Concrete, CO_2, and catalysis: merging industry and research goals for sustainable development

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Abstract

The concrete industry is expected to reach net-zero CO_2 emissions by 2050 to meet the 1.5°C global warming limit. However, CO_2 emissions have continued to increase, and mitigative progress has been slow by the industrial sector and governing authorities. In this article, we provide an overview of concrete, how it is manufactured and used, and the reasons underlying the high CO_2 emissions. Different research on mitigative techniques is brought to the reader's attention Finally, relevant policies to spur net-zero goals are briefed, and a new perspective of concrete culture to align research, industry and the government is proposed.

Concrete is the second most consumed material in the world, following water. It is an inert material, offering excellent fire resistance, passive cooling, long service life, and it is a notable *carbon sink*, slowly absorbing CO_2 from the environment over time. Its ease of use, affordability, and durability make a compelling case for its high demand. However, with the increasing concretization from global urban development, concrete's ~8% global CO_2 emissions contribution requires urgent mitigative efforts by the society (Chen et al., 2022; Guo et al., 2021). This article provides a brief overview of concrete CO_2 emission sources, research efforts to curtail these emissions, barriers in their industrial implementation, and policy recommendations that may accelerate us towards net zero CO_2 emissions from concrete by 2050.

Manufacturing cement

Commonly, a binder (cement) reacts with water and glues the aggregates (sand and gravel) to form concrete, and cement is the primary culprit of CO_2 emissions[1]. Colloquially, 0.9kg of CO_2 is produced for every kg of cement, and the massive production of cement and concrete understandably prompts grave concern (International Energy Agency, 2009).

Over the years, considerable quality control improvements have minimized energy waste from manufacturing cement. Using waste-derived fuels can further reduce thermal emissions from cement plants. Separately, techniques such as SCT[2] have been researched and practically implemented, reducing the reliance on fuels (Gonzalez et al., 2013; Moumin et al., 2020; Plaza et al., 2015). Of note is the emphasis placed on CCUS[3]: the GCCA[4] estimate CCUS to play the largest role in reducing emissions to net zero by 2050, at 36% total contribution (Global Cement and Concrete Association, 2021). This 36% jumps from <4% by 2030, hence there are considerable hopes placed on CCUS. However, CCUS is expensive and difficult to retrofit. Pilot-scale testing is in early stages, and constructing new cement plants is expensive, as cement/concrete manufacturing and construction sectors operate on low profit margins. Moreover, the IEA[5] (International Energy Agency, 2009, 2018) observes that CCUS techniques may reduce thermal efficiencies of cement power plants and increase power consumption by 50-120%, which results in further electrical demand.

Cement can possibly be manufactured from minerals that output less CO_2 and/or require less power consumption for formation, such as LC[3,6], but this pathway requires considerable investment (Ardoğa et al., 2019; You et al., 2021).

Towards alternative cements

Concrete has been widely used in non-industrial times, such as the Roman era. Hence it is not unheard-of to transition

[1] To make cement, raw ingredients limestone and clay are extracted from quarry sites, grinded into fine materials and heated to around 1400 °C in a rotary kiln with admixtures to fuse and form clinker, which is finally grinded to a flour-like size and sorted as cement. This formation of clinker directly releases CO_2 through a process called calcination. Moreover, significant energy is involved in heating and operating the rotary kiln at such high temperatures. Respectively, these account for 50% and 40% of the total cement CO_2 emissions (United Nations Climate Change, 2017).

[2] Solar Concentrating Technologies

[3] Carbon Capture Utilization and/or Storage: where the emitted CO_2 is captured for use at the cement plant, or rerouted for utilization in other industries, or stored.

[4] Global Cement and Concrete Association

[5] International Energy Agency

[6] Limestone Calcined Clay Cement. It replaces most of the calcining limestone with a higher clay content (Sharma et al., 2021).

towards environmentally friendly alternative cement. Overall reliance on PC[7] is reduced, subsequently lowering its demand. Geopolymer[8] cement has been successfully manufactured at small-scale facilities over the years (Singh & Middendorf, 2020). However, large scale implementation is difficult due to long-term structural concerns. Usage of various cement substituents, also called SCM[9], is highly dependent upon location. Additionally, current testing standards are primarily based on traditional PC-based concrete, limiting industrial SCM use (John et al., 2019). SCMs based on hazardous waste materials raises security concerns as well: over time these hazardous materials may dissipate into the environment (Marsh et al., 2022). Finally, waste based SCMs may become unavailable as their parent industries move towards renewable energy sources (Corvellec et al., 2022).

Optimizing concrete design, use, and reuse

Another approach to lower CO_2 emissions from concrete is to reduce the amount of concrete used in structures. This may be achieved by implementing more appropriate factors of safety in concrete construction, instead of a one-fits-all approach (Chris Bataille, 2019). GCCA estimates 7% and 22% reduction in CO_2 emissions through efficiency in design and construction by 2030 and 2050, respectively. Wastage is significantly reduced if concrete elements are fabricated at quality-controlled sites, through intelligent computer-based design with lower prescribed cement quantities. These prefabricated elements are transported and erected on site, lowering overall socio-environmental impact at neighbouring areas.

BIM[10] is the digitization of a structure's lifecycle. By simulating workflows, wastage is reduced, and designs are optimized. BIM is well established and used by the construction industry, with certain case studies showing greater than 8% reduction in CO_2 emissions (Sherif et al., 2022). AI can further streamline BIM use in future.

Another highly trending viable research is digital fabrication of concrete elements. Using topology optimization techniques, formwork may be tailored to hold concrete that fully utilizes its structural capabilities, while minimizing its physical volume. Tangentially, 3DCP[11] has also gained traction for automated construction of concrete elements. There is close to zero wastage, however it requires high cement/binder use which increasing CO_2 emissions (Flatt & Wangler, 2022).

Steel reinforcement plays a key role in structural concrete members, but steel rebar corrosion severely compromises structure durability. Noncorrosive FRP[12] rebars have been used (Hadi et al., 2021), with their own respective advantages and disadvantages. Recently, the ACI[13] have introduced code standards for FRP bars (ACI Committee 440, 2008). Instead of rebars, fiber reinforcement and the use of SHCC[14] allow for the construction of extremely ductile concrete (Zhu et al., 2022). This reinforcement goes down to the nano-level as well, incorporating nanomaterials such as graphene or carbon nanotubes (Sheikh et al., 2021).

In fact, tailored mix designs combine SCMs and fibers, optimize aggregate packing, and reduce cement use while reaching strengths comparable to steel structures (Hung et al., 2021). Although expensive, they illustrate the viability of designing concrete with low cement contents.

Reusing waste concrete as recycled aggregates have also gained traction. RAC[15] exhibits similar strengths to traditional concrete, although there is variability in its performance (Tam et al., 2021). RAC use may also streamline the circular economy potential of concrete (Monteiro & Roussanaly, 2022).

Conclusions, policy recommendations and concrete culture

The term 'concrete culture' refers to the perceptions and values placed on concrete use by relevant consumers, producers, and monitoring authorities. Research on sustainable ways of manufacturing, designing, and reusing concrete has far surpassed the current industry. This widened gap between research and application has led to a severe disconnect between different stakeholders actively invested in concrete culture: researchers are unable to secure the funding required as it is too 'expensive' for the producers, 'niche' for the relevant monitoring authorities, and ultimately inaccessible for the tertiary consumers (i.e., project clients).

[7] Plain Concrete
[8] an alkali-activated cement comprising of waste materials such as fly ash and requiring alkaline activators. It has been researched since the 1950s.
[9] Supplementary Cementitious Materials
[10] Building Information Modelling
[11] 3D Concrete Printing
[12] Fiber Reinforced Polymer
[13] American Concrete Institute
[14] Strain Hardening Cementitious Composites
[15] Recycled Aggregate Concrete

Bataille (Chris Bataille, 2019) excellently outlined numerous policies towards greener concrete culture[16]. Some of the proposed policies were for government and monitoring authorities to define clear objectives and long-term policy signals, following which pathways can be designed for action by industry stakeholders. Policy components include internal and external carbon risk assessment with full disclosure, measures to reduce demand, improve material efficiency and increase recycling pathways of concrete, providing substantial R&D especially for retrofit of existing plants, prioritize purchase towards net-zero steel and concrete alternatives, gradually removing subsidies in energy prices while increasing carbon pricing, establishing sunset regulations, decarbonizing the power emissions from cement plants, and developing transition plans for the industry with a transparent, organized regulatory backdrop. These policies are illustrated with the relevant research technologies in Figure 1..

However, it is also recommended to establish an expansive concrete culture, which involves marketing and educating society at general. Society has evolved consciousness on the dangers of CO_2 emissions, opting for environmentally friendly alternatives such as degradable packaging materials for everyday use. Hence, educating the public about concrete is essential to inject awareness at a ground level, through targeted campaigns[17] and curriculum incorporation at academic institutions.

As per the Paris Agreement to meet the global warming target of 1.5 °C, net zero global CO_2 emissions must be reached by 2050. Hence, it is necessary to enact the abovementioned policies. Improving concrete culture should be undertaken simultaneously, providing further incentives for the industry to act quickly and efficiently. It should not be used as a diversionary tactic to offload accountability by the relevant stakeholders. It need not be mentioned that time is severely limited if the goals are to be accomplished in due time.

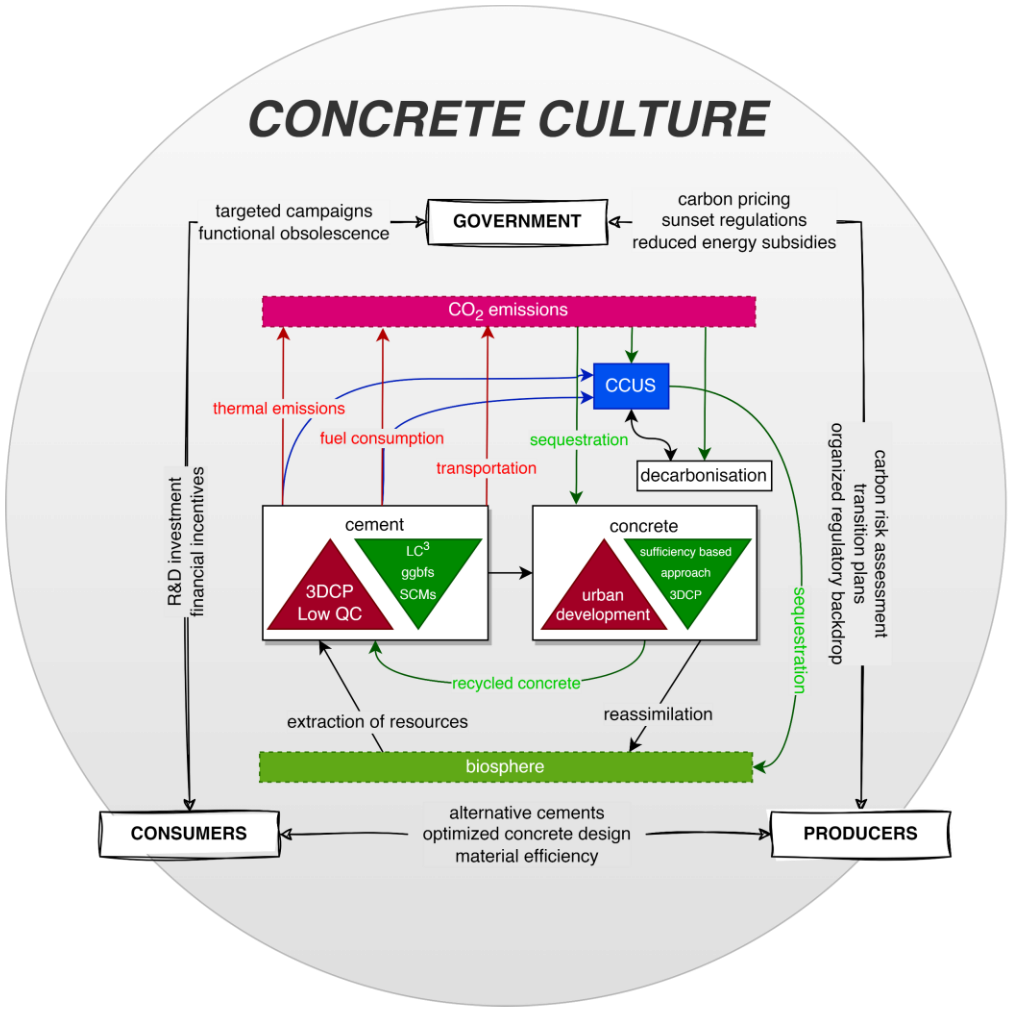

Figure 1. Concrete culture, policies, and research technologies for net zero concrete.

[16] These were outlined in the 2019 Green Growth and Sustainable Development (GGSD) Forum by the Organisation for Economic Co-operation and Development (OECD), regarding the greening of heavy and extractive industries.

[17] The merits of concrete can be brought to the forefront, such as its surprising assimilation in the biophysical environment via habitat creation of artificial reefs (Vivier et al., 2021), or its ability to absorb CO_2 in the environment (sequestration).

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