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Article

Sustainability of Concrete as A Civil Engineering Material

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Abstract. With increasing concern about the environment, energy consumption, climate change, and depletion of natural resources, the importance of sustainability has become mainstream among engineering and scientific communities. Concrete infrastructure is superbly durable and comes with a myriad of benefits. Yet, the production of concrete is energy intensive and represents a substantial portion of air pollution. Largely due to cement manufacturing, concrete represents 7% of greenhouse gas emissions globally and 1% in the United States. Focusing on sector-specific emissions in the United States., this paper outlines the environmental concerns of concrete production and discusses the forefront of research in reducing these effects including innovations in cement manufacturing, alternative clinker technologies, and carbon capture use and storage. Also discussed are various approaches and efforts in concrete recycling and incorporation of industrial wastes and supplementary cementitious materials into concrete. Finally, this study reviews the role of civil engineering design at various scales in the sustainability of concrete infrastructure.

Keywords: Sustainability, cement, greenhouse gas, concrete, infrastructure, recycled.

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1. Introduction

Concrete is one of Earth's most consumed man-made building materials and is used for construction projects large and small, from constructing infrastructure to building houses. Almost twice as much concrete is consumed globally than the total of all other construction materials combined [1]. Concrete's simple ingredients of cement or other cementitious materials, coarse and fine aggregate, water, and chemical admixtures, along with reinforcement rebar, add up to far more than the sum of their parts. Concrete's durability, strength, weight, material abundance, and formability make it a ubiquitous civil engineering material. With a fast growing global population and the need for new cities to support them, concrete is required everywhere to keep up with demand, with a 12-23% market increase expected by 2050 [2]. Its contribution has been critical to the growth of human society through the expansion of worldwide infrastructure.

Yet for all of its benefits, the mass production of concrete comes with significant environmental challenges and consequences. The production of concrete's constituents results in the release of substantial quantities of carbon dioxide (CO_2), other greenhouse gases (GHGs), and air pollutants. While the raw materials for concrete production have historically been viewed as abundant, exponential growth in material demand [3] has put strain on this assumption and increased haul distances. Sand, a primary concrete ingredient, is deceivingly scarce due to the need for sand of specific angularity to produce high strength concrete. Sand extraction from rivers, deltas, and coastal areas has resulted in the devastation of aquatic ecosystems, water quality and erosion issues, and a variety of other unintended consequences [4, 5].

As local material supplies subside and necessary regulation requires cities to source raw materials from farther away, transportation costs and emissions of the intrinsically heavy materials increase. Additionally, concrete consumption is often linked to suburban development and the replacement of natural lands with impervious built environs which do not allow rainwater to soak into the soil [6]. Numerous other challenges with diminishing natural resources, growing understanding of the benefits of ecosystem services, and rising costs of production and energy consumption are all closely connected to the cement and concrete industry. Addressing these challenges will play a critical role in the advancement of a sustainable society and industry throughout the 21st century.

In recent decades, numerous alternatives and sustainable practices have been explored to reduce environmental impacts caused by the production and use of concrete in the civil engineering domain. Cement production can be modified to reduce environmental impacts and GHG emissions. Concrete can be produced with a substantial proportion of sustainably sourced and recycled resources, have low maintenance requirements, and require a low inherent energy consumption while maintaining high durability [7]. Ultra-high-performance concrete (UHPC) can reduce material consumption while meeting project needs. Sustainable engineering and construction practices can take into account the influence of new and existing structures on human health, social wellbeing, energy conservation, and environmental and technological capital in both the short term and across the infrastructure life cycle. Construction and operating costs can also be reduced through an integrated sustainable design [8].

The subsequent sections present various sustainable solutions and recent development efforts to improve the sustainability of concrete infrastructure. Challenges and opportunities with concrete's long-term future use are highlighted. This paper also seeks to summarize the relevant considerations in assessing the sustainability of concrete as a civil engineering building material. Finally, select sustainable practices that have minimal barriers to implementation are also discussed.

2. Environmental Impacts of Portland Cement Production

Production of Portland cement requires a considerable quantity of natural resources, is energy intensive, and discharges GHGs. Natural resources and ecosystems as a whole have been depleted by 70 percent more from the Earth than they can be replenished or regenerated [9]. The depletion of natural resources in certain geographical areas is becoming a growing concern to the sustainability of the cement and concrete industry. Limestone is the most extensively used constituent in concrete production. It is used to manufacture Portland cement and as aggregate in concrete [10]. Approximately 1.6 tons of raw materials are required to produce one ton of Portland cement. In 2020, the United States consumed 102 million metric tons of Portland cement [11], meaning that roughly 163 million tons of raw materials such as limestone and quality clay are needed annually in the cement production in the U.S. alone. In some regions, cement production is becoming more difficult due to diminishing resources of limestone and quality clay. This will have a negative impact on the regional economy as numerous jobs associated with the cement and concrete industry may be discontinued if the production is decreased.

2.1. GHG Emissions

The production of cement is among the most energy consuming industrial processes alongside metals and petrochemicals. One metric ton of Portland cement requires approximately 5.5 million BTUs of energy [12]. A study by Miller et al. [13] reports that clinker production, an intermediate material in manufacturing cement, is responsible for roughly 90% of the energy used in the cement manufacturing process and is responsible for almost all of GHGs produced during cement production. A set of kiln systems is used to evaporate water in the raw materials and calcine the carbonate constituents during the clinker preprocessing [10]. In each aspect of the cement manufacturing process, 50%-55% of CO_2 and GHG discharges is from the calcination of limestone where CO_2 is a direct product of a chemical reaction creating quicklime, 40%-50% from fuel combustion, and around 10% from the use of electric power [9]. The cement industry produces about 7% of global GHG emissions [14].

Analyzing U.S. emissions from the cement industry specifically is challenging due to the manner in which the US Environmental Protection Agency (EPA) and Energy Information Administration (EIA) structure data on GHG estimates. While direct emissions from calcination and other processes at cement manufacturing facilities is reported directly, these notably do not include emissions from fuel burning for energy on site nor those associated with the generation of electricity used in cement processing. Thus, the authors could not find an industry specific emissions analysis in the literature. A data analysis effort was thus undertaken to inform this study with a comparison between the 1990 and 2018 data representing the maximum historical range for which all data were available.

Cement production data were collected from the United States Geological Survey Mineral Commodity Summaries [11]. GHG emissions from calcination and other on-site sources other than fuel burning are readily available from the U.S. Environmental Protection Agency (USEPA) Inventory of U.S. GHG Emissions and Sinks [15]. Data on U.S. cement energy consumption, in trillion BTU, from fuel burning and electricity use were taken from the EIA Manufacturing Energy Consumption Survey [16]. CO_2 emissions factors were used to convert between energy consumption and CO_2 emissions for individual fuel sources, in this case natural gas, coal, coke, fuel oil, and petroleum coke [17]. Finally, average U.S. GHG emissions per unit of electricity consumed (0.709 kg CO_2 Eq. per kWh in 2019) were utilized to calculate cement industry emissions from electricity use [18].

Figure 1 shows the result of this data assimilation after calculation to obtain results in common units for each category. Note that these do not include transportation emissions. Cement production in the U.S. has become 18% less carbon intensive from 1990 to 2018. To put cement emissions into perspective, data from various sectors are tabulated in Table 1 alongside the fraction of the cement industry total emissions of each overall sector. While cement only used 2.8% of the energy consumed by the industrial sector in 2018, it represented 4.7% of total GHG emissions, due to the unique emission of CO_2 from calcination. Table 1 shows that cement production represents just 1.0% of total U.S. emissions, which is notably much lower than the 7% typically reported globally [14]. This is understandable given the relatively slow growth of concrete infrastructure in the U.S. relative to the developing world, particularly China where it is estimated that 14.8% of total GHG emissions come from cement production [19].

Table 1. U.S. Greenhouse gas emissions of various sectors relative to cement production.

	CO_2 Equivalent Emissions in million metric tons (Cement Fraction %)			
Emissions Sector	**1990**		**2018**	
Total Cement	64.8		69.6	
Total US All Sectors	6374	(1.0%)	6671	(1.0%)
Electricity Generation	1872	(0.4%)	1798	(0.4%)
Industrial Energy Use	854	(3.0%)	816	(3.0%)
Total Industrial	1614	(4.0%)	1483	(4.0%)

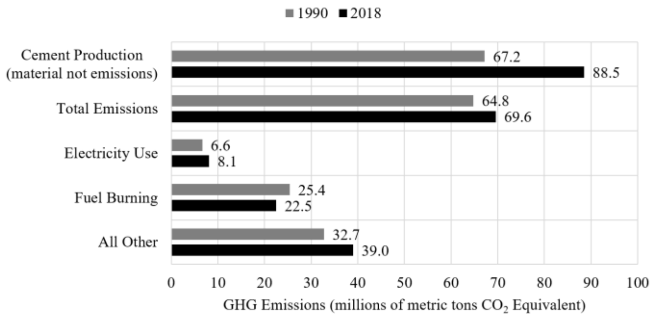

Fig. 1. Greenhouse gas emissions of U.S. cement production alongside material production of clinker. The vast majority of emissions from the 'all other' category is the result of direct CO_2 emissions from calcination.

2.2. Air Pollution

The World Health Organization (WHO) reports that more than 90% of the global human population lives in areas where pollutants in the ambient air exceed WHO guidelines [20]. In the United States, great strides have been made in reducing air pollution, however much work remains to be done. Air pollution causes elevated levels of pollutants in the ambient air and has serious implications for the health of humans and ecosystems.

The cement industry is a significant contributor to air pollution when including emissions from fuel burning and electricity generation which, with the current mix of fuels used and reliance on fossil fuels, emit particulate matter (PM), CO, NO_x and SO_x [19]. Additionally, fine particulates are swept away as mineral dust from various processing stages such as excavation, conveyor belts, crushing mills, and uncovered storage piles. Dubey and Bhopal note the volatilization of heavy metals and production of hazardous organics during high-temperature calcination in kilns [21]. The authors also indicate the importance of pollution control measures such as bag filters, water sprinkling for dust control, and coverings for storage piles.

Tables 2 and 3 show data collected from the USEPA National Emissions Inventory (NEI) from 2017, the most recent available with full quality assurance [22]. To provide perspective on the significance of air pollution from cement manufacturing, emissions data are tabulated for both the cement industry and the total emissions among

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all sectors, with a percentage provided. Table 2 provides data for the most common air pollutants of concern while Table 3 shows emissions of specific hazardous air pollutants for which the cement industry represents more than 0.5% of total emissions. Note that these data do not include emissions from materials extraction, transportation, or construction dust from the installation of concrete infrastructure. Several approaches can be taken to reduce the emissions from cement production, with much progress being made in the last decade.

Table 2. U.S. Cement manufacturing (CM) and total (among all sectors) emissions of criteria air pollutants (CAP) in 2017 [22] – Emissions given in billions of kg.

CAP	**CM**	**Total**	**Cement / Total**
Sulfur Dioxide	0.0236	2.3	1.03%
Nitrogen Oxides	0.0954	10.1	0.94%
Carbon Monoxide	0.0923	64.1	0.14%
$PM_{2.5}$	0.0060	5.1	0.12%
PM_{10}	0.0102	15.4	0.07%
Volatile Organic Compounds	0.0048	38.9	0.01%

Table 3. U.S. Cement manufacturing (CM) and total (among all sectors) emissions of hazardous air pollutants (HAP) in 2017: only pollutants for which cement represents > 0.5% of total emissions are shown [22] – Emissions given in kg.

HAP	**CM**	**Total**	**Cement / Total**
Dichloroethyl Ether	46	105	44.1%
Styrene Oxide	23	57	39.9%
Mercury	1,978	27,762	7.1%
Hydrochloric Acid	988,611	21,185,622	4.7%
Hexachlorobutadiene	67	1,543	4.4%
Selenium	2,724	129,221	2.1%
Manganese	9,472	758,047	1.2%
Chromium III	1,875	168,120	1.1%
Diethanolamine	1,149	114,780	1.0%
Ethylene dibromide (1,2-Dibromoethane)	127	19,620	0.65%
Chromium (VI) hexavalent	165	28,863	0.57%
Beryllium	27	4,806	0.55%
Arsenic	313	57,399	0.54%
Chlorine	29,981	5,953,789	0.50%
Vinylidene Chloride	85	16,862	0.50%

2.3. Reducing Cement Production Emissions

A shift away from using petroleum-based fuels in kiln heating, towards waste products and biomass may reduce CO_2 emissions by 10% [23]. A switch to cleaner burning fuels such as natural gas and away from coal, petcoke and fuel oil is also beneficial in reducing non-carbon air pollution from cement production. Gains in energy efficiency, heat recovery, and heating loss reductions also reduce emissions. Removing the burning of fuel for kiln heating altogether by switching to an electric process has the potential to remove 100% of heating emissions (40% of total cement production emissions) if the electricity is generated from renewable resources. Such a transition, however, will require a complete retooling of the manufacturing process and thus will not be a significant factor in near and medium term emissions reductions [23].

Ordinary Portland cement (OPC) will likely be replaced as the primary hydraulic binder used in concrete infrastructure in the long term due to its inherently high CO_2 emissions from clinker production. Alternative clinker technologies (ACTs) are in development, being designed from the ground up to be carbon neutral, allow for full electrification, meet the needs of the concrete industry in terms of strength, durability, and workability, and in general fitting into the norms and practices of the industry. ACTs are early in the development cycle and will not offset emissions in the short to medium term, but are crucial in the long term to achieve sustainability in concrete infrastructure. Antunes et al. provide a critical review of five ACTs in the context of carbon neutrality. The authors note that only two of the ACTs discussed would allow for full electrification, the patented Celitement approach and the 'X-Clinker' approach. Every ACT comes with significant challenges and the need for significant research and development before commercially viable. If ACTs were easy then OPC would not be ubiquitous today, but in the context of climate change, progress towards ACTs is a necessity in the long term unless an economical and sustainable strategy for carbon capture and sequestration of inherent OPC CO_2 emissions can be achieved. Antunes et al. predict that OPC will continue to dominate the concrete industry over the next 20-30 years, but that the incorporation of supplementary cementitious materials (SCMs) and increased efficiency in the use of cement will provide substantial emissions reductions while larger industrial changes to ACTs slowly ramp up [23].

2.4. Carbon Capture Use and Storage (CCUS)

CCUS, certain types of which are also referred to as carbon capture and sequestration (CCS), is a carbon emissions reduction approach that acknowledges the fact that CO_2 rich flue gas production is inherent to cement manufacturing and attempts to capture that CO_2 from this stream before it can be released into the atmosphere. The captured CO_2 can be injected into deep underground storage, utilized as a raw material to produce marketable goods, or infused into solids like concrete itself. This approach is also being studied in other carbon intensive industries such as coal and natural gas fired power plants, although cement kiln flue gases contain many air pollutants beyond CO_2, such as CO, NO_x, and SO_x that make CCS a challenge [23]. Adding additional purification steps to the gas stream further increases the cost of an already expensive technology.

Plaza et al. provide a review of CCS and beneficial uses of CO_2 produced from the cement industry [24]. The authors note that while many pilot-scale studies have been performed, no proven commercially viable techniques have yet been demonstrated. Even so, the authors conclude that CCUS will enable more GHG reductions than increasing thermal efficiency and switching to alternative heating fuels combined by 2050; with reductions in clinker use representing the greatest reductions. Plaza et al. overview several chemical absorption CCUS techniques. The SkyMine® Process represents the current largest pilot-scale demonstration and can capture approximately 13% of total cement production emissions while producing marketable products such as baking soda, bleach, and hydrochloric acid. Amine Scrubbing is a common CCUS technique for electricity generation power plants but is more difficult to apply in the cement industry. There have been a number of pilot-scale demonstrations of amine scrubbing for cement emissions although market viability has yet to be demonstrated [24].

As an alternative to absorption of CO_2 into liquids, adsorption methods sequester carbon onto the surface of solid particles. Eliminating the use of often hazardous and corrosives solvents and regents of absorption methods, adsorption is a relatively simpler and environmentally friendly approach. A variety of adsorption techniques, including low-temperature reactors and calcium looping systems, have been demonstrated at the pilot-scale with captured nearly-pure stream of CO_2 being either injected into concrete or used for the production of synthetic fuels. Oxyfuel combustion is another alternative that combusts the heating fuel for the kiln using oxygen instead of air. This yields a highly pure CO_2 gas stream, improves efficiency, and is reasonably low cost, although it can't be retrofitted into existing facilities and there is a lack of institutional knowledge in these techniques within the cement industry [13, 24].

Varying degrees of technological readiness, reliable funding streams and incentives are a perpetual challenge with CCS. Much progress has been made and many techniques are getting close to commercial viability. The use of the produced CO_2 streams to produce reliably marketable products for reuse is a co-industry that remains in its infancy. While there is much to be done and much needed in reducing emissions from cement production, the current lowest hanging fruit in making concrete sustainable are derived from reduction of cement use in the first place [13].

2.5. Concrete's Ability to Sequester Carbon Dioxide

An additional consideration with concrete use is its ability to sequester carbon dioxide from the atmosphere throughout its design life via carbonation. While carbonation has been traditionally viewed as undesirable as it hastens and exacerbates corrosion of steel reinforcement [25], it is an effect that must be accounted for in the net GHG emissions of concrete.

Souto-Martinez et al. conducted a modeling analysis of concrete columns to compare cradle-to-gate CO_2 emissions of column production against lifetime CO_2 sequestration from carbonation [26]. Results showed that up to 19% of the CO_2 emissions from production can be offset by long-term carbonation. Further, there is complex interplay between designed concrete mix strength and proportion of SCMs, with the designs sequestering the most CO_2 not representing the lowest overall net emissions. Souto-Martinez et al. found that high strength concrete, even with its higher cement usage, resulted in lower net CO_2 emissions due to reduced concrete volume required. Results also showed that square cross sections yield 90% slower carbonation rates over 25 years than crosses; a result that indicates a key tradeoff between encouraging CO_2 sequestration and preventing reinforcement corrosion [26].

Müller et al. note that the low porosity of UHPC results in very low rates of carbonation, eliminating any significant carbon sequestration offsets but also enabling a high degree of corrosion resistance, durability, and long service life, especially when compared to 'green concrete' with high uses of SCMs [27]. The authors show that designing for maximum carbonation to sequester carbon may often not be the most sustainable approach as there are other key factors, namely strength which enables more efficient cement utilization and service life which provides increased societal benefit per production emissions.

Galan et al. assessed the influence of several parameters on carbonation depth and rate by exposing several concrete specimens of varying cement type and additives to different exposure environments [28]. The study found that moisture content was a key parameter, with sheltered outdoor environments yielding the greatest carbon sequestration.

Gupta et al. found that incorporating biochar, which alone sequesters carbon from organic waste products, into a cement mortar further increases carbonation sequestration with manageable impacts on material properties, showing promise of a viable method to help decarbonize concrete [29]. Wang et al. evaluated a novel method of biochar incorporation into concrete combined with CO_2 curing and found that a 1-2% by weight biochar mixture increased the strength of concrete while 5% had a negative impact [30]. Further, results showed that CO_2 curing reversed the negative cement hydration effects of biochar addition, showing a promising value-added methodology for decreasing net carbon emissions from concrete. Another trend in construction may compliment this technology: prefabrication. Precasting of concrete members at a mixing facility is increasingly popular in construction and enables advanced technology such as CO_2 curing, which requires special conditions infeasible at a construction site [30].

Jeong et al. verified a sophisticated numerical model for carbonation to experimental results in an artificially high CO_2 atmosphere, demonstrating good agreement between the two and that a single-phase model ignoring the aggregate is sufficient to achieve accurate simulation results [31]. The study also shows the concrete specimens could sequester more than 5% of their total mass of CO_2 as tested.

The current literature demonstrates the difficulty in accurately reporting and predicting the amount of carbon dioxide sequestered in concrete via carbonation due to high sensitivity to site specific conditions [28]. This is a young field of study, despite a long history of research into carbonation from a reinforcement corrosion perspective [32], and more research is needed in this area. Predicting and accounting for carbonation in a lifecycle assessment of the carbon budget for concrete infrastructure remains difficult. It also remains to be seen how significant of a factor CO_2 sequestration through carbonation will be in the design optimization of sustainable concrete.

3. Green Concrete: Recycling and Innovative Mix Design

Industrial byproducts and other post-consumer wastes can be recycled as concrete aggregates and cementitious materials to avoid environmental costs associated with the production of concrete and cement-based materials and to reduce the amount of waste taken to landfills. In concrete industry, supplementary cementitious materials such as fly ash, silica fume, finely ground recycled glass or granulated blast-furnace slag can be used to substitute a considerable quantity of Portland cement and produce sustainable concrete. It also promotes dependency on recycled materials, such as recycled crushed concrete (RCC), lessens the burden on natural resources and requires less energy to produce. The complete recyclability of concrete, by incorporating into other infrastructure such as pavement subbase and indeed the ability to use RCC to make more concrete, is a key feature that lends concrete to a sustainable circular economy. Recycling industrial byproducts has gradually increased by the cement and concrete industries [33]. For successful use of these materials, however, potential changes to the performance characteristics of concrete as well as their adverse hydration reactions need to be carefully evaluated.

3.1. Supplementary Cementitious Materials (SCMs) and Recycled Aggregates

One way to lessen the environmental impact of the concrete industry while preserving the quality of concrete is to recycle industrial by-products as SCMs or aggregates in concrete. This recycling represents a move toward a circular economy with less material throughput, avoids the cost, space, and potential environmental burden of landfilling discarded by-products, and can decrease the overall emissions of concrete infrastructure. At present, at least a certain amount of cement is required to allow a proper setting reaction to develop a desired strength of concrete [34]. There are, however, alternatives to make cement and concrete production more sustainable and, at the same time, give a useful application to a waste product.

For decades, industrial by-products such as glass, tires, fly ash, wood ash, rice-husk ash, silica fume, blast furnace slag, and demolished concrete have been used in the civil engineering sector [35, 36]. For example, crumb rubbers recycled from the automotive industry are used in asphalt to build a smoother and better performing pavement. The use of recycled glass can improve concrete performance when used with an optimum proportioning and reduce material cost by up to 14% [37]. Every six tons of concrete made with recycled glass powders reduces one ton of CO_2 emissions. Fine aggregate waste flows from the granite industry can also be incorporated into concrete to offset virgin sand use without loss of compression strength, although workability and tensile strength are negatively affected [38]. Granite fines have also been tested in geopolymer concrete applications where it was found to increase slump and early compressive strength relative to 100% virgin sand with no effect on setting time and a negative effective on post-fire residual strength [39].

Blended cements are another option that typically consist of various amounts of clinker mixed with additives such as fly ash, slag, silica fume and other pozzolanic materials. Using blended cement to partially replace the necessary Portland cement can improve the production capacity, encourage the industry to recycle pozzolanic materials, and reduce fuel consumptions [35, 36]. From the environmental standpoint, the main benefit of using these additives is the reduction in GHG emissions. For example, replacing 50% of the cement with supplemental materials is estimated to reduce CO_2 emission by over one billion tons, equivalent to eliminating one quarter of all vehicles in the world [35].

Fly ash, which is a by-product from the coal industry, can be mixed with lime to produce durable concrete. Partial replacement of energy consuming Portland cement with fly ash is known to reduce shrinkage and bleeding and improve alkali-silica reactivity. Utilizing SCMs yields less environmental impact, decreases energy consumption, and still allows for concrete to maintain its strength and durability [40]. Swe et al. optimized the mix proportions of pervious concrete using 40-60% fly ash to achieve LEED credits for stormwater infiltration while maintaining strength [41]. The theoretical and experimental optimization of fly ash in concrete remains an area of active research, as highlighted by a recent study that mixed plastic waste aggregates, graphene nanoplatelets, and high volume fly ash to achieve improved strength and water absorption [42]. High proportions of fly ash and other recycled materials such as steel slag can also be found in controlled low-strength materials, commonly known as flowable fill [43].

Although fly ash has been used over several decades as one of the supplementary cementitious materials commonly used in concrete, it is expected that the procurement of fly ash will become more difficult going forward as society moves away from coal-fired power plants and towards natural gas and renewable energy such as solar and wind generated power, and concrete demand continues to rise. Many other pozzolanic materials, those which become cementitious once within a concrete mixture, have been frequently used in concrete infrastructure. Pozzolanic materials are known to react well with the calcium compounds in cement and require a lower temperature to be calcined than Portland cement, which means that less energy is needed. Micro silica also known as 'silica fume' is an extremely fine noncrystalline powder, which is a by-product of ferrosilicon alloy and silicon production. Silica fume can replace around 10% of Portland cement in concrete and is known to increase its compressive strength and durability and make it less permeable. Foundries are responsible for generating a vast quantity of by-products including foundry sand and slag. Ground granulated blast-furnace slag (GGBS) is produced during the quenching of molten iron slag into water from the blast furnace and can be incorporated as a cement substitute in varying quantities up to around 50%. Researchers have proven [44]. that the use of GGBS makes concrete stronger and lowers the risk of cracking because of low setting temperatures.

3.2. Construction and Demolition Debris: Recycled Crushed Concrete (RCC)

A significant percentage of landfill space is taken up by construction and demolition debris. Approximately 600 million tons of construction and demolition debris are produced annually in the US, 24% of which (145 million tons) is taken to landfills [17]. Increasing the recycling rate of this debris is critical to lessen the extraction rate of raw materials to reach a sustainable, mostly circular economy. Further, landfilling rather than recycling increases potential health and ecological risks associated with waste disposal, and available landfill space near metropolitan areas continues to diminish due to the NIMBI effect (not in my backyard), leading to increased haul distances and disposal costs, particularly as landfill regulations become increasingly stringent. A sustainable alternative to alleviate this issue is to recycle construction and demolition debris into concrete and pozzolanic materials [33]. Established under the umbrella of World Business Council for Sustainable Development (WBCSD), the Cement Sustainability Initiative (CSI) has encouraged the cement and construction industries to meet their environmental and corporate social responsibilities by instigating fundamental changes in the way they operate business [45].

Since the CSI was launched in 2002, the industry has looked into recycling concrete as a component of better business exercise for sustainable development. Recycling concrete has an immediate impact on reducing GHG emissions by reducing cement production, avoiding the extraction, processing, and transportation of virgin materials, and lessening the burden on landfills. As concrete cannot be broken down into its original constituents (e.g., cement, water, aggregates, admixtures, etc.), it is most common to recycle and crush it for reuse as aggregates. Concrete can be recycled from production, construction, demolition, and leftover in ready-mix trucks. Of these various sources of concrete wastes, demolition debris is the most abundant, yet most challenging source for reuse since the original proportioning of demolished concrete is often unknown. However, recycled concrete can be in some cases preferable over natural aggregates. For example, the Federal Highway Administration (FHWA) promotes the use of recycled concrete as aggregates for road construction because of the fact that they are cheaper and that physical properties of crushed concrete such as strength and compactness are often better than that of virgin aggregates, making them ideal construction materials for road-base and sub-base for pavement. At present, recycled and crushed concrete are mostly used as aggregates in roadway subbase and in construction of new concrete structures and other civil engineering projects. While the effort to recover and recycle concrete is underway, it still tends to be overlooked and a considerable amount is still taken to landfills. With well thought-out planning in design and demolition, more recycling and reuse of concrete can be achieved and will help push the concrete industry towards sustainability. Even a low-grade usage of recycled concrete wastes is significantly preferable to landfilling.

Concrete recycling is largely influenced by the extent to which building codes and green building rating systems recognize the use of recycled concrete. Some of the well-known green building rating systems include LEED (USA), Green Globes (USA and Canada), BRRAM (England), HQE (France), and DGNB (Germany), among others. Reusing recycled concrete as aggregates for fillings, sub-base and outdoor landscaping is becoming common; however, the use of RCC in structural applications is somewhat limited. One primary factor is the common perception that RCC is of unknown strength and quality. Some studies have examined the strength and behavior of concrete members made with RCC and showed that they are suitable materials for precast concrete products and other structural applications if precautions are taken [46, 47]. Lack of consideration is another factor limiting the use of RCC in structural concrete because the supply can be unstable which creates unpredictable timelines for project delivery. These perceptions and challenges can be changed by green building rating systems if RCC's usage and possible applications are specifically addressed.

3.3. Other Innovative Approaches

Albeit slowly, the civil engineering sector has made meaningful progress towards improving sustainability by adopting and introducing environmentally friendly materials or technologies in the concrete production. Another innovative sustainable alternative recently developed is biologically-hardened concrete masonry units (BioCMUs) [48]. BioCMUs utilizes a process called 'microbiologically induced calcite precipitation (MICP)' in which recycled aggregates are combined with microorganisms such as bacteria to initiate a setting process similar to how a natural stone is created or similar to that implemented by coral. BioCMUs can be formed into various shapes and styles and the final product, post-biological reaction, is strong enough to be used in housings and other structures. Because this process does

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not require heating the mix to high temperature for thermal hardening, which is needed in the production of bricks, a significant reduction in carbon emissions can be achieved.

MICP also shows promise in enabling 'self-healing' concrete, in which cracks are automatically sealed via the action of bacteria mixed into the concrete. MICP has been shown to reduce crack area by 85% and increase compressive strength by 43% relative to the cracked condition [49]. With significant potential in reducing maintenance and improving durability, this approach has gained attention in recent years. Pungrasmi et al. found freeze-drying to be the most effective approach in encapsulating the desired bacterial spores prior to mixing with concrete to maximize their survival and performance once cracks appear and they are exposed to moisture and oxygen [50]. Further study however has shown the alternative vegetated cell dropping method to perform better in mortars [51].

The use of natural fiber reinforced polymer (NFRP) made from materials such as hemp and jute also show promise for decreasing the embedded emissions of concrete while preserving strength. While a wide array of applications are available, recent studies have shown promise in the use of NFRP in retrofit strengthening of concrete members, either to compensate for degradation or to meet updated earthquake codes. Jute in particular has been shown to enhance the compressive strength of NFRP confined concrete [52]; the authors also advanced the theoretical framework of modeling these systems. A further study tested the performance of jute NFRP as an external reinforcing material on damaged reinforced concrete beams in retrofit applications with results demonstrating workable rehabilitated shear strength similar to that of conventional approaches [53]. Tidarut et al. further investigated the use of a water Hyacinth, a fast growing nuisance weed, as a source material for NFRP. Utilizing this waste material for concrete confinement, the authors showed promising strength performance of tested cylinders while impact assessments demonstrated advantages over conventional methods [54]. Another approach was taken in [55] with the use of waste plastic straws as the feedstock fiber feedstock, yielding retrofit strengthening effects slightly better than jute-based NFRP.

4. Achieving Sustainability Through Engineering Design and Construction

With increasing concerns about the environment, energy costs and depletion of natural resources, the importance of sustainability has become one of the mainstreams among the engineering and scientific communities. The American Society of Civil Engineers (ASCE) define sustainability as *"a set of economic, environmental and social conditions (aka 'The Triple Bottom Line') in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality or the availability of economic, environmental and social resources"* [56]. Sustainable engineering represents responsible and proactive decision-making processes and innovations that balance environmental, economic, and social values to enable continued growth, a flourishing society and healthy ecosystems.

The materials used in design and construction play a vital role in pursuing sustainability. Aspects of a structures' lifespan include extraction and processing of materials, transportation to the project site, construction practices, maintenance requirements and expected useful life, off-gassing of volatile organic compounds while in service, value provided to users, local environmental consequences, flexibility and resiliency to changing conditions, and end of life disposal or recycling. Thorough life cycle analysis (LCA) is required for optimization which is currently beyond the practical scope of most infrastructure development projects. The level of planning, engineering time, and foresight needed to optimize all aspects of a project towards sustainability is difficult to achieve in practice with limited budgets and quick delivery schedules.

Concrete has substantial upfront environmental costs; however, its durability and recycling potential counteract this effect relative to other materials such as steel and wood. Additionally, the material properties and form flexibility of concrete can be advantageous in building construction. The high thermal inertia of concrete walls, slabs, and structural members allows a building to maintain temperature through diurnal cycles, reducing energy consumption, costs, and GHG emissions. When combined with the exterior insulation, especially in low-rise and industrial buildings where insulated concrete form (ICF) construction is utilized, a concrete building can provide excellent energy efficiency. This also brings human benefits to occupants due to high thermal comfort and sound insulation. Concrete buildings are also typically more resilient to natural disasters. The LCA scorecard for concrete infrastructure relative to alternative materials is project dependent. This is still a young science, and the civil engineering and construction professions are slowly building capacity for incorporating LCAs in decision-making. For now, the focus must remain on reducing the harmful effects and quantity of concrete. Müller et al. summarize the factors in improving the sustainability of concrete to reducing production emissions, improving concrete performance during lifetime, and extending the lifetime and durability of the concrete and structure [27].

4.1. Increasing the Useful Service Life of Concrete Infrastructure

One of the biggest factors contributing to the level of concrete sustainability is how often concrete structures need to be replaced or repaired. For example, billions of dollars are spent annually on maintaining and repairing concrete highway bridges in the U.S. [57]. Even after maintenance and repair, they must be replaced at the end of their useful lifespan. By strengthening deteriorated structures, their lifespan can be extended by years, which delays the need to build a new structure [58, 59]. When this is done to many concrete structures, the cumulative effect will be a vastly reduced amount of concrete production. Of several ways concrete structures can be strengthened, the use of fiber reinforced polymers (FRP) has gained popularity and been frequently adopted by engineering communities due to its outstanding mechanical characteristics and noncorrosive nature [60, 61]. Because of their light weight, the installation of strengthening systems can be done faster and relatively easily when compared to structural steel plates. The two most common ways FRPs are used in strengthening are externally bonded reinforcement (EBR) and near surface mounted (NSM) methods [62]. The EBR method is a technique where one or multiple layers or laminates of FRP are bonded to the tension side of the member being strengthened while the NSM technique consists of inserting FRP rods or strips into the grooves that are pre-cut in concrete cover followed by filling up with epoxy adhesives.

Hooton & Bickley highlight the need to focus on durability in sustainable concrete design [63]. The authors emphasize the need for highly specific quality control of concrete construction including temperature, compaction, and protection in ensuring durability. Tight tolerances and explicit performance requirements of the installed concrete are equally as influential as mix design [63].

4.2. Efficient Material Utilization Through High-Strength Concrete

Designing concrete structures with high or ultra-high performance (UHPC) concrete allows smaller or thinner structural elements to be used and reduces material consumption and environmental impacts. Müller et al. compare UHPC concrete with 'green concrete' that uses SCMs. Both show significant advantages over OPC [27]. Peem et al. demonstrated the effective use of hybrid polypropylene-steel fibers as a reinforcement mixture to optimize UHPC [64]. UHPC offsets increased production impact with improved material use efficiency, but its key advantage is in longer lifetime durability. The low porosity of UHPC, among other physical characteristics, enable UHPC to withstand exposure to harsh environments including freeze-thaw cycles, chloride and carbonation penetration and subsequent reinforcement corrosion, especially compared to 'green concrete' with substantial use of SCMs.

4.3. Is All of This Infrastructure Truly Needed?

The concrete with the lowest emissions of all is the concrete that never gets produced in the first place. Detailed life cycle analysis of concrete infrastructure with careful consideration into how to reduce the emissions from each step of the process is extremely valuable. Small emissions throughout production add up to significant improvements. However, of equal importance is the careful planning of infrastructure to maximize societal benefit while minimizing material consumption. Global expansion of concrete infrastructure is inevitable and desirable as it will coincide with, and in many ways enable, the rise in affluence and population within developing nations. Just as engineers optimize the materials usage when designing a building or bridge, larger scale analyses and urban planning can optimize which infrastructure gets built outright. Practices such as increasing urban density, avoiding suburban sprawl, and prioritizing public transportation can reduce the total amount of concrete infrastructure needed to enable a flourishing city. Concrete infrastructure represents an incredible societal asset, but making the most of what is constructed, as well as avoiding wasteful expansion, is a key aspect of aligning practices with sustainable principles.

4.4. The Need for Education and Policy

None of the multitude of options discussed herein for reducing the negative effects of concrete and boosting the positive to move towards sustainability will have any impact if not implemented at scale. Perhaps the category of innovation and change that is most impactful is the human element. Mindess concludes that education of civil engineers in sustainability and the materials science of concrete is critical to reduce emissions [65]. Mindess also notes that greatly reducing emissions from concrete is currently not a technical challenge, but rather a need for education and incentives. Diffusion of rapidly advancing knowledge into a concrete industry entrenched in tradition, codes, and best-practices as well as getting people to change their ways is the key challenge [65].

The importance of public policy as a tool for shaping the incentive structures around those involved in concrete infrastructure in all domains cannot be overstated. This can mean adding sustainability-informed requirements to building codes or permitting processes and incentivizing green building/project certifications. Policy initiatives can arise from government or professional organizations. Market-based approaches are also influential, such as internalizing the various negative externalities of concrete into the cost of infrastructure through emissions and landfilling fees. While much more research and technical innovation is needed to bring net concrete emissions to zero and make concrete infrastructure truly sustainable, in the short to mid-term the largest wins will come from education and policy, not technology.

5. Concluding Remarks

Concrete is a durable, recyclable, and ubiquitous material that is being used to maintain and expand infrastructure around the world to enable the growing human population to flourish. The production of concrete, particularly cement, yields substantial upfront environmental cost in the form of GHG emissions and air pollution. Since concrete will continue to be the most widely used construction material, continued efforts are needed to explore sustainable solutions to preserve and effectively manage limited natural resources. If carefully planned and implemented, innovations in cement manufacturing, mix design, infrastructure design, construction practices, and public policy will play a vital role in overcoming the previously mentioned challenges, and thereby will allow the building of a sustainable world. It is critical for civil engineers to consider long-term sustainable and economic dimensions throughout the design process and take accountability for the lifecycle of infrastructure. While there exist many challenges, working towards a common future of sustainability in the concrete industry is essential as infrastructure development, stopping climate change, and protecting human and ecosystem health are all non-negotiable. Sustainability, after all, is *about "meeting the needs of the present without compromising the ability of future generations to meet their own needs"* [66].

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