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Portland Cement at the Crossroads: Environmental Imperatives and Pathways to Sustainable Production

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Abstract: *The cement industry is indispensable for global infrastructure development, yet poses severe environmental challenges, accounting for 8–10% of anthropogenic CO_2 emissions, 12–15% of industrial energy use, and extensive natural resource depletion. This review systematically examines the sector's ecological and health impacts, revealing that 40–50% of emissions stem intrinsically from clinker chemistry and kiln combustion, while co-pollutants (NO_x, SO_2, PM) exacerbate climate change, biodiversity loss, and respiratory diseases. To address these dual crises, we synthesize emerging sustainability strategies across the concrete lifecycle. Key findings demonstrate that supplementary cementitious materials (SCMs) like fly ash or slag can reduce CO_2 by ≤1 kg per kg of cement replaced while enhancing durability through microstructural refinement. Complementary approaches include alternative/recycled aggregates, conserving natural resources, fossil fuel substitution with waste-derived alternatives, and mix optimization, minimizing binder content. Though techno-economic barriers persist for carbon capture and storage (CCS) and recycled concrete aggregates, regulatory frameworks emphasizing life-cycle assessment can accelerate adoption. Critically, no single solution suffices; achieving sectoral decarbonization requires policy-driven integration of these strategies within a circular economy paradigm.*

Keywords: *Portland cement, CO_2 emissions, Supplementary cementitious materials, Carbon capture and storage, Recycled concrete aggregate, and Sustainability.*

I. Introduction

The cement industry plays a significant role in improving living standards worldwide by creating direct employment and providing multiple cascading economic benefits to associated industries (Mishra and Siddiqui, 2014). Despite its popularity and profitability, the cement industry is confronted with many challenges like high energy consumption, excessive harvesting of natural resources, and green gas emission (Worrell et al., 2001; Ali et al., 2011) with resultant global warming, climate change and sustainability issues (Mishra and Siddiqui, 2014). Global warming is the rise in global temperatures largely due to escalating concentrations of atmospheric greenhouse gases, and climate change involves the gradual alteration of climatic conditions for an extended period (Etim et al., 2021) because enormous CO_2 emitted from cement manufacturing operations is unrecoverable and reusable (Raajasubramanian, et al., 2011). The major influence of weather changes and global warming is weather unpredictability (Etim et al., 2021). The greenhouse gas (GHG) emissions from energy consumption i.e., calcinations of raw materials and the combustions of fuels (Durastanti and Moretti, 2020) rightly described as greenhouse double whammy (Etim et al., 2021) and from chemical reactions related to clinker production (Olivier et al., 2012) are the primary cause of global warming and climate change (Kumar, 2018). Ratio wise, 40% of the carbon emissions emanate from combustion happening in the kilns (Durastanti and Moretti, 2020), 50% from the chemical reaction to produce calcium and magnesium oxides that constitute the clinker (Olivier et al., 2012) and 10% from transportation of raw materials and the electricity consumed by the facilities (Benhelal et al., 2012). GHG emissions during clinker production come from calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) calcination according to equations (1) and (2) (Olivier et al. 2012).

$$CaCO_3(s) + heat \rightarrow CaO(s) + CO_2(g) \quad \text{……………………} \quad \text{Eqn (1)}$$

$$MgCO_3(s) + heat \rightarrow MgO(s) + CO_2(g) \quad \text{…………………….} \quad \text{Eqn (2)}$$

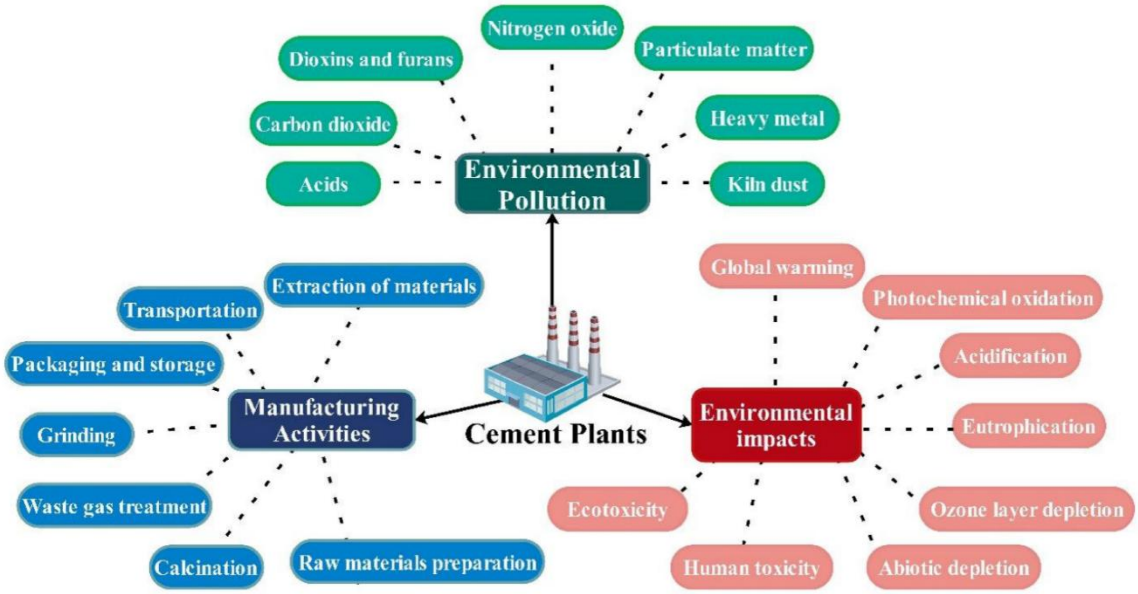

Figure 1: Key Pollution Sources Associated with Cement Industrial Areas (Suarez-Riera et al., 2024)

Current per annum global cement production of 4.1 billion metric tons account for about 8 to 10 percent of global anthropogenic CO_2 emissions (Poudyal and Adhikari, 2021), 12–15% of global industrial energy use (Usón et al., 2012, Summerbell, et al., 2016) and more than 30 billion tons of natural aggregates harvesting in concrete production worldwide every year (Monteiro et al., 2017). On average, the cement industry discharges about 500–950 kg of CO_2/ton of cement produced (Beltran and Arnesh, 2018). The cement industry contributes the most to global warming with CO_2 emissions ranging from 98% to 100%, as other greenhouse gases (GHG), for example, CH_4 and N_2O, have less impact (Josa et al., 2007; Gutiérrez et al., 2017). Apart from CO_2 emissions, cement production also emits other atmospheric pollutants, such as volatile organic compounds (VOCs), nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), Sulphur dioxide (SO_2) and hydrocarbons (Ige et al., 2022; Adeyanju and Okeke, 2019). Raw materials' extraction also leads to air pollution (Josa et al., 2007), besides natural resources depletion (Phair, 2006) and land degradation (Al-Dadi, 2014).

1. Environmental and Health Impacts

Cement factories and limestone-induced atmospheric pollution are seen to evoke severe occupational health hazards and adverse effects on crops, buildings, and persons residing in the vicinity of these industries (Parithielamvazhuthi, 2015). A slight worsening of the climate can lead to severe socioeconomic impacts in India, as the nation relies heavily on agriculture, with 70% of its rural population depending on farming for their livelihood. These emissions inflict adverse effects both on flora and fauna through ozone depletion, acid rain, biodiversity loss, reduced crop productivity, etc (Pariyar et al., 2013). Impacts related to global warming are due nearly exclusively to CO_2, those for acidification are mainly due to SOx (34%), NH_3 (30%), N_2O (17%), SO_2 (13%) and NOx (6%) and impacts for marine eco toxicity are essentially related to the emission of Fluorine and its inorganic compounds (54%), barite and Barium (34%) and many heavy metals such as Vanadium (3%) (Devi et al., 2018). Human health is affected adversely in a variety of ways, like itchy eyes, respiratory diseases like tuberculosis, chest discomfort, chronic bronchitis, asthma attacks, cardiovascular diseases, and even premature death (Mehraj et al., 2013). However, pulmonic-connected diseases are prevalent mostly among indigenous persons living around cement industries (Etim et al., 2021). Environmental considerations have thus rightly become one of the main criteria while formulating social and economic policies (Miccoli et al., 2014).

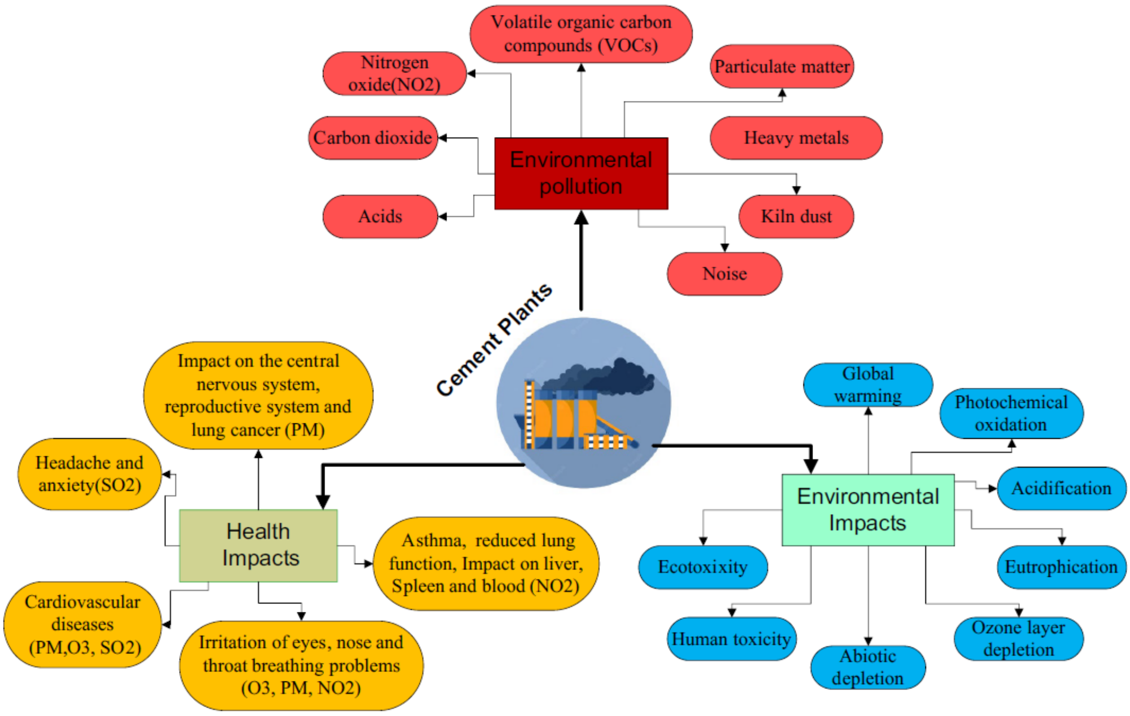

Figure 2: Environmental and Health Impacts of Emissions from Cement Production (Sudhakar and Reddy, 2023)

Climate change is attributed not only to global warming, but also to the global dimming due to the pollution present in the atmosphere (Ramanathan, 2007). Global dimming involves a decrease in sunlight reaching the Earth, primarily caused by particulates in the atmosphere that block solar radiation. Attempts to lessen air pollution might cause global dimming, but could potentially intensify global warming.

Globally, carbon dioxide levels in the atmosphere at present are about 570 ppm (Hamouda et al., 2020), which is targeted to be maintained below 550 ppm by 2050 by the Cement Technology Roadmap, thereby mitigating global warming (Etim et al., 2021). This goal can be achieved by capturing and storing CO_2 directly from the atmosphere (Wang et al., 2015). Techniques of pre-combustion capture, post-combustion capture, and oxy-fuel combustion are broadly used for CO_2 capture in the cement industry (Dunuweera and Rajapakse, 2018). More interesting to observe that about 80% to 90% less emissions of greenhouse gas are released in the manufacture of FA (Duxson et al., 2007), so a cent percent substitution of OPC by GGBS or FA would have a substantial effect on the environment.

2. Concrete and Portland cement: Environment-friendly Sustainability Strategies

The current global population, growing at a rate of around 1% per year, adding ~80 million people annually, is anticipated to reach 9.8 billion by the year 2050 (Najafi and Khanbilvardi, 2019). The need for cement and concrete is growing due to urbanization and the extraordinary development of the world's population, which demands the manufacture of 10–30 million new residences annually in addition to other infrastructural improvements (Javadabadi et al., 2019). cement and concrete production releases substantial amounts of environment-polluting greenhouse gases (GHGs), responsible for 8–9% of the total worldwide anthropogenic CO_2 emissions, consumes a large volume of energy and natural resources, and comes with environmental and sustainability issues (Monteiro et al., 2017).

Sustainability is one of the major concerns for the whole world at present, with the construction sector no exception (Ramasubramani and Gunasekaran, 2021). Economic development, social equity, and environmental protection, considered three significant pillars of sustainability (Samad and Shah, 2017), need to be balanced and harmonious for long-lasting impacts of concrete constructions (Aïtcin and Mindess, 2011). The overall social effect of a sustainable concrete construction is kept to a minimum over its whole life cycle (Kusuma et al., 2015) has an extremely high thermal mass, builds long-lasting structures, generates very little waste, is built from a few abundant resources on Earth, is made from recyclable components, and has an extremely low intrinsic energy need. (Naik, 2008).

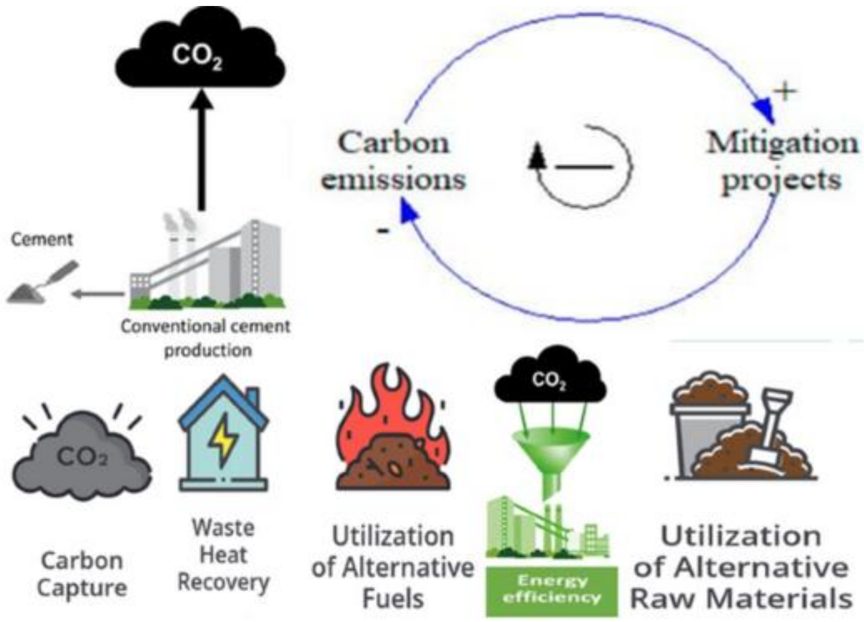

Figure 3: A Systems Dynamics Framework for Mitigating Environmental Impact in the Cement Sector (Ige et al., 2024)

Sustainability in cement and concrete manufacture is thus aimed at reducing GHG emissions, preserving natural resources, decreasing waste, and conserving energy (Javadabadi et al., 2019). A more relevant measure of sustainability is embodied CO_2 (ECO_2), which is the total amount of CO_2 produced in extraction and transportation of raw materials and their manufacture into the final product and expressed as CO_2 per unit mass, or CO_2 per unit volume (kg CO_2/tonne or kg CO_2/m^3) (Samad and Shah, 2017). Main sustainability strategies considered to offset the damaging effects of concrete manufacture are reported below:

2.1. Reduction in binder amount through supplementary cementitious materials.

Sustainable concrete construction requires reduction in embodied CO_2 and offsetting its cost, which is achievable by fractional substitution of OPC with fine siliceous and pozzolanic cementitious industrial and agricultural waste byproducts such as GGBS, pulverized fly ash (PFA), rice husk ash (RHA), silica fumes (SF), metakaolin, etc, succinctly termed as supplementary cementitious materials (SCMs) (Samad and Shah, 2017). Substitution of every kilogram of cement with cementitious material reduces CO_2 emission by up to one kilogram (Sonebi et al., 2016). SCMs, besides reducing greenhouse gas production, help in saving natural resources, reducing waste disposal by incorporating urban and industrial wastes into concrete according to the concept of circular economy (Ricciardi et al., 2020). Reduction in binder cement content with supplementary cementitious materials (SCMs) does not jeopardize the performance of concrete but instead significantly improves some of its durability properties, except for carbonation in most cases, especially foundation and underwater structures near chloride-enriched environments (Brito and Kurda, 2021). SCMs refine the microstructure within concrete by effectively filling among voids between cement particles, reducing porosity and thereby increasing the density and concrete's strength (Gao et al., 2023). This particle-packing effect also significantly enhances the compressive strength and rheological behaviour of concrete (Kashani et al., 2014). Denser and stronger matrix is achieved by formation of additional calcium silicate hydrate (C–S–H) gel through key binding phase of pozzolanic reaction when SCMs interact with calcium hydroxide discharged while hydration of cement takes place (Wang et al., 2023). The incorporation of SCMs makes the concrete mixture more cohesive and easier to work with (Feng et al., 2022), besides mitigating alkali-silica reaction (ASR) to prevent expansion and cracking in concrete (Barragan-Ramos et al., 2022; Mahmood et al., 2022). The type, proportion and optimal percentage of SCMs in the mix significantly influences their effectiveness (Wang et al., 2023).

2.2. Alternative aggregates

Aggregate is one of the basic components of concrete, occupying about 70–80% of its volume (De Brito and Saikia, 2013). Aggregates utilisation in the enormous manufacture of concrete is accountable for an unjustifiably limited natural resource consumption (Schneider et al., 2011). Due to the increased pace of extraction, non-renewable natural resources like river sand and limestone are at risk due to the large production of concrete brought on by rising urbanisation (Pepe et al., 2014) because current mining practices often exceed the natural replenishment rates of sand (Hackney et al., 2021). Finding alternative materials has thus become imperative to meet sustainable infrastructure demands with growing raw material costs and natural resource use (Kan and Demirbo, 2009). Manufactured sand from industrial by-products in place of river sand and coconut shell from agricultural waste in place of crushed stone aggregate are reported to be sustainable alternatives for fine and coarse materials, respectively, for concrete production (Ramasubramani and Gunasekaran, 2021). An optimal replacement of around 20%-30% of waste foundry sand, which originates from the ferrous and nonferrous metal casting industries and primarily comprises ferric metal residues in concrete, significantly improves properties such as voids, specific gravity, and density (Mehta, 2024). In Europe, the average annual rate of replacing concrete components with waste and by-products has risen to above 60% for an industrial sector and up to 95% for individual cement plants (Collivignarelli et al., 2020).

2.3. Recycled concrete aggregate (RCA)

Sustainable development and circular economy, aiming at reducing carbon emissions and conserving natural resources (Messerli et al., 2019), employ the idea of 3Rs (Reduce, Reuse, and Recycle) for construction and manufacturing sectors (Bramley and Power, 2009). Huge conventional construction practices taking place to meet the demands of an ever-increasing population, urbanization and industrialization results in generation of an enormous amount of wastes that have severe environmental consequences like air and groundwater pollution because of toxic heavy metals present in it percolating down during its disposal in landfills (Ugwuanyi and Isife, 2012). This ample waste generation causes storage problems with significant economic implications (Alabduljabbar et al., 2024), thus posing a serious challenge pending their proper disposal (Mehta et al., 2020). However, after being treated and processed to create new aggregates known as recycled aggregate (RA), these building and deconstruction wastes can be used in concrete as a substitute for natural aggregate (NA) (Linares et al., 2024). RA as a partial or whole replacement for natural aggregates is advantageous in multiple ways such as diminished demand for natural aggregates, waste reduction, energy conservation, and cost-effectiveness, thus offering a sustainable and environmentally responsible approach to construction material usage (Kim, 2022) but proves to be not that effective in dipping GHG emissions (Kurda et al., 2018).

RCAs are used mainly in place of coarse aggregate because crushed recycled concrete usually contains old cement mortar and paste, which contributes to loss of strength, workability, and rise in creep and drying shrinkage (Rada et al., 2014). The strength of the concrete made from RCA is impacted due to the substitution percentage, water-to-cement ratio, amount of air content, the type of RCA, and the source of the RCA (Collivignarelli et al., 2020). Since the company of weaker adhered mortar, higher porosity, and greater water absorption in RA as related to NA, a weak inter facial transition zone (ITZ) amid the RA and the cement paste results in the concrete mixture (Yong Ho et al., 2013), however, incorporating SCMs and RA in concrete mixtures helps in attaining the desired compressive strength of the concrete (Gao et al., 2023). The type of RA is another crucial factor. High-quality recycled aggregates, when used in combination with SCMs, can lead to more substantial improvements in strength than lower-quality aggregates (Wang et al., 2023).

2.4. Optimize concrete mix design and structural optimization

Concrete mixture design, also known as mixture proportioning, is the process of selecting the type and quantity of individual constituents to yield a concrete that meets specifiable characteristics for a particular application (DeRousseau et al., 2019). Concrete mixture design affects the concrete very significantly because the latter is a composite material (Naseri et al., 2020). Mix design optimisation is challenging as concrete characteristics depend on both the chemical and physical characteristics of the components and their relative proportions (Shobeiri et al., 2023). The quantity of cement, water-to-binder ratio, aggregate packing, additives, and admixtures are all connected to the optimization of concrete mix design (Javadabadi et al. 2019). Besides being environmentally friendly, concrete mixture design should be so optimised that it ensures maximizing compressive strength concomitantly with minimizing the cost of concrete (Ahmad and Alghamdi, 2014). The work of the cement paste is to bind the aggregates together and fill voids. Therefore, by reducing the void volume between the aggregates, it is possible to lessen the quantity of cement paste, which contributes to fewer CO_2 emissions (Goltermann and Lars, 2021**)**. Proper aggregate packing and additive use decrease the cement consumption and lessen the CO_2 emission (Javadabadi et al., 2019). Likewise, fine aggregate addition in concrete stops the voids between the cement paste and the coarse aggregates to reduce cement consumption and GHG emission (Gjerp et al., 1998). Aggregate shape plays a great role in optimizing concrete mixture design. Rounded grains will slide easily onto one another, while angular grains tend to easily stick to each other, which prevents mass movement and workability (Javadabadi et al., 2019). The ratio of aggregates also affects the sustainability of the concrete. Little fine aggregate and much coarse aggregate leave larger voids in the mix for more cement to occupy the space with adverse environmental and structural implications (Javadabadi et al. 2019). The quantity of water has a great effect on the concrete's consistency. The increased amount of water in concrete increases the distance between solid particles, causing the heaviest and largest particles to settle down. Meanwhile, excess water mixed with fine particles accumulates on top, leading to bleeding (Gjerp et al., 1998). This bleeding can be avoided by proper aggregate packing and a decreased water-to-binder ratio to make the concrete durable and sustainable. The resultant increase in cement consumption can also be avoided by using pozzolanic materials and fillers as well.

2.5. Replace fossil fuels in cement production

Concrete, though counted as highly durable and cost-efficient but is still disadvantaged with harmful consequences for the environment and consumption of high energy loads during its production (Albidah, 2021). Producing 1 ton of cement, approximately 1.5 tons of raw materials, 4000 MJ of energy, 140 kW h of electricity (Feiz et al., 2015), and 125 Liters of fossil fuel are needed (Vazinram and Khodaparast, 2009). Recycling and reusing industrial wastes are considered an effective tool for decreasing power consumption in different industries, like the cement industry (El-Salamony et al., 2020). Energy consumption in the cement industry is high, usually accounting for 30-40 per cent of production costs, mainly expended on the traditional fuels used in traditional kilns like coal, oil, petroleum coke, and natural gas (Chatziaras et al., 2016). During the use of electric power, combustion of fuel, and the process of calcination, each ton of cement produced emits about 0.66–1.5 tons of CO_2, depending on the production system and technique (Carreño-Gallardo et al., 2018). The high burning temperature, the long retention time inside the kiln, the oxidising atmosphere, the ash absorption in the clinker, and the chemical conditions render the cement kilns ideal installations where wastes can be burned safely (Karagiannis et al., 2008). To avoid huge greenhouse gases emitting consumption of fossil fuels, upsurge in energy efficacy and the practice of substitute fuels (IEA, 2019) like used tires, animal meal, refused derived fuels, solvents, used oils and biomass (Karagiannis et al., 2008) could prove sustainable contribution towards the circular economy (Collivignarelli et al., 2020). Furthermore, these measures would help in the reduction of environmental impact, conservation of fossil fuels, reduction of waste, and reduction in cement production costs (Chatziaras et al., 2016). In the process of producing 1 ton of cement, 125 lit fossil fuel and 118 KWH electricity are consumed, while cement transportation is 11.9 percent of the country roads' transportation (Vazinram and Khodaparast, 2009)

2.6. Carbon capture and storage

Carbon capture and storage (CCS) is today often considered a technically viable and economically affordable option (Zhang et al., 2013) to combat climate change and facilitate socio-economic development in the long-term carbon abatement strategies of many countries and international organisations (Markusson et al., 2012). Capturing CO_2 from the cement production in cement plants, transporting and storing it underground is aimed at preventing atmospheric pollution and making cement production environment friendly (Zhang et al., 2013) but not economical as critical CO_2 emissions cost can be close to the CO_2 capture cost under some circumstances (Karagiannis and Soldatos., 2010). The carbon capture process can be done by three different methods: pre-combustion, post-combustion, and oxyfuel-combustion. Pre-combustion is the elimination of carbon from the fossil fuels before burning. In the post-combustion method, CO_2 is separated after burning of the fossil fuels, and in oxyfuel-combustion, fossil fuels are burned in pure oxygen rather than in air (Mukherjee et al., 2015). Though the carbon capture and storage technology is incredibly costly and risky, yet highly effective in reducing the environmental impacts and mitigating global climate change (Araujo and de Medeiros, 2017).

2.7. Increasing durability

The most effective way to improve the sustainability of concrete structures is by making them last longer through design for durability and by minimizing construction defects (Hooton and Bickley, 2014). Highly durable concrete has high compressive strength and is more resistant to freezing, thawing, corrosion, and chemical attacks such as sulphate ingress, which otherwise could shorten its service life (Javadabadi et al., 2019; Yadav et al., 2025a). Several factors influence the compressive strength and durability of concrete. Water-to-cement ratio (w/c) is among the most influential factors on the concrete's strength and durability. Normally, the w/c ratio is around 0.5, and a substantial reduction in the w/c ratio increases the durability of concrete (Javadabadi et al., 2019). Use of SCMs with fine particles such as fly ash, slag, and silica fume results in a blended concrete with very low permeability and consequent crucial improved durability performance against the most pernicious forms of deterioration, such as chloride-induced corrosion of reinforcing steel and alkali silica reaction of aggregate (Mackechnie and Alexander, 2009). However, the required concrete durability cannot be achieved without a proper mix design that is a balanced proportion of all the concrete constituents

(Kusuma et al., 2015). Increasing the durability of concrete conserves natural resources, reduces air pollution, prevents water contamination, reduces energy consumption, ensures proper disposal of wastes, and offsets other environmental impacts related to concrete production (Javadabadi et al., 2019). Geopolymer concrete made with fly ash and GGBS demonstrates superior durability compared to conventional concrete (Jalal and Srivastava, 2025)

2.8. Extending the longevity of existing infrastructures

Doubling the service life of a structure from 50 to 100 years does not require a significant increase in construction resources but only a slight adjustment in concrete resistance or cover depth to embedded reinforcing steel from environmental agents such as moisture and salt that cause corrosion (Mackechnie, 1995). However, the service life of existing concrete infrastructures can be extended through repairs and rehabilitation by good maintenance management schemes. The main objective of implementing maintenance management is to avoid further damage due to delays, reduce the maintenance costs, and keep or extend the service life of the building (Clark et al., 1992). Maintenance costs increase with the age of the building. Older buildings constructed of well-established materials and components and using well-tried and tested techniques may not be subjected to heavy maintenance works or expenditure (Abdul-Aziz, 2015). The failure of the concrete structure could be due to several reasons such as age, design fault, fire, flood, earthquake quack and chemical attacks. The repair and rehabilitation process aims to restore the concrete to its initial effective state (Abdul-Aziz, 2015). Repair and rehabilitation methods not only reduce costs but also play an important role in conserving natural resources and protecting the environment (Javadabadi et al., 2019).

2.9. Mitigation of water consumption in concrete production, during its use, and post-use processes.

The concrete manufacturing and construction are increasing with the increase in population, which requires enormous amounts of water during its production process (Sabir et al., 2001). Water is used throughout the concrete's making, using and post using processes; in the generation of energy to power certain manufacturing process, such as separations of aggregates, to quarry, wash the aggregates, in the process of mixing and batching and transportation and hugely for washing out tuck mixer drums in the ready-mix concrete plants (Tsimas and Zervaki, 2011). According to a cradle-to-gate analysis, the production of concrete accounts for about 18% of the total industrial water consumption worldwide each year (Miller et al., 2018). Binder is made utilising around 43% of the water that is extracted and 38% of the water that is used in concrete. (Miller et al., 2018). The usual practice employed to cut water utilisation in concrete manufacture is the decrease in batch water (Kosmatka et al., 2002). Among other probable ways of reducing water demand are selecting the suitable electrical energy fuel mixes and enhanced preparation of raw materials (Tay and Yip, 1987); besides establishing water cleaning system at pre-mix cement plants to reuse the water for the industrial purposes or to return clean water to the nature (Tsimas and Zervaki, 2011). Another way towards concrete sustainability could be the utilisation of recycled wastewater for concrete manufacture to lessen the carbon footprint of the construction industry and to provide a reliable water source for future generations (Zeyad, 2023). The concrete samples containing wastewater recorded 7%–27 % lower porosity than the control concrete because of the hydration process of cement with time, along with pozzolan reactions and higher Coulomb charges because of high chloride ions in wastewater than those of tap water (Hamada et al., 2023). Geopolymer concrete, when subjected to ambient curing, conserves significant quantities of water traditionally utilised in the curing process of concrete (Jalal et al., 2025; Yadav et al., 2025). This way preserves water resources and also emerges as an exemplary alternative for reducing water consumption in post-production.

2.10. Regulations and measures

To ensure that buildings are being constructed in the right manner so that both people and the environment are safe, vigilant monitoring and meticulous regulation are to be followed. The sustainability and environmental friendliness of a building are measured by EPDs, which are based on life-cycle assessments (LCA) of environmental data from raw material withdrawal, production, use phase, and disposal (Khatib, 2008; Ponmala and Abraham, 2015). These regulations ensure the longevity of these structures and therefore minimize waste and maximize sustainability (Javadabadi et al., 2019).

Conclusion

This review underscores the cement industry's critical juncture: soaring demand driven by urbanization conflicts with its status as a top global polluter. Beyond its 8–10% share of CO_2 emissions, the sector drives resource scarcity, health hazards, and ecological degradation, necessitating urgent, multi-faceted intervention. Our analysis establishes that emission reduction hinges on synergistic strategies:

- Material innovation proves foundational, where SCMs cut emissions by 80–90% versus OPC while improving concrete performance, and recycled/waste-derived aggregates reduce virgin resource demand.

- Process optimization offers immediate gains: fossil fuel replacement in kilns lowers carbon intensity, while advanced mix designs enhance durability, extending infrastructure lifespan and indirectly reducing emissions through avoided reconstruction.
- Systemic solutions like CCS show long-term potential despite cost challenges, and water conservation measures (e.g., wastewater reuse) alleviate stress on ecosystems.

Regulatory instruments remain pivotal for scaling these advances. Carbon pricing, strict LCA standards, and industrial symbiosis policies (e.g., mandating foundry sand recycling) must incentivize circularity. Future efforts should prioritize cross-sector collaboration to strengthen SCM supply chains, refine RCA processing techniques, and develop low-clinker cements. Only through such integrated, policy-anchored transformation can the cement sector align with global climate targets while fulfilling its essential role in sustainable development.

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