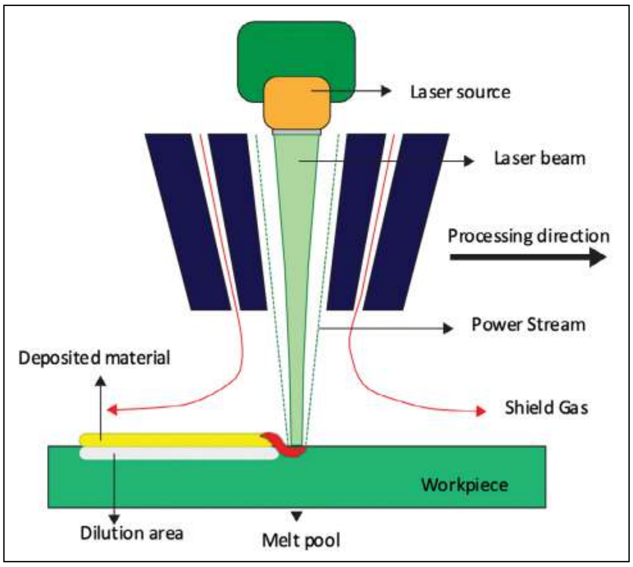

Figure 17. Visual representation of the LMD method.

3.2.2. Direct Metal Laser Sintering (DMLS)

Direct Metal Laser Sintering (DMLS) creates complex objects from powder-based materials using 3D computer designs, as illustrated in Figure 18. According to the design, the method involves spreading a thin layer of metal powder (0.1 mm thick) on a platform and using a high-powered laser to fuse the powder layer by layer. After each layer is fused, the platform lowers, a new layer of powder is applied, and the process repeats until the object is fully formed [77].

3.2.3. Selective Laser Melting (SLM)

SLM is a 3D printing process that melts and fuses metallic powders using a high-density laser. SLM creates a part by combining and melting particles within and between layers, as seen in Figure 19. This process, sometimes referred to as direct selective laser sintering or direct metal laser sintering, may create components with a relative density of up to 99.9%, which enables the creation of nearly full-density functioning parts at a substantial cost advantage [78]

3.2.4. Electron Beam Melting (EBM)

Electron Beam Melting (EBM) is a 3D printing technique that uses an electron beam to melt metal powder within a vacuum chamber, as shown in Figure 20. This process ensures material purity and minimizes hydrogen risks. The chamber is kept at a temperature of 700°C to reduce residual stresses and prevent distortion. EBM constructs each layer in two phases: first shaping the outer boundary, then melting the inner powder, repeating this cycle until the entire 3D object is completed [79].

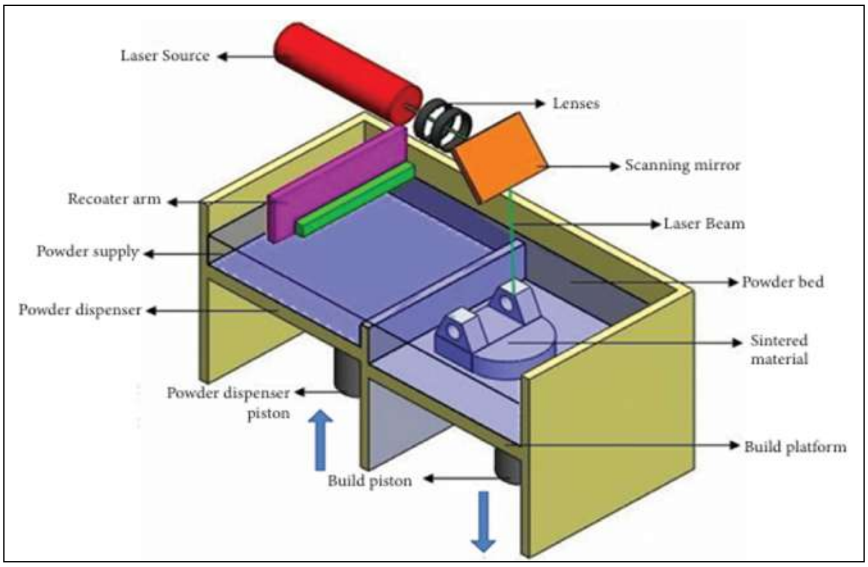

Figure 18. A visual representation of the DMLS technique.

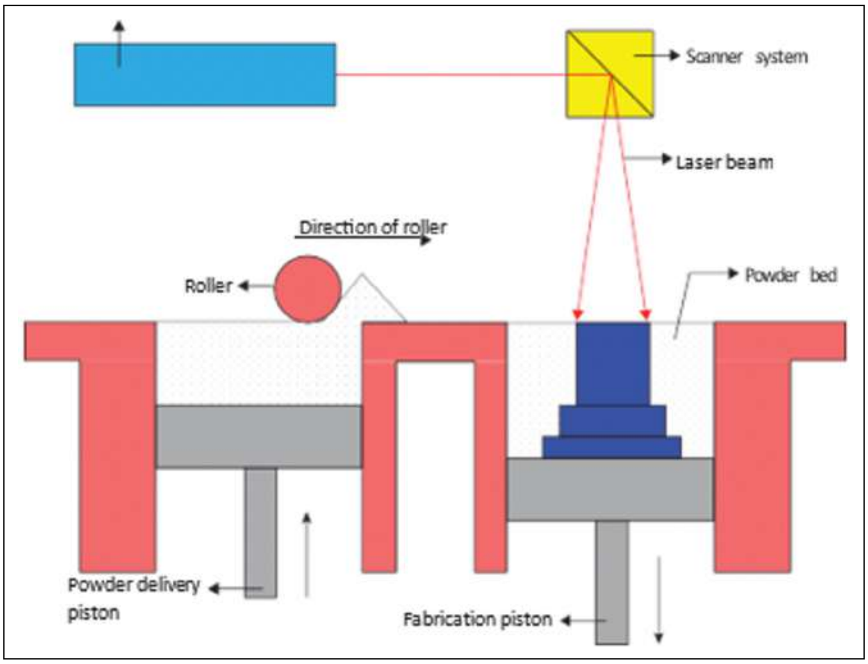

Figure 19. A schematic representation of the SLM approach.

3.3. Solid-Based Systems

Solid-based 3D printing uses solids—such as fibers, wires, sheets, rolls, or pellets—as the primary material to create components or models, distinguishing it from fluid-based photopolymerization methods. While powder-based techniques are discussed separately, the main categories of solid-based systems include Fused Deposition Modeling (FDM), Electron Beam Freeform Fabrication (EBFF), and Wire Pulse Arc Additive Manufacturing (WPAAM).

3.3.1. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) prints layers using a continuous thermoplastic filament, as illustrated in Figure 21. The filament melts in the nozzle, is deposited as semi-liquid material onto a platform or previous layers, and solidifies at room temperature. Deposition thickness, filament properties, and layer alignment influence mechanical strength. While FDM is fast and cost-effective, it faces challenges like limited material choices and the inherent nature of layer-by-layer construction. However, using fiber-reinforced composites has enhanced the mechanical properties of FDM-printed parts [80].

3.3.2. Electron Beam Freeform Fabrication (EBFF)

EBFF (Electron Beam Freeform Fabrication) is an emerging method for producing metal components, as shown in Figure 22. It builds complex parts layer by layer, enhancing segments from castings, forgings, or plates. The process uses a high-powered electron beam in a vacuum (1 × 10−4 torr or lower) and wire feedstock. Operating in a vacuum ensures cleanliness and eliminates the need for

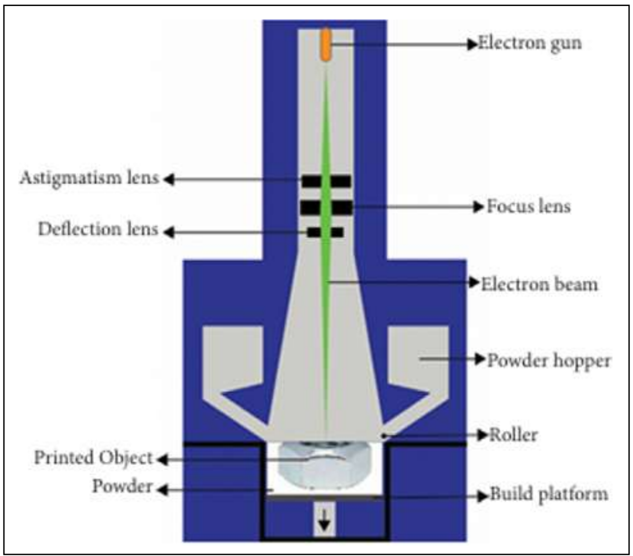

Figure 20. An EBM method graphic representation.

a shield gas. EBFF is highly efficient, using nearly 100% of feedstock and 95% of power, and works well with conductive materials like aluminum and copper. Deposition rates range from 330 to 2500 cm^3/hr (20 to 150 in^3/hr). The research aims to improve acceptable detail resolution and increase deposition rates using different wire sizes. EBFF offers solutions for deposition rate, process efficiency, and material compatibility [81].

3.3.3. Wire Pulse Arc Additive Manufacturing (WPAAM)

Wire Arc Additive Manufacturing (WAAM) is gaining prominence for efficiently producing large, intricate metal parts with minimal waste. This method uses an electric arc to melt metal wire, building parts layer by layer. WAAM's appeal lies in its ability to create substantial structures quickly, reduce material waste, and utilize cost-effective equipment [82]. The standard welding procedure, often involving gas metal arc welding, uses metal filler wires to maintain heat on the frame surface. This method has led to several beneficial outcomes, including a better buy-to-fly (BTF) ratio compared to traditional manufacturing processes, virtually no size limitations for part production, and

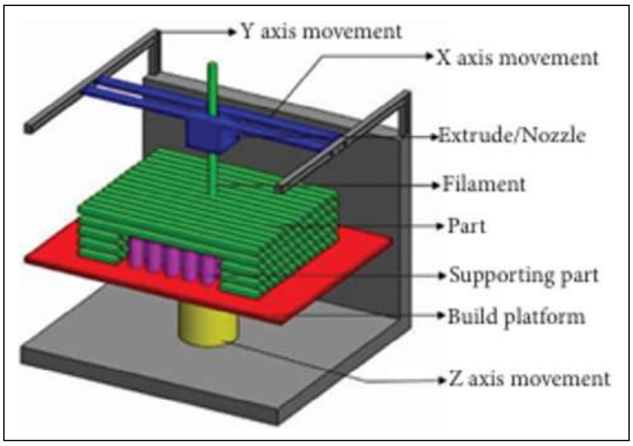

Figure 21. A visual representation of the FDM process.

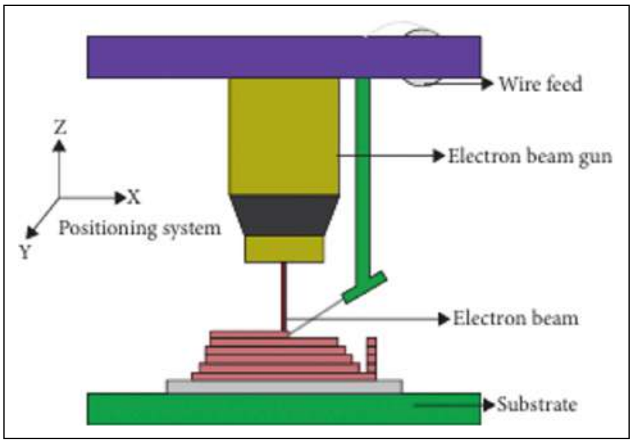

Figure 22. An EBFF method graphic depiction.

greater cost-efficiency compared to powder-based methods when considering material expenses [83]. Figure 23 provides a visual representation of the WPAAM technique.

3.4. Liquid-Based Systems

In liquid-based 3D printing, a powerful laser beam hardens a special light-sensitive resin (photopolymer) layer by layer to build the object. This method, also known as stereolithography (SLA), is a popular type where the printer solidifies a liquid resin with a laser as it moves across a vat of liquid. Some SLA printers can even use multiple resins

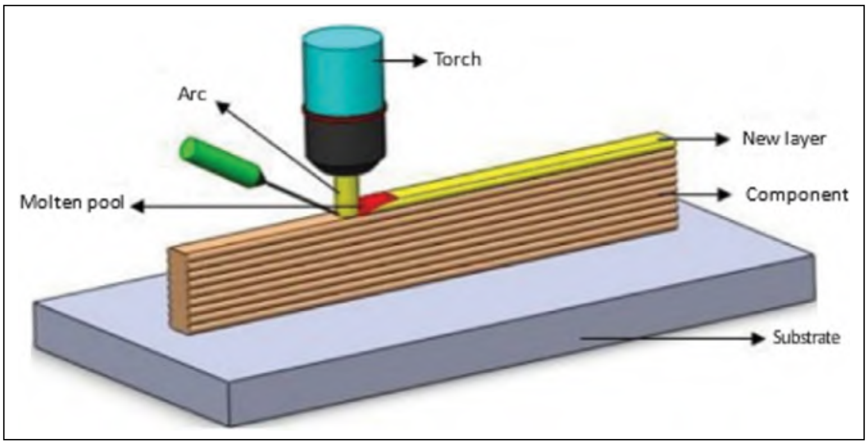

Figure 23. A visual representation of the WPAAM technique.

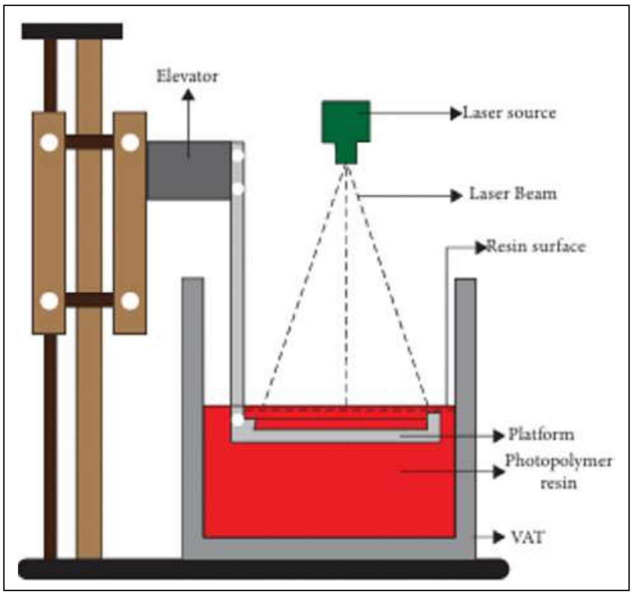

Figure 24. A schematic representation of the SLA technique.

in one print, allowing for objects with different materials. Another type of liquid-based printing, Digital Light Processing (DLP), works similarly but uses a projector instead of a laser to cure the resin.

3.4.1. Stereolithography (SLA)

Stereolithography (SLA) is illustrated in Figure 24. Introduced in the late 1980s, SLA remains an exact and versatile 3D printing method. It allows for manufacturing parts from CAD files through an additive process. SLA uses a computer-controlled laser or digital light projector to harden liquid resin by photopolymerization selectively. A pattern is illuminated on the resin surface, solidifying it to a defined depth and adhering it to a support platform. The platform then moves, and another layer of liquid resin is added and cured. This process repeats to build a solid 3D object. The final structure is obtained after removing excess resin [84].

3.4.2. Direct Light Processing (DLP)

Digital Light Processing (DLP) 3D printing, shown in Figure 25, uses projection light to polymerize materials and construct pre-designed structures. This method offers high printing resolution, efficiency, and favorable operating conditions. While both DLP and laser-assisted printing use photopolymerization, they differ in mechanism, speed, material options, and resolution. DLP employs a digital micromirror device (DMD) of millions of tiny, programmable mirrors from optical microelectromechanical technology. These mirrors project light onto photosensitive resin, achieving high resolution, typically at the micron scale [85].

3.5. Modular Formwork Systems

Formwork is crucial for supporting and shaping freshly mixed concrete until it gains sufficient strength. The type of formwork used significantly influences the geometry and surface quality of the final concrete structure. By the 20th century, various formwork types had been developed, essential for constructing concrete structures. These systems can be classified as classic, flexible, or recyclable based on material stiffness, recyclability, and manufacturing methods. A formwork system must be strong, rigid, and durable, ensuring construction safety and enduring lateral concrete pressures. Wood and metal can directly support fresh concrete, whereas flexible materials may require additional structures. Formwork costs can account for up to half the total expenses for concrete structures, making minimizing material use and maximizing reusability vital for cost efficiency. Weather-resistant, durable materials are also favored to reduce maintenance and prolong lifespan [86].

3.6. Traditional Formwork System

Traditional formwork, typically wood or metal, is used for simple concrete structures. Skilled workers build these temporary molds by hand, relying on well-established techniques for cutting, assembling, and erecting them. This section dives into the specific characteristics and uses of wooden, steel, and aluminum formwork.

3.6.1. Wooden Formwork

Wooden formwork, or timber or lumber formwork, is the most commonly used type in engineering. It is typically constructed on-site from wood members, with larger pieces called timber and smaller ones referred to as lumber. Wood offers several advantages as a formwork material; it is relatively lightweight and easy to handle during construction.

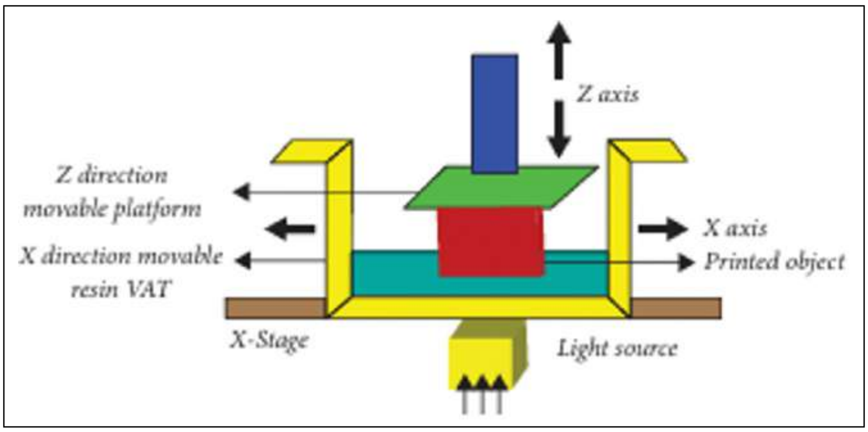

Figure 25. A visual representation of the DLP technique.

Plywood, a crucial component of wooden formwork, is made from thin sheets of cross-laminated veneer bonded with strong adhesives and heat [86]. Plywood panels provide superior dimensional stability and strength-to-weight ratio compared to regular wood. This study investigates the use of fast-growing, economical poplar and eucalyptus veneers as a base reinforced with strong, lightweight carbon fiber fabric. The findings reveal that this composite plywood notably enhances the impact resistance and bending strength of formwork beyond that of traditional wood. Additionally, excessive loads can deform wooden formwork, necessitating extra scaffolding, which is both unsustainable and inefficient [87].

3.6.2. Metal Formwork

Another traditional technology commonly used worldwide is metal formwork, primarily made of steel and aluminum. First off, steel formwork is not only strong and rigid enough, but it can also be quickly assembled, disassembled, relocated, and reassembled. [88]. Steel formwork is cost-effective for repeated use, especially in orthogonal structures, and is ideal for large spaces like warehouses and gymnasiums due to its durability. It can also become a permanent structure, forming long-span decks that reduce the need for support structures, thus lowering costs and construction time.

Aluminum formwork, lighter due to its lower density, is typically prefabricated into modular systems. This facilitates quick assembly and disassembly, enhances efficiency, reduces costs, and ensures high-quality concrete finishes with precise dimensional consistency [89].

Steel and aluminum formwork are ideal for repeatedly casting simple, right-angled concrete shapes. However, they become less practical for complex, custom geometries. This is due to the difficulty of creating metal forms for complex designs and the potentially expensive fabrication and maintenance costs associated with steel and aluminum.

3.7. Flexible formwork system

Flexible formwork significantly reduces the cost of formwork materials and labor while enabling the production of non-standard geometries, in contrast to traditional rigid formwork, which demands enormous quantities of material and physical effort. The digitally produced and fabric formwork systems are the two most popular flexible formwork systems, which will be discussed in this section.

3.8. Construction Practices for Environmental Impact Reduction

Environmental economics and sustainable development are increasingly important across various disciplines and nations, with the construction sector playing a significant role due to its substantial environmental impact. This impact ranges from local issues like indoor air pollution to global challenges like ozone depletion and climate change. The construction industry contributes to environmental degradation through the depletion of natural resources and the emission of greenhouse gases (GHG) from fossil fuels. There has been a focus on using sustainable building materials to mitigate these effects. This approach not only aids in environmental protection but also promotes sustainable construction practices. Key considerations in selecting sustainable materials include meeting performance requirements and choosing options with the lowest GHG emissions [90].

3.8.1. Sustainable Sourcing of Materials

The construction sector, consuming about 24% of all raw materials globally, has a significant environmental impact due to its extensive use of energy-intensive materials like steel, concrete, aluminum, and glass. These materials affect the entire lifecycle of buildings—from construction through to operation, maintenance, and refurbishment. Informed designers can greatly enhance sustainability by incorporating eco-friendly materials into their building designs.

Choosing the right building materials is critical for sustainable construction. High embodied energy materials can dramatically increase greenhouse gas emissions due to the energy required for production. Conversely, sustainable building materials, often sourced from natural materials, provide benefits such as lower maintenance, enhanced energy efficiency, and improved occupant comfort while reducing environmental impact. However, not all natural materials are safe; substances like turpentine, asbestos, and radon pose risks. Thus, truly sustainable materials should be eco-friendly, derived from renewable resources, and free from harmful emissions or contaminants throughout their lifecycle [91].

3.8.2. Waste Reduction Strategies

The primary sources of construction waste are diverse and largely stem from the pre-construction phase. Key issues identified in building procurement include inconsistent documentation, unclear responsibilities, and poor coordination. Additionally, 33 percent of material waste is attributed to architects' inadequate waste planning. Despite global efforts, the adoption of waste reduction strategies in construction remains inconsistent. Current research spans thirteen broad areas, emphasizing the complexity of addressing construction waste effectively worldwide. The current and ongoing research on building waste management and minimization can be broadly categorized into the thirteen areas listed below.

- Quantification and source analysis of building waste.
- Waste minimization techniques for procurement.
- Planning for waste.
- Techniques and protocols for on-site debris sorting in construction.
- The development of waste data collection methods, such as waste management mapping and trash flows, to make managing waste produced on-site easier.
- The development of tools for trash audits and assessments on-site.
- Rules' effects on waste management procedures.
- Improvements to the on-site waste management protocols.
- Reuse and recycle when constructing.

- Benefits of cutting waste.
- Handbooks on waste reduction, which provide guidelines for designers.
- Perceptions regarding the reduction of building waste.
- Studies on comparative waste management.

However, for waste minimization to be effective and sustainable, all stakeholders in the construction supply chain must adopt a more proactive approach to waste management or, in other words, "design out" waste [92].

4. ENVIRONMENTAL BENEFITS AND PERFORMANCE ASSESSMENT

The construction industry significantly impacts social and economic development and contributes extensively to environmental contamination. A construction project encompasses several phases—mining, manufacturing, construction, operation, and demolition. Each stage not only consumes substantial energy but also generates significant pollution. Energy is utilized directly during construction, operation, and demolition and indirectly in manufacturing building materials through embodied energy [93].

Numerous studies have been conducted to reduce building energy consumption and environmental effects due to increased public awareness of environmental issues and pressure from governmental bodies and environmental activists [94].

The Life Cycle Assessment (LCA) approach is one of the most essential instruments for thoroughly assessing environmental impacts, while its implementation in the construction sector is relatively recent. A systematic method for evaluating industrial processes and products, LCA measures waste emissions and material and energy usage and explores options for minimizing environmental effects [95].

Decision-makers, engineers, and designers can benefit from applying LCA, which provides an environmental review through in-depth analysis. Without LCA, decisions are often based primarily on initial costs rather than considering the long-term environmental benefits [96].

4.1. Environmental Impact Assessment

4.1.1. Fundamental Principles of Life Cycle Assessment (LCA)

LCA is a methodological framework used to estimate and assess the environmental impact of a product throughout its entire life cycle, from production to disposal (cradle to grave) [97]. The aim and scope defining phase of an LCA specifies the system's boundaries, chooses suitable functional units, and states the purpose of the study. Gathering information on all pertinent inputs and outputs throughout the product's life cycle is the second stage, the Life Cycle Inventory (LCI). The third step uses Life Cycle Impact Assessment (LCI) data to assess possible environmental effects and calculate resource consumption. The last phase, interpretation, highlights the most critical points, draws inferences from the data, deals with shortcomings, and makes suggestions.

4.2. LCA Concept and Methodology in the Building Industry

Research on LCA has expanded dramatically in the last ten years, particularly emphasizing building material manufacturing and construction procedures. Because every structure is different and has distinct qualities, evaluating buildings becomes more difficult because of their size, range of materials, and inconsistent production processes [98].

Because there are so many case study buildings with different material choices, locations, construction techniques, designs, and uses, the methodology for LCA research in the construction industry is still dispersed. This diversity leads to different definitions of goals and scopes, each with limitations. Additionally, the goals and scope of a study may need to be adjusted if unforeseen issues arise during the research [99].

4.2.1. Goal and Scope Definition

According to ISO 14044, the system boundary in an LCA defines which processes are included based on the study's objectives. For buildings, the LCA boundary can be established in three ways: gate-to-gate, which focuses on construction processes; cradle-to-grave, which evaluates building products from production to end-of-life (EOL); or a combination of both. The cradle-to-grave approach is the most common, encompassing the entire lifecycle from pre-use to EOL. This boundary also sets specific spatial and temporal limits, acting as both a constraint and a reference for future research. The lifespan of a building, which varies in previous studies from 40 to 100 years, with 50 years being typical, significantly affects LCA outcomes, mainly due to energy consumption during the use phase [100]. The lifespan of commercial buildings is generally reported to be between 40 and 75 years. However, much like residential buildings, a 50-year lifespan is frequently used as a standard for analysis [101].

4.2.2. Inventory Analysis

Building plans and field measurements can be used to estimate quantities, or the bill of materials or amounts can be the source of data [102].

The construction phase contributes a relatively small portion to the overall environmental impact [102]. Including installation waste in the inventory is critical if expected quantities are determined using drawings or a bill of quantities. Some studies estimate that approximately 5% of materials are wasted on-site during construction, attributed to product vulnerabilities, mishandling of materials, and unusable remnants from inaccurate installation [103]. Energy use for operations and maintenance is a part of a building's use phase. In this stage, natural gas is the primary energy source, followed by electricity. Earlier research on LCA for buildings often overlooked the end-of-life (EOL) phase. Nonetheless, because construction materials may be recycled, thus lowering the overall life cycle impact, subsequent studies have emphasized its significance [102]. Materials like aluminum and steel are frequently considered recyclable, whereas non-metallic materials are typically sent to landfills, except concrete,

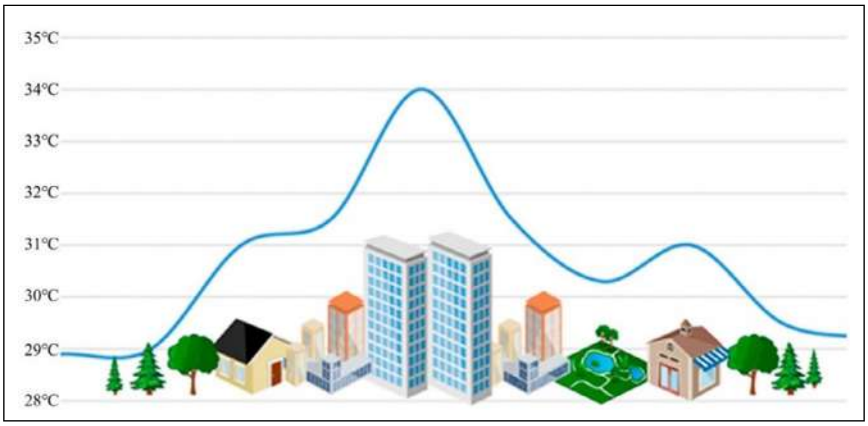

Figure 26. The urban heat island effect phenomena.

often reused as aggregate [104]. The energy consumed by demolition-related machinery is evaluated at the end-of-life (EOL) phase, and average transportation data to landfills or recycling facilities is also provided.

4.2.3. Impact Assessment

The effect assessment phase is the next stage of the LCA. In this phase, possible environmental effects are assessed using the inventory data. Similar to the inventory phase, the goal and scope specification inform the method and impact category selection in the evaluation phase. Most LCA practitioners would instead employ existing, well-established assessment procedures rather than develop new ones from the ground up [105].

Impact assessments can be carried out using either the problem-oriented (midpoint) or damage-oriented (endpoint) approaches. Midpoint methods focus on specific points in the cause-effect chain of an impact category following the Life Cycle Inventory (LCI) but before reaching the endpoint [106].

4.2.4. Interpretation

Interpreting the results is the last stage of LCA, when data from the impact assessment are examined for robustness and sensitivity to other inputs [107], and judgments are made regarding the LCA's aims and objectives [108].

4.3. Hydrological Performance and Stormwater Management

4.3.1. Urban Heat Island Mitigation

In recent decades, one of the most important effects of climate change has been the urban heat island (UHI) effect. It refers to the temperature disparity between urban areas and their surrounding suburban and rural regions [109]. Key factors contributing to the rise in urban temperatures include the release of heat from human activities, the retention of solar energy by urban structures, the scarcity of green spaces and water bodies in densely populated cities, and the limited air circulation in urban canyons, which hampers the release of accumulated heat.

Global academics and researchers have significantly progressed in implementing various mitigation measures for the UHI effect [110]. Mitigation strategies for the UHI effect include using permeable and water-retentive surfaces, high-reflective materials, parks, street tree planting, green walls and roofs, integrating water bodies, and optimizing urban geometry (e.g., building height-to-width ratios, sky view factor, and street canyon orientation). These approaches aim to balance heat accumulation and dissipation by reducing heat absorption and enhancing heat release. As shown in Figure 26, large-scale implementation of these methods has demonstrated significant climatic benefits, reducing urban temperatures and mitigating the UHI effect [111].

4.3.2. Cool Material

Urban planners and architects employed cool urban surfaces, which are cool materials with high reflectivity, used on pavements and building roofs in urban areas to lessen the impact of the urban heat island (UHI) effect and minimize solar energy absorption [112]. Cool materials are specifically designed to reflect a higher percentage of sunlight and absorb less heat than traditional surfaces, helping lower surrounding temperatures and reduce the energy demand for air conditioning. These materials typically have a higher solar reflectance index (SRI) and albedo, which allows them to reflect more sunlight and absorb less heat. In addition to reducing UHI, using cool materials for walkways and roofs enhances outdoor thermal comfort and air quality. Cool materials include reflective roofing membranes, light-colored or white roofing, cool pavements made from high-reflectance concrete or asphalt, and cool green roofs. Green roofs, for instance, provide insulation and temperature control and contribute to biodiversity and stormwater management. Similarly, cool pavements, such as permeable pavements or those coated with reflective coatings, improve surface temperatures and reduce urban heat retention.

4.3.2.1. High-reflective Materials

Reflective pavement involves substituting traditional construction materials with highly reflective ones for pavements [113]. These materials typically possess a high capacity to reflect shortwave radiation and emit longwave radiation [114]. As a result, reflective pavements can reflect a significant portion of solar radiation, absorb and store less heat, and ultimately maintain lower surface temperatures

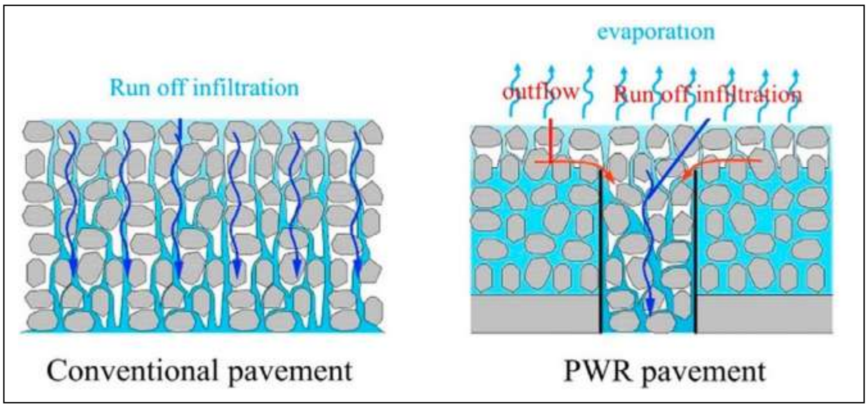

Figure 27. An analysis comparing PWR and traditional pavement was conducted.

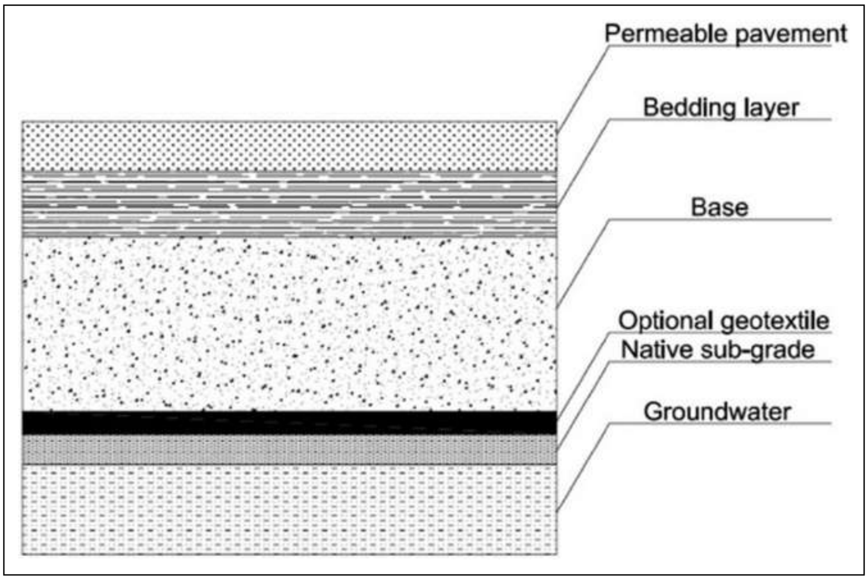

Figure 28. A PWR pavement's typical schematic setup.

than conventional pavements. Several investigations have shown that high-reflectivity pavement has a colder surface temperature than traditional concrete pavement.

One of the most significant markers of a pavement's thermal characteristics is the temperature differential between the air surrounding the pavement and the surface. In an experimental study by Kalinkat et al. [115], they contrasted the temperatures of the two types of pavement—air and surface. According to the findings, traditional black asphalt's surface temperature was about 35 K higher than the surrounding air temperature. Still, for white pavement, the difference was just 5–7 K. Reflective pavements and reflective roofs both work by decreasing the absorption of solar energy.

Scherba et al. [116] simulated to examine how roof reflectance affects the surrounding air temperature in New York City, USA, at a height of two meters. The findings showed that while the peak air temperature dropped by 0.31–0.62 K, the city's daily average air temperature declined by 0.18–0.36 K. In 2013, Zhang et al. [117] investigated the potential benefits of green and highly reflective roofs in reducing the impact of the Urban Heat Island (UHI) in China's Yangtze River Delta. According to their simulation results, cool and green roofs helped reduce the air temperature close to the surface and above it. They also observed that the decrease in external air temperature becomes more noticeable as roof reflectivity rises.

4.3.2.2. Permeable and Water-retaining (PWR) Material

Due to their density and lack of water retention, traditional pavements composed of gray concrete or black asphalt absorb and store a substantial amount of solar radiation, exacerbating the Urban Heat Island (UHI) effect [118]. On the other hand, water evaporation is used by permeable and water-retaining (PWR) pavements to reduce surface temperatures and lessen the impact of the urban heat island (Fig. 27). PWR pavements have more surface layer gaps than ordinary concrete pavements, which permits water to pass through to storage structures or equipment in the ground's sublayers. During sunny periods, the stored water evaporates, regulating the pavement's thermal properties.

The standard schematic layout of a permeable pavement is shown in Figure 28. The evaporation of water can absorb a significant quantity of heat. Because so much of the solar energy collected by wet pavement surfaces is used for water evaporation, the pavement absorbs and releases less heat, thereby reducing air temperatures. Water evaporation in pavements is critical in mitigating the Urban Heat Island (UHI) effect and lowering road surface and urban air temperatures. Moisture on the pavement surface also increases sun reflection, which raises the surface [119].

4.3.3. Vegetation

Urban vegetation helps lower temperatures by absorbing heat through transpiration, providing shade, and altering wind patterns, as noted by Oke et al. [120]. It effectively mitigates urban heat islands by integrating them into urban environments like parks, lawns, building facades, green roofs, and street trees. Studies have consistently shown that urban green spaces are typically cooler than the surrounding built environments, with temperatures ranging from 1 to 7 degrees.

5. POLICY AND REGULATORY FRAMEWORKS

The International Energy Agency (IEA) estimates that the building sector has the potential to save 1.509 million tons of oil equivalent (Mtoe) in energy by 2050, making it one of the most cost-effective industries to do so. Furthermore, increasing building energy efficiency can significantly drop the sector's overall energy demand and CO_2 emissions, which are expected to be reduced by 12.6 gigatons by 2050 [121].

To ensure compliance with energy and environmental regulations and legislative frameworks, it is crucial to implement effective assessment tools and methods for evaluating sustainability in the built environment. Building rating systems are influenced by other sectors, benefiting from their knowledge of environmental processes, decision-making, and management tools. As a result, many rating systems share features with environmental management systems and are primarily based on the life cycle analysis (LCA) approach. To ensure compliance with energy and environmental regulations and legislative frameworks, it is essential to implement effective assessment tools and methods for evaluating sustainability in the built environment.

5.1. Green Building Codes and Standards

Based on the number of certifications awarded, the most popular certification schemes are the following:

- Building Research Establishment Environmental Assessment Method (BREEAM) [122]. Developed in the UK in 1990, the Building Research Establishment Environmental Assessment Method (BREEAM) is a globally applicable European rating system recognized alongside LEED. Over 200,000 buildings have been certified, with 500 more awaiting assessment. BREEAM evaluates environmental aspects such as energy efficiency, water usage, indoor health, pollution, transportation, and materials, assigning credits based on performance.
- LEED: Created by the US Green Building Council in 2000, Leadership in Energy and Environmental Design (LEED) is widely used in North America and internationally, including South America, Europe, and Asia. Its user-friendly interface simplifies the evaluation and monitoring of buildings' environmental performance.
- HQE: Managed by the Association for High Environmental Quality, the French HQE system, introduced in 1994, assesses buildings across 14 target areas within four categories: comfort, health, environmental management, and construction. It incorporates Environmental Product Declarations (EPDs) with life cycle analysis (LCA) data to guide material selection.

All of the previously mentioned systems have a set of shared approaches and objectives, such as [123]

- These systems evaluate buildings' environmental performance based on on-site potential, energy efficiency, water conservation, material use, indoor air quality, and operational and maintenance practices.
- Their goals include recognizing environmentally friendly buildings, encouraging innovation, exceeding regulatory standards, and reducing costs while enhancing living and working conditions.

5.2. Overview of Building Certification Schemes and Standards

All assessment methods evaluate similar environmental elements, such as energy consumption, water efficiency, indoor environmental quality, resource use, and operational management, though they differ in structure and grading systems [124]. However, energy efficiency contributes to over 20% of the overall certification score in all rating systems.

Sustainability in building management remains a global priority, requiring unified approaches and standard evaluation tools to address limitations and realize benefits. The International Organization for Standardization (ISO) plays a critical role in establishing requirements for sustainable building management [125].

The International Organization for Standardization (ISO) has been actively involved in establishing requirements for sustainable building management. As mentioned, ISO standards offer a foundation for environmentally friendly architecture and construction practices [122].

To guarantee that the end product is an environmentally friendly building, the standard "Sustainability in Building Construction: Framework for Methods of Assessing the Environmental Performance of Construction Works – Part 1: Buildings" covers all stages of a construction project, including design, construction, operation, maintenance, refurbishment, and deconstruction. It is intended to be used with the ISO 14020 series on environmental labeling, ISO 14040 on LCA, and ISO 15392 on general sustainability principles in building construction [123].

The methodology and procedures for creating environmental statements for building products that consider a building's complete life cycle are outlined in the standard "Sustainability in Building Construction: Environmental Declaration of Building Products." The ISO 21930 framework is the foundation for Type III environmental declaration programs for building components.

According to ISO 16813, the standard "Building Environmental Design: Guidelines to Assess Energy Efficiency of New Buildings" provides recommendations for assessing the energy efficiency of structures. Its goal is to meet the definitions set forth by building designers and assist practitioners and designers in obtaining and supplying the data required for different design processes. This standard applies to existing air conditioning systems and heating plants, even though it is primarily meant for new construction.

The European Committee for Standardization (CEN) has developed standards for assessing buildings' life cycle costs, environmental impact, and comfort. With around 3,000 civil and building engineering work items, CEN addresses thermal performance, ventilation, lighting, and building management systems to support comprehensive evaluations.

5.3. Climate Change Adaptation and Resilience Strategies

5.3.1. Role of Concrete Green Infrastructure

There are many mitigation and adaptation strategies, but none is effective. By 2150, it is estimated that over 70% of the world's population will live in urban areas, up from 50.0% in 2010. Mitigation aims to reduce greenhouse gas emissions that gradually drive global warming. At the same time, adaptation focuses on minimizing the vulnerability of environmental, social, and economic systems while improving their resilience to climate impacts [126].

Urban areas account for most energy consumption and must prioritize the sustainable management of resources across social, environmental, and economic dimensions to enhance residents' quality of life. Heatwaves in cities pose serious challenges for vulnerable populations, particularly the elderly and young. High population densities, significant land use changes, and reliance on non-local natural resources characterize urban socio-ecological systems.

One significant consequence of urbanization is the "urban heat island" (UHI) effect, where cities are warmer than surrounding rural areas. Climate change is expected to exacerbate UHI, particularly in hot regions with dry summers, such as the Mediterranean Basin. Protecting, enhancing, and expanding urban and peri-urban forests and street trees is crucial to strengthening green infrastructure (GIs) to promote sustainable urban development. These green spaces act as "demand areas for ecosystem services," providing essential goods and services that nature offers to humanity. To mitigate local and global pollutants, reduce energy costs for homes and businesses, support climate change adaptation, and enhance urban climates, it is beneficial to implement new urban designs, energy-efficient buildings, green spaces, and advanced technologies. Integrating green infrastructure (GI) into urban planning is one of the most effective ways to improve microclimates and address climate change impacts, particularly the urban heat island (UHI) effect.

GIs include green roofs, green walls, urban forests, bioswales, rain gardens, urban agriculture (community gardens, urban farms, peri-urban agriculture), river parks, local product markets, constructed wetlands, alternative energy farms, and nature conservation zones.

Green infrastructures provide vital climate-related services that significantly aid climate change adaptation and contribute to mitigation efforts. These nature-based solutions are increasingly recognized as a "win-win" strategy, offering a range of social, economic, and environmental benefits. However, the European Environment Agency (EEA) and other European initiatives prefer terms like "green spaces," "green systems," or "green structure" when discussing urban environments [127].

The goals of the EU Green Infrastructure Strategy (2013) [128]:

- To improve the permeability of the landscape, reduce fragmentation, and strengthen the functional and geographical connections between natural and semi-natural areas to sustain, increase, and restore biodiversity.
- It is vital to preserve, bolster, and, when required, restore good ecosystem functioning to ensure the provision of a range of ecological and cultural services.
- To raise the economic worth of ecosystem services by enhancing their functionality.
- It is important to improve humans' bonds with nature and biodiversity to increase the economic value of ecosystem services, acknowledge their social and cultural significance, and provide incentives for stakeholders and local communities to support their delivery.
- To restrict urban development and its detrimental effects on environmental services, biodiversity, and living standards.
- To reduce vulnerability to natural catastrophe hazards such as flooding, droughts, water shortages, wildfires, landslides, avalanches, and the urban heat island effect, as well as to adapt to and mitigate the impact of climate change.
- To optimize the use of Europe's limited land resources.
- To promote healthy living and create better environments by providing open spaces recreational opportunities, enhancing urban-rural connections, supporting sustainable transportation, and fostering a stronger sense of community [129].

Studies show a strong link between urban green spaces and climate, especially in reducing heat island effects. Parks and trees provide shade that cools the air and blocks sunlight. Green surfaces absorb less heat than asphalt or concrete due to their lower thermal inertia. Adding greenery to building roofs and facades further helps control interior temperatures.

5.3.2. Green Infrastructures as Tools for Urban Climate Adaptation: Experiences and Assessments

Numerous international studies have proven a clear link between cities and climate change, stressing the harmful effects on human well-being and environmental ecosystems. Among the well-known events are pollution, heat islands, and urban decline [130].

Urban adaptation techniques emphasize "no-regret" approaches that solve current problems and offer immediate socioeconomic advantages by actively involving citizens and other stakeholders. These strategies aim to enhance adaptive capacity by adopting an ecosystem-based or "green" approach [131].

To address climate change, urban planning must adopt strategies like reducing pollution, promoting green spaces, energy-efficient buildings, innovative designs, and advanced technologies to support adaptation. Green infrastructures (GIs) have gained global recognition for their social, environmental, and climate mitigation benefits. Cities like New York, Chicago, and Washington D.C. have integrated GI strategies into climate protection plans. At the same time, initiatives like Greenworks Philadelphia aim to make Philadelphia “the greenest city in America” with comprehensive GI metrics [124].

The British Green Belts in UK urban planning, Barcelona's Anella Verda (a network of 12 protected areas connected by progressively improved ecological corridors), Milan's Vertical Forest, the Green Belt in Turin, the green ring surrounding the municipality of Mirandola (Modena), and urban gardens in Catania are a few examples of green infrastructure initiatives [132]. More research studies and projects in Europe and Asia have included different types of green infrastructure in urban planning. For example, in Copenhagen, [133] Green infrastructure (GI) development promotes a holistic approach to land management and produces favorable results in the social, economic, and environmental domains. Within a resilient and sustainable future city model, GIs are essential for promoting social cohesion, enhancing ecological services and biodiversity, and adapting to climate change.

5.3.3. Maintenance and Management Strategies

Large building stocks are becoming increasingly prevalent worldwide, which has brought considerable attention to their sustainability and made it a top priority for governments, legislators, local governments, organizations, and scholars. Existing structures are critical in promoting social, economic, and environmental development. Although all three categories are included in sustainability, the environment appears to be the main focus [134].

Implementing sustainable and efficient building maintenance practices in tandem is imperative, as practical approaches also contribute to creating a safer and cleaner environment. Inadequate maintenance of Heating, Ventilation, and Air Conditioning (HVAC) systems, for example, can result in higher energy consumption and increased CO_2 emissions if the systems do not satisfy efficiency criteria. On the other hand, appropriate maintenance guarantees reduced energy consumption [135].

Maintenance procedures such as inspection protocols, choice of materials, and disposal of maintenance waste are also crucial [136]. Inconsistent maintenance practices that do not align with sustainable methods can negatively affect the surrounding environment. Thus, it is essential to implement sustainable and efficient building maintenance practices simultaneously.

5.4. Strategies Development

Friday-Stroud & Sutterfield [137] suggest that the primary aim of the introduced strategy is to reduce internal weaknesses and external threats while enabling organizations to enhance their competitiveness by focusing on internal strengths and external opportunities. Boyne & Walker [138] highlight that the goal of a strategy is to "establish a clear direction for collective efforts, guide those efforts toward specific objectives, and ensure consistency in management actions over time."

Strategies should be carefully crafted and understood within the construction industry as a tool for organizations to reach their goals, such as enhancing sustainability and delivering improved services. This is often achieved by aligning current conditions with a flexible strategy that adapts strategic planning accordingly [139]. To develop effective and sustainable building maintenance strategies, it is necessary to determine the problems, obstacles and needs today [140].

The neglect of existing structures, excessive energy use, high maintenance costs, decreased safety, challenges integrating new facilities, and a lack of long-term planning for maintenance growth are all linked to building aging-related issues [141]. As a result, strategic approaches have been designed to address both present concerns and future challenges, considering their negative impacts, which obstruct sustainable and effective building maintenance practices as part of responsive strategies.

5.4.1. Approach for Environmentally Related Issues

Physical examinations still frequently employ destructive inspection techniques to find construction flaws, although these procedures are bad for the environment. They contribute to increased waste, generate noise, and heighten maintenance workers' risk of accidents and injuries [142]. On the other hand, non-destructive inspection methods, such as infrared thermography, provide a speedier and less intrusive means of finding possible flaws without the need for costly and time-consuming physical inspections [136].

Despite advances in maintenance techniques, some materials still contribute significantly to carbon emissions due to their embodied carbon. Chiang et al. [143] explained that these materials are preferred because they are cheaper, whereas environmentally friendly alternatives are often more costly than conventional options.

A key factor in sustainable building maintenance is using eco-friendly materials during maintenance activities [144]. Organizations can promote sustainable materials by prioritizing suppliers with long-term sustainability policies, consulting green experts, and enforcing regulations like mandatory environmental reporting. Effective waste management during building maintenance is vital, given the significant waste generated. Practices should align with the three Rs principles: reduce, reuse, and recycle, to maximize waste reduction and resource efficiency.

5.4.2. Approach for Organisational-related Aspects

In an organizational structure, clearly defined responsibilities are crucial for guiding employees in their roles. An effective organizational structure, which includes a clear outline of responsibilities, is key to distinguishing successful organizations and helps minimize confusion and disorder in the workplace [142].

Engaging important stakeholders in building maintenance is vital for organizational collaboration, as they offer diverse perspectives, feedback, and suggestions. This partnership enhances maintenance procedures by providing valuable insights and solutions to common challenges. Managers, contractors, maintenance teams, building users, and maintenance organizations are among the stakeholders included in this study. Engaging these stakeholders is a doable approach to accomplishing the objectives of maintenance management and dramatically enhances the provision of maintenance services [145].

5.4.3. Approach for Aspects of Human Resources Development

Building maintenance requires a diverse team of professionals with expertise in sustainability. Staff must stay updated on industry needs, developments, and challenges, ensuring they meet high competence standards through organizational-level management and development.

Adopting advanced technologies in maintenance improves efficiency, saving time and money. Organizations should enhance staff skills through workshops, industrial training, and teamwork policies to achieve this. This study highlights the importance of training in areas like Building Information Modeling (BIM), non-destructive inspection tools, sustainable practices, and occupational health and safety. Providing practical, hands-on training tailored to current and future challenges equips organizations to meet evolving industry demands.

5.4.4. Approach for Matters About Finances

In the building maintenance industry, a financial development strategy ensures cost-effectiveness, balances income and expenses, and manages budgets well to promote maintenance success. Selecting the best fund allocation strategy can enhance a building's performance over time. As Au-Yong et al. [146] suggest, maintenance organizations or departments should implement systematic processes to determine the necessary budget to meet critical maintenance requirements accurately. Long-term planning is essential to cover the total budget within the specified timeframe.

A cost-benefit analysis should guide a maintenance budget to control expenditures and align spending with demands. An optimal and sufficient budget is essential to maintain a building's value and functionality. The maintenance management department should adopt an ideal cost-value strategy to reduce costs and promote financial growth.

5.4.5. Approach to Include Aspects Related to Aging

Buildings are aging quickly, with the age of existing structures on the rise. Older buildings often come with higher maintenance costs and increased energy consumption, posing significant safety risks to the structures and their occupants. These risks may also create potential health and safety hazards for pedestrians and those nearby [147]. Aging buildings present ongoing challenges, with limited awareness of their maintenance and future costs. Long-term plans are essential to support their preservation and restoration. Common issues in structures over 30 years old, such as leaking pipes and crumbling walls, highlight the need for mandated inspection programs. These programs should include clear guidelines and precise standards for inspections and repairs to ensure adequate upkeep [147].

Routine maintenance often proves insufficient for aging buildings unless supplemented by more extensive restoration efforts, such as rehabilitation. Shahi et al. [148] define rehabilitation as "the process of repairing, modifying, or enhancing a deteriorating building to ensure it remains suitable for use," focusing primarily on restoring damaged structural components. Rehabilitating aging buildings is highly effective, particularly for structural restoration, as it addresses material consumption, waste generation, and system failures caused by reliance on corrective maintenance.

Older buildings often consume excessive energy, negatively impacting sustainability. Upgrading systems like HVAC and building envelopes can improve energy efficiency, helping these structures meet modern standards while enhancing cost efficiency, safety, and environmental performance. Shahi et al. [148] define retrofitting as "adding or upgrading features or capacities to an existing building, which it was not originally designed with, to enhance energy use and efficiency." Mandatory inspections are essential to address maintenance neglect in aging buildings. Rehabilitation improves structural elements while retrofitting enhances energy efficiency, particularly in building envelopes and HVAC systems. From a lifecycle perspective, restoring aging buildings is more environmentally sustainable than demolition and reconstruction.

5.4.6. Approach to Developing Aspects Linked to Users

The performance of energy systems largely depends on how well each system is maintained from the outset. According to a study by Au-Yong et al. [149], deteriorating building components often reflect the care users provide rather than the effectiveness of maintenance operations. Encouraging positive and responsible interaction with facilities is crucial for preservation. Building management can promote this by raising awareness about proper usage and maintenance, engaging users to ensure safety and prevent degradation, and encouraging prompt reporting of issues to maintain buildings in excellent condition.

Almeida et al. [150] argue that building rules should be created to satisfy the requirements of its occupants, improve their comprehension of the structure's capabilities, and offer guidance on enhancing performance and preserving ideal circumstances. All users must understand how the building works and take action to make sure it runs well. In addition, building maintenance management ought to set up a platform for gathering user input on maintenance tasks and monitoring user satisfaction with various factors, including safety, punctuality, communication of repair activities, and general service quality [140].

These strategies aim to guide maintenance organizations and stakeholders by promoting efficient and sustainable maintenance practices aligned with operational standards. As buildings age, waste generated from maintenance activities rises globally. However, there is a significant gap in research on systematically classifying maintenance waste by quantity, content, and hazardous nature from actual case studies. Furthermore, insufficient studies have been conducted on sustainable treatment methods for this waste. [151].

6. FUTURE DIRECTIONS AND EMERGING TECHNOLOGIES

6.1. Advancements in Sustainable Concrete Materials

The worldwide building industry has one of the most significant environmental impacts of all the sectors. Building material production and transportation, along with construction and demolition (C&D) waste, account for 30–50% of all waste and 10–30% of greenhouse gas (GHG) emissions. Supplied to waste sites [152].

6.1.1. Reducing Cement in Concrete: Environmental and Economic Gains

Cement is the most carbon-intensive and costly component of concrete, with its production emitting about 0.5 kg of CO_2 per kilogram during the clinker production process, excluding CO_2 from fuel combustion. Reducing cement content addresses these environmental and economic issues and improves the structural integrity of buildings. Using supplementary cementitious materials (SCMs) such as blast furnace slag, fly ash, and silica fume is a prevalent strategy in North America, where these materials are added directly to the concrete mix to enhance its properties and lower emissions. Furthermore, optimizing aggregate particle packing can significantly reduce the need for cement. This method improves the density of aggregate particles, reducing the cement paste required and potentially incorporating inert microfines from crushed aggregates. However, this could change water requirements and impact durability. Approaches such as discrete element models and analytical particle packing models help simulate and optimize particle arrangements and density, reducing cement content by over 50% while maintaining or enhancing concrete performance. This comprehensive strategy mitigates the environmental impact and sets a course toward establishing global benchmarks for cement use efficiency and significantly reducing carbon emissions [153].

6.2. Recycled Materials

6.2.1 Coarse Recycled Concrete Aggregate

Despite extensive research, recycled concrete aggregate (RCA) is rarely used for structural purposes. This is due to the variability in RCA properties based on the concrete source and the high cost and time involved in aggregate pre-treatment and quality monitoring. Additionally, concrete with high RCA content often underperforms compared to natural aggregate (NA) concrete in serviceability, strength, and durability. [154].

Several pre-treatment techniques have been proposed to enhance the properties of recycled concrete aggregate (RCA) by consolidating the adhering mortar layer and reducing aggregate porosity. These methods include mineral admixtures, scouring, carbonation, surface improvement agents, and modified mixing processes [155].

Carbonation is not a practical solution for reinforced concrete applications, even though it has been shown to improve significantly the mechanical properties of concrete incorporating recycled concrete aggregate (RCA). The concrete's lower pH may increase the steel reinforcement's susceptibility to corrosion [156].

The equivalent mortar volume (EMV) method is a new mix design technique that calculates the total mortar volume while considering recycled mortar content (RMC). This approach reduces the amount of cement paste required in new concrete. Findings indicate that reinforced concrete members designed using this method exhibit structural performance in flexure and shear equal to or better than that of similar members made with conventional concrete mixtures. [157].

When employing the EMV approach, the bond strength between steel reinforcing bars and RCA concrete was up to 33% higher than when using traditional methods, and it was comparable to that of conventional concrete [158].

6.2.2. Fine Recycled Concrete Aggregates

The structural performance of reinforced concrete elements containing fine RCA—frequently thrown away as low-quality waste—has not received much attention in the literature. Concrete workability, strength, and durability are widely believed to be adversely affected by the high water absorption of hydrated cement particles, which are present in large quantities in fine RCA [159].

6.2.3. Other recycled materials

Other waste elements like rubber and glass have been added to concrete formulations with varying degrees of success. Usually, the main goal is to keep these waste materials out of landfills instead of improving performance. These practices don't directly enhance the sustainability of the concrete construction industry despite being beneficial in that they reuse waste and lessen the environmental impact of other industries (i.e., creating a closed-loop system where concrete materials can be continuously recycled like steel). Thus, they are not given any more consideration here [160].

6.3. Integration of Smart Technologies

Nanotechnology manipulates a material's chemical and physical properties to improve its performance. The end product is a material with its original name but capable of remarkable things. These materials create a sense of something beyond the usual for both the user and the observer. By delving into the atomic level and altering its properties, nanotechnology enables the creation of new materials that can achieve previously difficult or impossible objectives.

6.3.1. Fundamentals of nanotechnology

An overview of the fundamentals of nanotechnology is as follows [161]:

- The ability to manipulate and rearrange individual atoms allows for constructing materials at the atomic level since atoms are the fundamental building blocks of all materials.

- Materials exhibit different chemical and physical properties at the nanoscale than at larger scales.
- The discovery of unique properties at the nanoscale opens up possibilities for numerous new inventions.
- Nanotechnology is grounded in scientific research with strong potential for practical and beneficial applications.
- What was once considered science fiction has now become a reality through nanotechnology.
- It bridges various scientific disciplines and encourages collaboration among specialists, positioning itself at the forefront of scientific advancement.

6.3.2. Smart Materials and Nanotechnology Applications

Smart materials are known for their exceptional responsiveness in delivering peak performance. They are described as substances and structures that can respond to stimuli in both internal and exterior contexts. These materials have many functions built into their structures, allowing them to sense, detect, and adapt to various stimuli. They are susceptible to electrical, chemical, or magnetic stimulation [162].

Innovative nanomaterials, influenced by the Industrial Revolution and technological progress, have led to advanced building materials with exceptional thermal, electrical, and mechanical properties. Innovative concrete is one example designed to enhance appearance and environmental performance while maintaining its strong structural qualities.

Titanium dioxide: This ingredient strengthens durability, increases flexibility, and promotes photocatalysis, which makes the surface of the concrete resistant to pollutants and bacteria. It also can purify the surrounding air. The impact of this technology can be seen on two levels:

- Aesthetic impact: It allows for the design of streamlined buildings with dynamic and flexible forms.
- Environmental impact: It helps purify the air and combat environmental pollution.

Transparent concrete is a cutting-edge material that allows natural light to pass through, reducing the need for artificial lighting and saving energy. It is lightweight, provides insulation, and is used in construction for structural and decorative purposes, enabling unique designs on concrete facades [163]. Glass fibers have been added to concrete to improve it, giving architects a material perfect for flexible facades and organic forms. This substance is easily shaped, making it possible to create intricate forms [164].

6.3.3. Carbon-Negative Concrete Formulations

"Net zero," or carbon neutrality, is the condition in which the quantity of carbon dioxide that human activity releases into the atmosphere is balanced by removing an equal amount of CO_2. A nation, company, or organization must remove more CO_2 from the environment than it emits to achieve carbon negativity [165].

Carbon-negative materials such as wool, cork, biochar, and green cement provide sustainable alternatives. Unlike traditional cement with a high carbon footprint, green cement uses materials like magnesium silicates or hemp waste that absorb CO_2. Other carbon-capturing options include bioplastics, mycelium panels, 3D-printed wood, structural timber, olivine, carbonation concrete bricks, and innovative products like solein and vodka [166].

6.4. Construction Industry' Carbon Footprint

A significant portion of the world's carbon emissions comes from buildings, responsible for a substantial share of global greenhouse gas emissions. One study indicates that buildings account for over 30% of the GHG emissions associated with energy use worldwide [167]. Common building materials include rammed earth, metals (such as steel and aluminum), glass, stone, reinforced and conventional concrete, softwood, and cross-laminated timber. Among these, metals and other energy-intensive materials have the largest carbon footprints due to the energy required for raw material extraction, melting, purification, packing, and transportation before distribution. Carbon emissions can be used as a measure of the energy consumed during these processes [165]. While it is well known the construction, industry is a major contributor to carbon emissions, it is possible to reduce its overall impact by up to 90% through innovations in various operational stages. One promising solution involves the development of carbon sinks using engineered building materials [168].

Concrete optimization for carbon-negative outcomes involves two strategies: 1) reducing the carbon footprint of materials and 2) sequestering CO_2 directly into the concrete. Fresh concrete can be injected with liquid CO_2 or carbonate binders, producing stronger, low-carbon materials. Ferrock, made from limestone, metakaolin, fly ash, and iron powder, absorbs CO_2 during production. Another example is carbon-negative cement, made from magnesium ions (Mg2+) sourced from seawater, an abundant resource [169].

6.4.1. Biochar and Nano Biochar

Certain materials, such as biochar, can absorb and hold carbon dioxide. To increase carbon sequestration, these materials can be applied in various industries, including building and agriculture [170].

Biochar can be used as an alternative construction material and applied in pellets and wall plaster for carbon capture and sequestration. The carbon adsorption capacity of biochar is influenced by its activation process, which is determined by pyrolysis conditions (including temperature, heating rate, and pressure) and activation methods (without surface modification). The characteristics of biochar, along with its production and application in construction materials, can be summarized as follows [171]:

- Derived from waste materials.
- Capable of large-scale carbon absorption.
- Features a porous structure.
- Possesses a highly functionalized surface.
- Acts as a provider of nucleation sites for reactions.
- Compatible with polymers, asphalt, and cement in composite formation. Sourced from waste products.
- Able to absorb carbon on a large scale.
- Has a porous structure.

- Exhibits a surface with high functionality.
- Provides nucleation sites for chemical reactions.
- Works well with polymers, asphalt, and cement in composite materials.

6.4.2. Nanobiochar

Nanocomposites that incorporate biochar and nanobiochar are examined in [172]. Production methods for nanobiochar from biochar, biomass (such as rice husks), and various residues are well-established. For instance, the high-energy ball milling process can produce biochar micro- and nanoparticles with 500 nm or smaller sizes, enhancing CO_2 sequestration [173].

6.4.3. Biomass and Biomanufacturing

The most straightforward and natural approach is using biomass as a carbon store. Carbon obtained from the atmosphere by plants through photosynthesis can be found in any biological raw material, including organic waste and plants. This contrasts with the carbon from fossil fuels, which is present in plastics. Various organic wastes, such as mine tailings, blast furnaces, steelmaking slags, and high-reactivity biomass ashes (preferably low in sulfur), can be used as valuable raw materials for CO_2-cured concrete.

Some biowaste-based strategies, including "Hydrogen Bioenergy with Carbon Capture and Storage" (HyBECCS), include the capture and storage of CO_2. This technique combines the absorption and storage of CO_2 with the thermochemical or biotechnological synthesis of biohydrogen from renewable biomass [174].

6.4.4. Nanomaterials and Nanocomposites

CO_2 capture, which includes CO_2 absorption reduction and detection, holds promise for achieving a carbon-neutral society [175]. It is possible to attribute the efficacy of different nanomaterials in environmental protection, including Metal-Organic Framework (MOF) and MOF-derived carbonaceous nanomaterials, nano silica, nano zeolites, nanocomposites, nano packaging, nanometals, nano lubricants, and nano coatings, to their distinct features. These materials provide partial answers to the problems associated with greenhouse gas sequestration in addition to helping with wastewater treatment, environmental remediation, bioenergy, and catalysis [176].

6.5. Life Cycle Assessments and Circular Economy Principles

Life Cycle Assessments (LCAs) and Circular Economy principles are crucial for carbon-negative materials. LCAs measure a product's environmental impact, while Circular Economy practices promote resource efficiency and waste reduction. Together, they help create sustainable systems that reduce carbon emissions and fight climate change [177].

Circular Economy principles focus on reducing waste and optimizing resource use by encouraging materials reuse, recycling, and regeneration. These principles aim to create a system where resources are continually repurposed, minimizing environmental impact and maximizing sustainability [178].

6.5.1. Policies That Support the Creation and Use of Carbon-Negative Materials

Promoting carbon-negative materials requires collaboration between governments and the private sector. Financial support through subsidies, grants, and tax incentives can drive research and adoption, while lower carbon taxes and regulations prioritizing these materials in public projects encourage their use. Educational campaigns can boost demand among industries and consumers.

Sub subsidies, competitions, and Carbon Capture and Storage (CCS) technology integration can enhance collaboration. Practices like reforestation and sustainable agriculture support engineered wood materials. Transparent production processes must be tracked, and international cooperation should minimize trade barriers. Extracting CO_2 via Direct Air Capture (DAC) and carbon mineralization to create valuable commodities is a key strategy. A united effort from academia, industry, and government is essential to achieve these goals.

Collaborations between the public and business sectors are essential to further creating materials that emit no carbon dioxide. This partnership has several components:

- Funding for research and development
- Establishing regulatory frameworks, such as standards, building codes, and carbon pricing mechanisms, while also setting emission reduction goals
- Joint research initiatives
- Promoting education and information sharing
- Government investments in infrastructure, such as facilities for carbon capture and storage and efficient transportation networks
- Labeling and certification to boost consumer confidence and drive demand for carbon-negative materials
- Implementing market incentives, such as carbon offset programs or cap-and-trade systems
- Adopting procurement policies that prioritize carbon-negative materials
- Launching public demonstration projects to showcase the use of these materials
- Creating collaborative innovation centers or hubs
- Managing intellectual property and licensing to facilitate the commercialization and adoption of materials
- Providing incentives for technologies that remove carbon from the air
- Promoting international coop

7. CONCLUSION

This study aims to comprehensively explore the use of sustainable concrete materials in advancing green infrastructure development, focusing on their properties, design considerations, and environmental benefits. It examines innovative solutions like permeable pavements, green roofs, vegetated systems, bioswales, and vegetated channels alongside optimized concrete mixtures and construction practices that minimize environmental impacts. The research highlights the pivotal role of sustainable concrete in enhancing urban resilience through improved stormwater management, reduced heat island effects, and ecological growth. With the depletion of natural resources such as river sand and coarse aggregates, the study underscores the importance of industrial byproducts like steel slag and mill scale and emerging technologies such as 3D printing, nanotechnology, and carbon-negative materials to reduce environmental footprints. Integrating lifecycle assessments (LCA), green infrastructure, and frameworks like LEED and BREEAM advocates a holistic approach to creating resilient and eco-friendly urban environments. The following are the conclusions in detail:

1. In conclusion, sustainable concrete materials, predominantly permeable concrete (PCs), and vegetated concrete systems mark significant advancements in green infrastructure. PCs enhance stormwater management and improve urban environments by boosting air quality, reducing urban heat islands, and promoting groundwater recharge. The properties of porous concrete, including its strength, optimize performance while balancing environmental benefits and mechanical resilience.
2. Innovative applications like green roofs and bioswales further demonstrate how integrating vegetation with concrete can mitigate urbanization's negative impacts. By adopting these sustainable practices, we can promote ecological growth, improve water quality, and create more resilient urban landscapes. These strategies are backed by scientific research and are increasingly featured in policy discussions to tackle contemporary environmental challenges.
3. The construction industry faces significant challenges due to the depletion of natural resources essential for concrete production, like river sand and coarse aggregates. This depletion increases material costs and raises environmental and economic concerns. Consequently, there is a growing shift towards sustainable building materials, mainly industrial byproducts such as steel slag and mill scale. Research indicates that incorporating these byproducts can enhance the mechanical properties of concrete, paving the way for innovative and sustainable construction practices.
4. Additionally, advancements in design and construction techniques, including 3D printing and innovative formwork systems, provide solutions that minimize waste and improve efficiency. These technologies enable the development of complex geometries while reducing labor and material costs. Prioritizing sustainable material sourcing and waste reduction strategies is essential for fostering a more environmentally responsible construction industry, ensuring that future infrastructure meets economic and ecological needs.
5. The construction industry significantly affects environmental sustainability, with its stages—mining, manufacturing, construction, operation, and demolition—contributing to energy consumption and pollution. Implementing LCA is a vital strategy for evaluating the environmental impacts of building projects, enabling informed decision-making that considers long-term benefits over initial costs. This comprehensive assessment systematically analyzes resource usage, waste emissions, and energy consumption, promoting eco-friendly construction practices.
6. Furthermore, using cool materials, permeable pavements, and urban vegetation effectively mitigates urban heat island effects and improves stormwater management. These approaches enhance thermal comfort in urban areas while improving air quality and energy efficiency. By integrating these solutions within the LCA framework, stakeholders can ensure that construction practices align with broader environmental goals, fostering a sustainable future for urban development.
7. Integrating green building codes and standards, such as BREEAM and LEED, is essential for enhancing the sustainability of the construction industry. These frameworks assess environmental performance across various dimensions, including energy efficiency, water conservation, and indoor environmental quality. The ongoing development of standards by organizations like ISO and CEN highlights the need for consistent methodologies to evaluate and improve building sustainability. Additionally, green infrastructure in urban areas can mitigate climate change impacts while promoting ecological benefits and social well-being.
8. Strategic maintenance and management practices are vital to tackle the challenges of aging buildings. Comprehensive guidelines for rehabilitation and retrofitting should focus on enhancing the performance and safety of older structures while contributing to environmental sustainability. Engaging stakeholders and raising user awareness is crucial for building integrity and functionality. A holistic approach incorporating advanced technologies, sustainable materials, and proactive management strategies will ultimately facilitate the transition toward resilient and environmentally friendly built environments.
9. The future of sustainable construction relies on significant advancements in concrete technology and the integration of eco-friendly materials. As a major contributor to global greenhouse gas emissions, the building industry can benefit from adopting low-cement concrete, supplementary cementitious materials (SCMs), and optimized particle packing to reduce carbon footprints while maintaining structural integrity. Additionally, exploring recycled materials, primarily recycled concrete aggregates, underscores the need for innovative pre-treatment techniques to enhance their performance, promoting a circular economy in construction.
10. Emerging technologies like nanotechnology and the development of carbon-negative materials are essential for fostering environmentally responsible building practices. Collaborative efforts between the public and private sectors will be vital in driving research and implementing these advanced materials. The construction industry can significantly mitigate its environmental impact and progress toward a more sustainable future by embracing strategies that prioritize carbon capture, resource efficiency, and sustainable production processes.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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