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Cement and Alternatives in the Anthropocene

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Abstract:

Globally, the production of concrete is responsible for 5-8% of anthropogenic CO_2 emissions. Cement, a primary ingredient in concrete, forms a glue that holds concrete together when combined with water. Cement embodies approximately 90% of the GHG emissions associated with concrete production, and decarbonization methods primarily focus on cement production. But mitigation strategies can be accrued throughout the concrete life cycle. There are rapidly implementable or innovative decarbonization strategies in cement manufacture, use, and disposal, to address the global challenge of equitably meeting societal needs and meeting climate goals. This review presents: (a) how our reliance on cement and concrete developed and the consequential environmental impacts; (b) pathways to decarbonization throughout the concrete value chain; and (c) alternative resources that can be leveraged to further lower emissions while meeting global demands. We close by highlighting an associated research agenda to mitigate the climate damages from our continued dependence on cement.

Keywords: Cement; Concrete; Greenhouse gas emissions; Sand; Decarbonization; Health

1. Introduction

While not commonly the first item considered in mitigating environmental damages, how we engineer, use, and dispose of concrete is a key aspect of meeting global environmental sustainability goals. The planet is currently on the verge of crossing 1.5°C warming, with current models suggesting it will fail to remain below the 2°C warming threshold even with mitigating greenhouse gas (GHG) emissions in the near term (1). Concrete, composed of Portland cement (referred to herein as 'cement'), water, and aggregates (crushed rocks) is critical to infrastructure systems as a relatively inexpensive material that can be produced around the world (2). Yet at the same time it is also critical to climate change goals as cement, the primary binder in concrete, is among the most difficult to abate industrial GHG emissions sources worldwide (3). We currently have notable dependence on concrete, as our most consumed construction material by weight, and our per capita consumption continues to rise (4, 5); in 2015 estimates of the concrete market were 20-30 billion metric tons produced, with projections to 40 billion metric tons in 2040 (6).

Researchers have examined methods to decarbonize concrete, given our anticipated continued global reliance on this material (7). The vast majority of this work focuses on the manufacturing of cement for use in concrete (e.g., (8)), with more limited exploration of benefits that could be accrued in other stages of the life cycle. However, subsequent life cycle stages have shown promise to contribute to GHG emissions mitigation efforts as well (9), emphasizing the need to engineer concrete throughout its life cycle to reach emissions goals. GHG emissions mitigation strategies need to be paired with our understanding of resource demand and availability, viable alternatives in terms of performance and applicability, and concomitant environmental and societal burdens (e.g., localized health impacts) that could shift with implementation of GHG emissions mitigation strategies. Solutions for GHG emissions mitigation must be paired appropriately with region-specific growth, demands, and limitations.

2. Material consumption and environmental impacts

2.1. Global material demands

Between 1900 and 2015, global production of building materials was nearly equal to the total mass of energy, human food, animal feed, and other resources consumed (10). In this time horizon, the consumption of building materials has grown rapidly since World War II, with limited indication of plateauing (11) (Figure 1). The built infrastructure consists of systems such as homes, roads, schools, sewers, and hospitals; however, the high levels of production for these systems results in an environmental burden. These impacts are myriad: resource consumption, which can lead to localized scarcities (particularly for concrete as discussed later) (12); waste flows that are generated throughout the supply chain (13); energy resources used, chemical reactions that occur, and material handling required all can contribute to air pollutant emissions (14). Further, not unlike the energy-water nexus, in which energy resources consume water resources and water resource availability is reliant on energy resources (15), there is a materials-energy-water nexus, in which the manufacture of materials requires energy for resource transformation, and our energy system requires materials for energy infrastructure. Simultaneously, materials production requires water (e.g., for dust suppression, cooling, or as a reactant) (16) and water resource availability is reliant on material resources (e.g., pipelines, wells, water treatment infrastructure).

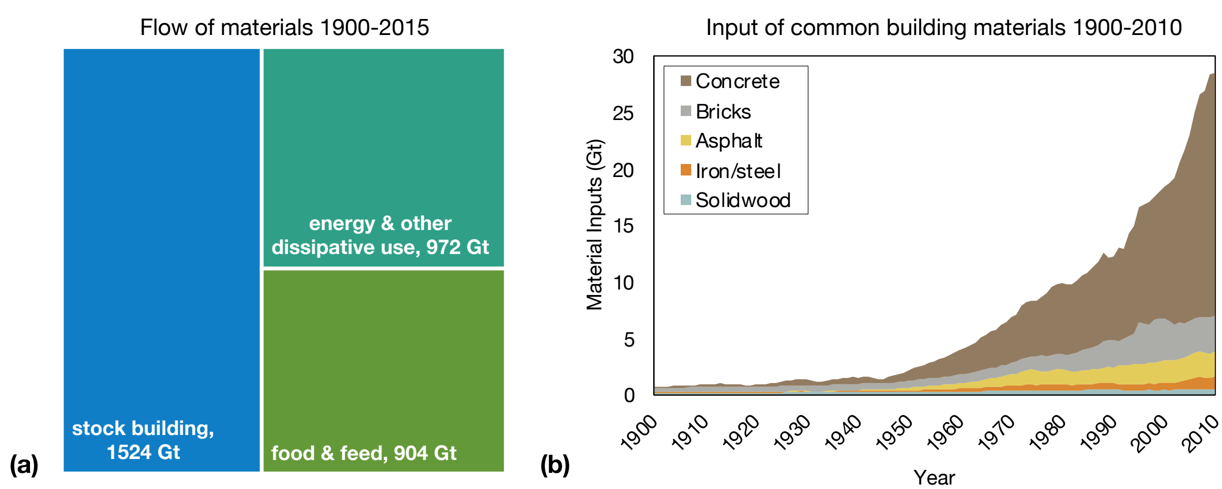

Figure 1. Resource consumption of construction materials. (a) Cumulative resource demand is represented as global flow of resources for stock building and other consumption from 1900 to 2015, based on data from (10). (b) Input of common building materials is shown over 1900 to 2010, based on data from (11).

Of our conventional building materials (e.g., woods, concrete, steel, other alloys, plastics, glass, asphalt), concrete is the most widely used material (see Table 1). Originally driven by broadly available resources (7), there are few other materials that can be produced at the same scale as concrete. We currently produce approximately 4 Gt of cement annually (17), but considering the additional constituents used, concrete demand has been estimated as approximately 7 times greater than cement (18). In the recent decades, China has driven the world's consumption for cement and concrete, but now other countries are starting to build up more demand, such as India and several countries within Africa and South America (19).

Further exacerbating this consumption-related issue, it is expected that society will increase the use of concrete to help improve resilience of existing and new infrastructure in the face of disasters and more extreme weather events from climate change (20). Society is likely to use this material for building resilient housing, levees, and other critical infrastructure. Current projections suggest 22% growth in urban populations by 2030, with many of these being urban areas in coastal regions, which may have unique durability concerns (9). Exposure conditions for concrete are expected to alter as a function of climate change, and in coastal areas, these shifts could accelerate corrosion rates of steel reinforcement in concrete and decrease the useful life of exposed concrete structures (21). In addition to this concerns, other studies have suggested there can be increased failure rates driven by altered humidity, temperature, atmospheric CO_2 concentrations, and weather (e.g., changes in wind, changes in snow loadings) (22, 23). As such, technical solutions to potentially mitigate the impacts of concrete must be considered within the context of both mitigation of emissions and adaptation of future systems within their ability to meet societal demands.

2.2. Environmental impacts

2.2.1. Greenhouse gas emissions

The production of construction materials is a significant contributor to global CO_2 emissions. In 2016, materials production was responsible for over ¼ of global CO_2 emissions (24), with the majority of those emissions from construction materials (over 6 Gt of annual CO_2 emissions) (25). Materials with high contributions to these emissions include steel; approximately 50% of steel produced annually is used in the built environment (26). The production of plastics also produces high GHG emissions, and approximately 20% of plastics produced each year are put into building and construction applications (27). However, the cumulative GHG emissions from these materials for construction remains lower than that of concrete (see production statistics and relative CO_2 emissions in Table 1).

The volume of concrete produced results in it being the largest contributor to construction material-related CO_2 emissions (i.e., ~60% of these emissions each year (25)). Concrete production has been estimated as contributing 5-8% of anthropogenic CO_2 emissions (7), with the cement in concrete contributing approximately 90% of those emissions (the water and aggregates have substantially lower emissions) (28). The GHG emissions associated with cement production stem from two primary sources: (1) limestone decarbonation, in which chemical-derived CO_2 is emitted during the conversion of limestone to a reactive product through calcination; and (2) energy use, primarily that of creating the high kiln temperature for pyroprocessing, which occurs at ~1450°C. The output of kilning these materials is the formation of clinker. Clinker is then ground together with mineral additives to form cement, which then is batched (mixed) with other constituents to make concrete, applied in the built environment, and eventually disposed (see Figure 2). While this material currently has a relatively linear life cycle, there have been several efforts to reutilize end-of-life resources from the cement and concrete value chain, improving circularity, which we discuss in Section 3.

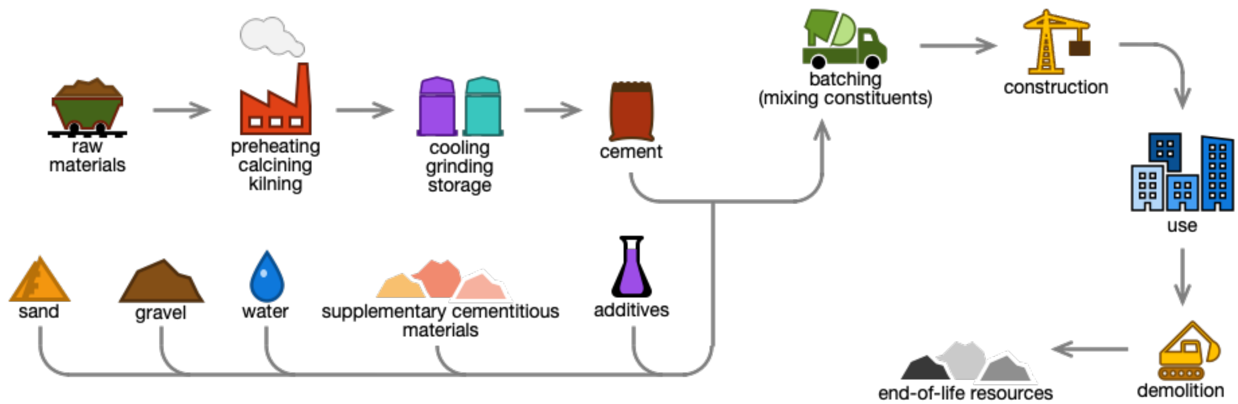

Figure 2. Cement and concrete value chain. The dominant source of CO_2 emissions for concrete occurs in the calcining and kilning stage of cement production. However, additional emissions from electricity, transportation and equipment fuel, use/maintenance, and demolition occur. Additionally, there are various waste flows and various pathways for CO_2 uptake at different life cycle stages. We discuss the role of these life cycle stages in CO_2 emissions and uptake in Section 3.

Concrete typically has very low CO_2 emissions per unit strength of material (29) relative to other commonly used engineered materials. Table 1 presents fossil-CO_2 emissions to produce 8 construction materials (biogenic uptake is not presented), which we compare on a weight-basis, on a volume-basis, and on an emissions per unit volume of material per unit strength. It is important to note that strength is not the only performance criterion by which materials are selected; it is simply among the most prevalent properties specified for construction materials, and we use it here to elucidate there are key considerations that must be made when comparing materials beyond a given mass or volume of product. Other considerations such as other mechanical performance (e.g., fracture toughness, ductility, elasticity, strength:weight), durability, thermal characteristics (e.g., thermal conductivity), electrical properties (e.g., resistivity), cost, aesthetics, constructability, local social acceptance of materials, and many other parameters drive materials selection (30). Further, this table does not reflect other GHG fluxes, including the uptake of CO_2 by wood during photosynthesis, the uptake of CO_2 by hydrated cement during carbonation, as well as emissions from construction, maintenance, and end-of-life management. Each of these fluxes occurs on different, commonly decadal, timescales, which can complicate carbon accounting (31), and notably for biogenic resources, can lead to net-GHG emissions even with biogenic carbon (32). We focus here on the industrial production-related emissions for each of these materials and discuss the contributions of these other life cycle stages for concrete in Section 3.

For each of the three metrics examined, concrete produces among the lowest CO_2 emissions (the challenge is the sheer quantity of concrete used). On a weight-basis and on a volume-basis, concrete rivals asphalt pavement and sawn wood for the lowest emissions. On a per unit strength-basis, concrete is among the lowest emitting materials, along with glass and sawn wood. For all three metrics used, alloys, such as steel and aluminum, and plastics have consistently the highest CO_2 emissions. The low relative CO_2 emissions of concrete suggest that scaling any of these other materials may result in similar or greater CO_2 emissions. Further, there may be inadequate resource availability for other materials to scale, as has been suggested for forestry products for building applications (33). And of course, this is coupled with the long lifespan of concrete and wide number of functions for which it is well suited relative to these other materials (e.g., dams, bridge decks, foundations). The relatively low cost and historically abundant nature of the resources used in cement and concrete, as well as the desirable performance of these materials, have resulted in infrastructure around the world being reliant on concrete (2). Suitable alternatives must be able to meet this material performance need, be cost competitive, and offer equivalent or lower environmental burdens.

Table 1. CO_2 emissions from common materials production, material properties, and CO_2 emissions per unit strength (Note: comparisons of emissions exclude biogenic carbon, compressive strength used for ceramics and pavement; tensile yield strength used for alloys, polymers, and wood) Data from (34) and based on the year 2019, with the exception of asphalt pavement (2016) and flat glass (2014) due to limitations in data availability.

	Production (Gt)	Production for use in construction (Gt)	CO_2 emissions, fossil (kg/kg)	CO_2 emissions, fossil (kg/m^3)	Density (kg/m^3)	Strength (MPa)	CO_2 emissions per unit strength (kg/m^3 per MPa)
concrete	31.5	31.5	0.09 – 0.16	236 – 363	2300 – 2600	20 – 50	7 – 12
brick	2.18	2.18	0.15 – 1.83	240 – 3840	1600 – 2100	15.1 – 88.2	3 – 254
flat glass	0.15	0.059	0.99 – 1.15	2379 – 2885	2400 – 2500	1000	2 – 3
asphalt pavement	2.24	2.24	0.03 – 0.04	67 – 91	2300	1.4 – 2.5	27 – 66
cast iron and low alloy steel	1.87	1.02	1.54 – 1.80	11705 – 14220	7100 – 7900	140 – 1500 *	8 – 86
aluminum	0.063	0.015	13.56 – 20.70	33911 – 60040	2500 – 2900	30 – 500 *	68 – 2001
Plastics	0.41	0.08	1.57 – 6.14	1480 – 7373	890 – 1600	18 – 70 *	42 – 141
Wood	3.14	0.98	0.09 – 0.14	71 – 94	660 – 800	2 – 70 *	1 – 47

* reflects yield strength; other strengths denote compressive strength

2.2.2. Additional environmental concerns

<u>2.2.2.1. Air pollutant emissions</u>

While climate change is among the most pressing challenges of this generation, other environmental impacts result from material production beyond GHG emissions. Among these impacts, emissions of air pollutants are often highlighted for industrial manufacturing processes due to known human health impacts from their inhalation (35) and because of their prevalence resulting from use of fossil-derived energy resources (36). These include emissions such as sulfur oxides (SO_X), nitrogen oxides (NO_X), particulate matter (PM), and heavy metals. Some

SO_X emissions can come from mineral resources, but most SO_X and NO_X emissions are from fuel resources (14). Heavy metal emissions can occur from cement production if there are metals present in the raw minerals used as inputs. Refractory metals tend to concentrate in the clinker and are not released as an emission; however, volatile and semi-volatile metals can be emitted if proper scrubbing mechanisms are not in place (37). PM emissions can be more difficult to mitigate as they occur throughout the cement and concrete value chain. These emissions can occur from quarrying activities, losses during transportation, raw mineral preparation, pyroprocessing, cement grinding, concrete batching, energy-resource utilization, as well as from other sources (38).

There are several key differences and key similarities between GHG emissions and air pollutant emissions from cement and concrete production. Distinctly, while GHG emissions are of global concern as they contribute to continued global warming, air pollutant emissions are a localized environmental impact. They tend to remain near the production facility, and depending on the physiochemical properties of these emissions, there can be a range of impacts on the local communities (39). While GHG emissions from concrete are predominantly from the production of clinker, air pollutant emissions, particularly PM emissions, occur throughout the value chain, and as a result, can be more difficult to mitigate as there is not a single point source. Air pollutant emissions are also not consistently as well quantified as GHG emissions. In some regions, there are reporting mechanisms in place to limit effects of such emissions on air quality (40); however, such reporting mechanisms are not globally implemented. While data collection on GHG emissions are also not globally performed, there are reporting schema in place to address GHG emissions (41), and the similarity in GHG emissions sources for concrete worldwide facilitates estimates of these impacts. In addition to air pollutant emissions sources occurring throughout the value chain, there are a wide range of factors that can influence the magnitude of their burden (42), including the height of the emissions source (e.g., ground level, from an industrial stack), environmental conditions (e.g., rain removing pollutants from the air, wind blowing pollutants), mineral resources (e.g., has volatile or semi-volatile metals), and control systems (e.g., scrubbers to mitigate emission from the stacks, spraying mining activities to mitigate dust). Yet there is a key similarity between GHG emissions and air pollutants as well: the magnitude of emissions is driven by the magnitude of production. Estimates have suggested air pollutant emissions from cement and concrete production could be contributing a similar order of magnitude to global emissions as CO_2 emissions from cement and concrete production: ~ 5% of global PM emissions smaller than 10 microns (14). While such estimates have greater uncertainty than estimates of global CO_2 emissions from cement and concrete production, the large fraction of global impacts from one class of materials is again a function of the huge material demand.

2.2.2.2. Resource consumption and scarcity

With high concrete demand, there is a high demand for raw material resources. While the limestone that forms the basis of cement is available abundantly throughout the world, other resources used in concrete are becoming scarce. Even if there is enough global availability of the materials needed, they are commonly produced with local resources driven by factors such as cost of transporting materials (2). Water requirements for concrete as a constituent and in processes through its value chain conventionally rely on local resources. Similarly, most construction minerals, such as limestone, clays, and aggregates, are not exported (43). While there can be some trade of these constituents and cement, most concrete and concrete products are not traded to a similar degree as other commodities (2). The local consumption of resources can drive local scarcities where enough of a given resource is not available in the quantities required for future production, and localized supply shortages can arise. Scarcity of these resources can have implications on vital infrastructure and services, and minerals used in construction have closer ties to local economies and poverty reduction than minerals that are more heavily traded (e.g., alloys) (43).

Water is consumed at several points in the production of concrete. Most commonly discussed is the utilization of potable water as a constituent in concrete, which is necessary for the formation of hydrate minerals that hold aggregates together. However, only about 15% of water consumption in the concrete value chain is used as a constituent in concrete (16). And of the water used as a constituent, approximately 30% becomes bound in the formation of hydrate minerals, with a small fraction of the remainder being trapped in interspace layers between minerals, and approximately 70% is released through evaporation (44). As such, only an estimated 5% (30% of 15%) of water needed for concrete production is in fact present in the concrete product.

Most of the water consumed in the production of concrete occurs throughout the production value chain. Energy resources, whether for processes like extraction, purification, or use in cooling towers, require water resources. Because of the energy demands for cement and concrete production, there is associated water consumption. For electricity, water consumption has been reported as ranging from negligible levels to over 18 kg of water for a MJ of electricity; for thermal energy, water consumption has been reported as ranging from negligible levels to over 46 kg of water for a MJ of energy (16). These variations depend on the type of energy resource, e.g., wind energy tends to require lower water demand whereas irrigated biomass requires more. Water is also used in various processes during the production of cement and concrete. For aggregates, which make up the bulk of concrete, negligible demands for water to over 1 kg of water per kg of aggregate has been reported, with water used for quarrying activities (e.g., dust suppression) and for washing (45).

As a result, water consumption for concrete production, while small relative to activities such as agricultural or domestic uses, are leading to notable global demands (16). These demands can lead to localized scarcities if freshwater is not abundantly available. Utilizing freshwater resources has been proposed as one of the planetary boundaries that human activities have a potential for destabilizing earth systems (46), with models suggesting climate change will exacerbate water scarcity in some regions around the world (47).

Recent estimates have suggested that sand is currently the most consumed resource globally after water (18, 43), with a substantial fraction of that sand being used in concrete. The management of sand resources is a growing issue with environmental, economic, and sociopolitical implications (48). While sand is commonly thought of as a readily available resource, it is currently being extracted at a rate that exceeds its generation (43, 49). Further, not all sand can be used for concrete applications, for example if it is too fine, too rounded or contains chlorides, it may not be suitable for use in conventional concrete applications (49). Developed economies, where much of the needed concrete infrastructure has been built up and most new concrete uses are focused on maintenance and replacement, are expected to have stable sand demand, whereas parts of Asia and Africa are expected to have notable increases in sand demand in coming years

(49). Future sand demand in some of these areas are expected to exceed the availability of natural sand resources, with some areas already experiencing scarcities and relying on imports for concrete production (50).

In addition to scarcities associated with the primary sand product, there are hidden flows of resources that do not contribute to the final commodities we consume but are rather discarded. For minerals, these include resource flows associated with quarry overburden, impurities in deposits, and mineral losses during processing (13). Depending on whether industrialized production systems are used, quantities of different constituents needed, and quarrying activities, these hidden flows have been reported as being able to exceed the weight of resources that are actually used in commodities (13). For mineral resources such as aggregates and limestone, waste associated with quarrying activities (e.g., overburden and mineral impurities, but not processing losses) have been reported as ranging from negligible losses to exceeding a 1:1 mineral loss : mineral product (13, 51, 52). Further, the mining and recovery process for acquiring sand can lead to water and quality issues through pollution, as well as effects on local ecosystems and biodiversity (53). The efficient use of sand and use of sand substitutes, such as sea sand and synthetic or manufactured sand, may become increasingly necessary as challenges associated with this scarcity continue to evolve (50).

2.2.2.3. Equity and environmental justice

There is a relationship between environmental impacts accrued, the growth of populations able to afford products (a function of both population size and affluence), and the technologies that can be leveraged to decouple demands from environmental burdens (i.e., the IPAT equation) (54). The concept is commonly linked to work by Erlich on linking population and per capita impacts (55). Recently, it has been argued that consumption patterns themselves (less so population growth) is a key driver in impacts, with consumption trends acting as an accelerant having outstripped the ability or rate of technological breakthroughs to retard impacts (56).

The ability to consume concrete in areas with growing populations and affluence who require infrastructure and building systems is a pressing issue. Consumption patterns of cement in the past three decades was driven by demand in China and more recently India (19). These trends indicate most new concrete consumption will occur in areas with newly developing infrastructure (as opposed to regions maintaining infrastructure). However, as noted previously, in addition to creating necessary construction, the production of these materials contributes to localized air pollutant emissions, resource scarcity, and continued climate damages. Industrial manufacturing and resource extraction cause disproportionate impacts on localized populations, who are exposed to conditions like air pollutant emissions (57), which in turn create a human burden of disease (58). Further, climate change impacts have been linked to initial inequalities within countries corresponding to exacerbated susceptibility to the effects of climate change, leading to greater inequalities (59).

Efforts to mitigate GHG emissions must consider concomitant impacts on localized impacts and their potential disproportionate impacts (60). The social costs and who carries the physical and economic burden of environmental damages must be addressed in deriving methods to mitigate GHG emissions. There is the potential to engineer solutions with co-benefits. For example, improving energy efficiency, thus lowering energy demand, and selection of appropriate energy resources may lessen both GHG emissions and burdens to local communities from air pollutants

(36). Further, if implemented carbon capture utilization or sequestration (CCUS) methods require high purity of CO_2 streams, additional scrubbing methods may lower air pollutant emissions from systems leveraging carbon capture technologies. We will discuss the role of such manufacturing alterations on GHG emissions in the next section. While our subsequent focus will be on mitigating GHG emissions, it is critical that future solution spaces consider what materials are needed for given populations, what resources are available, what disproportionate burdens accrue from materials production, and how we use science and engineering to change patterns in materials production, composition, and use so that we can both provide access to infrastructure and reduce emissions.

3. The concrete value chain

Concrete is also unique relative to the majority of building materials produced (24) in that it is nearly exclusively used in building/infrastructure applications (61) (e.g., steel is used for appliances, automobiles, as well as buildings (62); wood/cellulose is used for fuel, paper, furniture, and equipment as well as buildings (63)). Because the impacts from concrete are driven by high consumption, there can be significant benefits associated with just moderate improvements on a per kg or per m^3 scale and through better engineering throughout the value chain (see Figure 3). By developing appropriate concrete mixture proportions, improving structural design, and leveraging the longevity of building components (64), material efficiency can contribute to drastic reductions in CO_2 emissions (65). Further, due to the ability for hydrated cement to carbonate, in which cement can mineralize atmospheric CO_2 under appropriate conditions, concrete can uptake low levels of CO_2 during its use, and even greater levels upon disposal if it is crushed to have high surface area (19, 66). However, notably, this uptake is occurring on a different time-horizon (decadal) relative to emissions from cement production. In this section, we highlight key mechanisms throughout the value chain that can drive down GHG emissions from cement and concrete noting that emissions reducing strategies should encompass all stages (67).

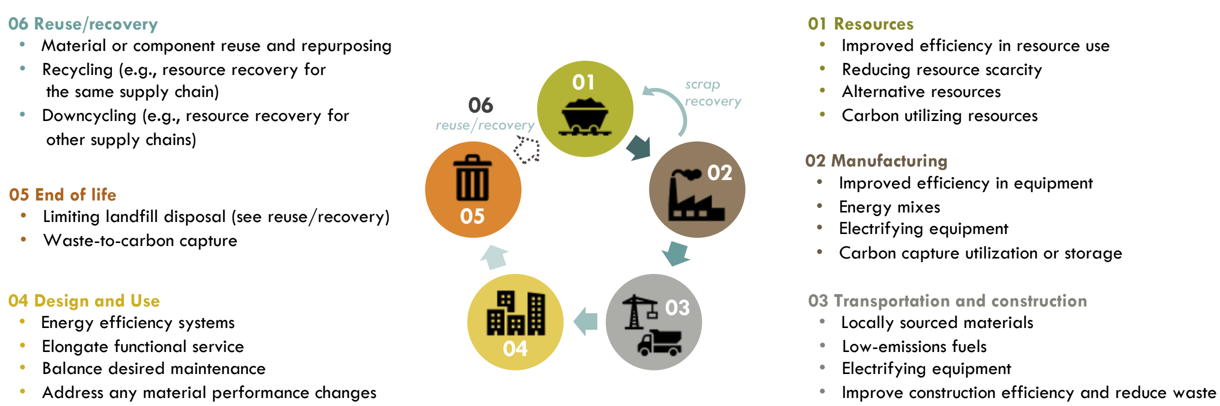

Figure 3. Summary of improvements possible throughout the life cycle

3.1. Mitigation through altering resources

Noting that the production of clinker (the kilned product that is blended with mineral additives to create cement) is the primary driver for GHG emissions in concrete, pathways to limit clinker use in concrete are often – and must remain – central to decarbonization. Clinker contains the reactive calcium silicates that support formation of the hydrate that act as a binding matrix in concrete, holding together aggregates. While there are limits to how low the utilization of clinker can be, currently concrete mixtures are overly cemented with high clinker contents. This over-utilization arises from concerns over quality control, risk management for field testing, and a lack of knowledge (68). Prescriptive mixture designs regularly contain more cement than necessary due to their need to work with a wide range of materials. Approaches have been developed to better utilize resources through improved mixture design by using specific material chemistries and by designing for all constraints simultaneously (e.g., strength, corrosion resistance, freeze-thaw performance) (69). High early strength concrete mixtures commonly leverage high cement content to achieve performance at a more rapid rate than conventional mixtures (70), but many times, these early strength requirements are overly conservative (71). One method of driving down clinker content and achieving similar, or improved, performance is through use of alternative mineral additives, such as supplementary cementitious materials (SCMs), which we discuss in greater detail in Section 4. It has been shown that using these resources could lead to 30-60% reduction in cement content (72, 73) while achieving equivalent compressive strength, and in some cases, improvements to other material properties (74). It is also possible to drive down clinker content through measures such as appropriate aggregate gradation, which can influence the amount of cement paste needed (75). Use of plasticizing admixtures can further reduce cement content (76) by driving desired workability without requiring higher levels of cement paste. Finally, mineral and chemical additives and admixtures have been developed to increase early strength development, by accelerating cement hydration even when present in more limited quantities (77–79).

3.2. Mitigation through manufacturing improvements

Manufacturing improvements for cement are among the most prominently discussed mechanisms for mitigating GHG emissions from cement and concrete in decarbonization roadmaps (e.g., (80–82)). Improving kiln efficiency is one mechanism to reduce GHG emissions from cement production by lowering fuel demand, and, as a result, fuel related emissions. Wet kilns, which leverage water to mix raw materials and then must evaporate water in addition to other processes, require almost twice the energy relative to dry kilns with preheaters and precalciners, which are technologies to dry raw materials and perform limestone decarbonation processes prior to formation of reactive compounds in clinker (83). Wet kilns have been largely updated over the last several decades, and most current kilns (over 85%) leverage more efficient technologies (84). Several start-up companies are developing new approaches to cement manufacture, seeking to disrupt the industry's continued reliance on massive rotary kilns.

An additional strategy is the utilization of lower emitting energy resources which have the potential to drive greater emissions reductions (80). However, fuel selection must be performed in a way that ensures desired heating value is achieved and that ensures deleterious compounds present in the energy resources cannot contribute to unwanted additions to the clinker.

Utilization of CCUS, while commonly discussed for energy resources, may be well adapted for cement production as the emissions from cement kiln stacks have much higher CO_2 concentration than energy stacks, a function of the limestone decarbonation. CCUS is increasingly anticipated to be a key strategy in decarbonizing many industrial processes (85). However, establishing efficient systems, pipelines, and storage reservoirs will require significant future investment, and readily implementable decarbonization strategies must be considered imminently.

More recently, there has been movement to electrify cement kilns and leverage battery storage (86), which could reduce emissions by an even greater extent by using very low emissions renewable electricity resources (e.g., wind, solar). While not the largest contributor to GHG emissions in cement production, further reductions can be achieved by also switching electricity grids to use of these lower emitting sources for processes that already require electricity (e.g., mills, plant operations).

3.3. Mitigation through transportation and construction alterations

Construction- and transportation-related emissions play a more minor role in concrete GHG emissions than the constituents themselves, but they can still contribute to emissions reduction pathways. Improper storage of concrete constituents, over-ordering of materials, and redoing poorly placed concrete have been linked to concrete waste on construction sites (87). It has been estimated as ~5% in the United Kingdom, 3% in Hong Kong, and 2-8% of ready-mixed concrete batched in California (87, 88). Where applicable, precast concrete elements can be used to avoid several of these sources of wastage (87). While the transportation of products can lead to high GHG emissions linked to trade (89), as noted previously, construction minerals such as aggregates, are not commonly traded (43). Rather, the resources used for concrete are typically locally sourced and GHG emissions from transportation are often low relative to other emissions sources in the value chain (28, 90). However, as with all fossil fuel resources, the conversion to lower emitting energy resources can contribute to a reduction in emissions for transportation in the concrete value chain.

3.4. Mitigation through design and use

While the physical requirements of an application cannot readily be altered to reduce material consumption, demand-side emissions mitigation strategies for built systems can utilize engineering design to reduce impacts. Namely, decisions that drive efficient use of materials, can drive down the GHG emissions associated with material production (91). In the design and use of concrete, this can include aspects such as downsizing elements, improving maintenance regimes, and considering the different demands of concrete within the same project (e.g., varying durability concerns for interior and exterior concrete). Unlike other decarbonization methods, efficient utilization of resources could have a benefit to mitigating other environmental damages as well by lowering material production- and consumption-related burdens.

Improving materials selection particularly in multi-material systems (e.g., concrete with steel reinforcement) can offer a material efficiency pathway given the range of acceptable concrete strengths and steel reinforcement ratios specified in design codes. This variation results in acceptable designs with differing GHG emissions. For reinforced columns, a 50-90% variation in GHG emissions between the lowest and highest emissions design meeting code requirements for the exact same application have been recorded, with similar ranges for members in bending (e.g., slabs) (9, 92). For structural frames, optimizing steel members and concrete deck depths can yield notable reductions in GHG emissions, with estimates being up to 50% of the frame's GHG emissions (93).

It must be noted there are other material efficiency strategies that have been proposed as well. Among these is 3D printing, which allows a designer to place concrete where it is most effective (e.g., in load-bearing locations) and not in places where the material is not needed (94). For 3D printed concrete in particular, it has been shown that to achieve desired rheological characteristics (e.g., flow) and to avoid nozzle blockage, higher levels of cement paste are regularly specified (95), which have the potential to increase GHG emissions despite lower overall material consumption. For novel methods such as 3D printing and others, it is imperative to couple environmental impact assessment with technology engineering to ensure new alternatives reduce environmental impacts.

Extending concrete service life is also a powerful method for reducing emissions if it leads to reduced demand for new material production. Depending on the time horizon being examined and the extension achievable, elongating concrete service life has been reported as potentially cutting 5-45% of GHG emissions from concrete systems (9, 65, 96, 97). This extension can be extremely effective in areas with relatively short-lived concrete structures because they more rapidly offset new production (65). For example, the average lifetime of both residential and non-residential concrete buildings in China has been reported as 40% of the use period of concrete buildings in the European Union (98). Benefits can still be achieved even with increased upfront impacts; for example, an assessment of pavement design showed that a higher-impact-to-produce 40-year road design had lower life cycle GHG emissions than a lower-impact-to-produce 20-year road design (99). Beyond ensuring systems do not reach functional obsolescence, use of appropriate repair or rehabilitation regimes that reduce environmental impacts are a critical aspect of mitigating impacts from concrete systems (100).

3.5. Mitigation through end-of-life management

While the majority of CO_2 fluxes associated with concrete occur during the production of cement, under appropriate conditions, hydrated cement paste can remove CO_2 from the atmosphere by forming carbonate minerals (i.e., carbonation) (66). The uptake and mineralization of these CO_2 fluxes occur over decades, with small levels being taken up as concrete only partially carbonates during use; higher levels of uptake are possible after use if the concrete is crushed to have a high surface area to volume ratio and left in appropriate CO_2 and environmental conditions (101). The timing of both the decadal uptake of CO_2 during use and the potential greater update of CO_2 at end-of-life relative to the rapid pulse of CO_2 emissions at cement production can have dynamic effects on cumulative radiative forcing and should not be considered a simple summation of CO_2 (102). Further, the quantity and type of SCMs used in a concrete mixture will affect the rate and magnitude of CO_2 uptake (103). And as the uptake reactions are tied to the decarbonated limestone (CaO) that can interact with CO_2 (103), CO_2 uptake will never exceed limestone decarbonation emissions: emissions associated energy resources or other processes will not be recovered through this mechanism. Despite these limitations, strategies exploring end-of-life management of concrete by crushing concrete to increase surface area and leveraging this carbonation potential could contribute to beneficial carbon fluxes, albeit likely much less beneficial than some earlier studies suggested (19, 66, 102). Further, other environmental impacts (e.g., the formation of PM during concrete crushing, the utilization of land, the release of leachate) should be weighed for this end-of-life method.

3.6. Mitigation through reuse and recovery

There are several pathways that have been explored to reuse or recover concrete to avoid disposal, elongate its use, and to mitigate environmental impacts. Currently, many regions either dispose of concrete removed from service in repositories like landfills or use that concrete in a lower-value application, such as road base (i.e., downcycling) (96, 104). However, repurposing concrete structures can have greater environmental benefits by extending their service life albeit for a different application. A recent case study examining structures in California suggested that reuse of structural components or repurposing building floor space (both concrete structures and other structures) could contribute to an over 40% reduction in GHG emissions relative to erecting a new structure (105). Conventional ownership of structures is also being challenged, with rental or leasing of structures to owners until their end of life, when ownership is transferred to the producer, favoring initial design for circularity of all the building components, including the concrete elements (106). This utilization pathway presents a new way of mitigating concrete waste and aligns with the elongation of concrete lifetimes highlighted in Section 3.4.

Recycling concrete as a coarse aggregate replacement (recycled coarse aggregates) in new concrete mixtures can both lower waste from end-of-life concrete and reduce demands for natural aggregates (e.g., quarried aggregates taken from the environment). While remnant cement paste and sand adhered to the surface of coarse aggregates can alter the performance of recycled coarse aggregates relative to natural aggregates in newly batched concrete, appropriate processing conditions at recycling can limit these deleterious effects (107). Even when poor quality recycled concrete aggregate is used, appropriate reinforcement detailing can produce elements that perform well, even under seismic conditions (108). Further, appropriate coarse aggregate recycling, can reduce GHG emissions by reducing transportation of aggregates and reduce raw material depletion (107). A recent review well addresses carbonation of recycled concrete, including through accelerated means (109).

Unlike aggregates, hydrated cement has historically been considered a material that cannot be recycled (110) as the hydration process results in the formation of new minerals and the cement paste remains bound to aggregates after concrete demolition. But the ability for hydrated cement and even SCMs to carbonate, and the high surface area of recovered hydrated cement powder offers a new opportunity (111). Using recovered hydrated cement as a carbon-uptake mechanism, in which carbonation of hydrated cement paste is performed to create a reactive SCM, is being explored (112). Separately, if hydrated cement from concrete at end-of-life has not carbonated, it could be reused as a decarbonated mineral feedstock to produce more cementitious compounds (113). Recycled cement has been proposed as well, with some routes suggesting low temperature processing (e.g., 450 – 700ºC) can result in a hydratable mineral that can contribute to similar strength development as conventional cement (113, 114). These pathways may be most applicable in areas where the quantity of cement being removed from service aligns with cement demands. It must be noted, difficulty separating hydrated cement from aggregates remains an area for further research in trying to best utilize recovered hydrated cement from demolished concrete structures (112, 114).

3.7. Summary

There are pathways throughout the concrete life cycle that could be leveraged to mitigate GHG emissions. The primary source of GHG emissions from concrete is the production of clinker;

thus, reducing the amount of clinker used is crucial to the decarbonization efforts. This reduction can be achieved through several means, including use of mineral additives, which could up to halve GHG emissions depending on current baseline production (68). Improvements can be made in cement manufacturing, such as using alternative fuels, and implementing CCUS technologies. Emissions from construction and transportation are less substantial than several other life cycle stages, yet efficient practices here too still offer opportunities for reducing the overall GHG emissions. Concrete design and usage strategies that promote material efficiency, including downsizing components, enhancing maintenance, and tailoring concrete properties to specific project needs, have significant potential to lower emissions by reducing the demand for material production. Similarly, prolonging the lifespan of concrete, for instance, through improved durability and adaptive reuse, serves as an effective means of emission reduction by cutting down the need for new materials. Together, improved design and use could lead to up to a 75% reduction in emissions (9). Lastly, end-of-life management practices, such as crushing concrete to utilize its potential to carbonate, are being investigated for their positive impact on carbon reduction.

4. Alternative resources and methods to lower CO_2 emissions

While there are mechanisms to lower CO_2 emissions throughout the cement value chain, these methods alone will not lead to net-zero emissions necessary to meet climate goals (2). This issue is exacerbated by an anticipated growth in environmental impacts related to growing populations (115) and growing affluence (116). Without technological breakthroughs, impacts will climb with greater populations capable of acquiring more goods (54). Here we summarize recent advancements in alternative resources to further mitigate CO_2 emissions from concrete.

4.1. Reducing clinker demand with supplementary cementitious materials

Increased efficiency of clinker use within concrete, such as through the use of greater levels of pozzolanic materials, can drive emissions reductions (117). Supplementary cementitious materials (SCMs) are considered the low-hanging fruit of strategies for reducing the carbon footprint of cement because they are already a commonly used and understood technology, so can be expanded and extended to help reach environmental goals. SCMs are inorganic powders that react either pozzolanically or hydraulically when combined with Portland cement in concrete. Both pozzolanic and hydraulic reactions form calcium silicate hydrate (C-S-H) and related binding phases, enhancing the strength and durability of the concrete. Traditionally used sources of SCMs, like fly ash from coal burning power plants and slag from iron manufacturing, are decreasing in supply and are not available in quantities sufficient to meet the growing demand caused by the simultaneous growth in concrete construction and push to decarbonation. Alternative SCM sources are critical in the efforts to immediately address concrete mixture sustainability, and there are a wide range of materials with varying geographic availability. For example, calcined clays are heavily promoted as SCMs because of their worldwide availability. Clays selected as SCMs generally contain a moderate fraction of kaolinite, though other clay minerals also have potential. The clays are calcined, or heated, to 600-800°C, significantly lower than the temperatures used in cement kilns. When combined with ground limestone, cement clinker, and gypsum, a cement called LC^3 can be manufactured, shorthand for limestone calcined clay cement. LC^3 cement can be manufactured with only 50% by mass Portland cement clinker and achieve similar mechanical properties as traditional cement (118).

Volcanic natural pozzolan often fill the gap where clays are not naturally occurring such as in the southwestern United States. Pumices are the most common natural pozzolan, but other sources such as volcanic tuffs and perlites are also used (117). Natural pozzolans and calcined clays alike participate in pozzolanic reactions and also both increase the water demand of concrete mixtures. This can cause the need for some adjustment in concrete mixture proportioning and admixture use, but benefits to concrete long-term performance and sustainability may outweigh these modifications.

In addition to natural SCMs, a wide range of industrial byproducts are being examined, including concrete recycling fines, harvested landfilled fly ash, recycled glass, and agricultural ashes, among others (119). Also, there is an increased interest in synthetic and manufactured SCMs (120). Given the substantial volume of resources that could be appropriately engineered to act as reactive SCMs in concrete, notable fractions of conventional cement clinker can be reduced through their use. It was estimated that just a portion of these potential SCMs could have provided 85% the weight of cement produced in 2018 (121), see Table 2. Alternative SCMs often involve different degrees of processing prior to use, to increase their reactivity, with novel approaches to processing being developed (122–124). It is important to understand how processing can impact their embodied energy and carbon footprint, and these should be evaluated before use. Furthermore, standards and test methods to assess the impact of new SCMs on concrete performance are lagging, but increasing attention to them will facilitate their adoption and use (125). New approaches exist to quantify the reactivity of a range of SCM sources, which can be coupled with mixture proportioning procedures (126).

Table 2. Global availability of supplementary cementitious materials in 2018 (121)

Cementitious material	Quantity produced or potential production (Gt)
Cement	4.05
Coal fly ash	0.35
Granulated blast furnace slag	0.34
Other industrial by-products	0.54
Agricultural residue ashes	0.80
Forestry residue ashes	0.11
End-of-life cement paste	1.29

4.2. Alternative cements

While Portland cement is the dominant cement used around the world, there are other cements that could be used as well. Non-Portland cements are used in some key applications, e.g., masonry cement. However, there have been growing discussions as to how alternative cement, and more broadly binding material, compositions could be used as Portland cement replacements. In the context of decarbonization, cements in which the mineral compositions of the clinker are altered to lower energy demands and limestone decarbonation emissions are being investigated (5, 127). Other proposed compositions rely on relatively small amounts of clinker to activate more minimally processed minerals, including precipitated lime and natural pozzolans

(128). There are also alternative cements that do not require clinkered components, such as alkali-activated binders, which bypass emissions-intensive clinker production (129). A summary of classifications of these cements is presented in Table 3.

Table 3. Classification of alternative cement technologies (adapted from (130))

Definition	Examples
Clinkered alternative cements – Cements that are produced using similar technologies as Portland cement (e.g., pyroprocessing), but with process and compositional changes that preclude conventional Portland cement production	• Reactive Belite • Calcium aluminate • Calcium sulfoalumminate • Carbonatable calcium silicate
Calcined alternative cements – Cements that require calcining of the raw material, but do not require further pyroprocessing, to produce desired mineral phases	• Magnesium phosphate • Magnesium oxychloride • Carbonatable magnesium oxide
Non-clinkered alternative cements – Cements that are produced without a need for pyroprocessing and are capable of setting with the addition of an activating solution.	• Alkali-activated materials • Supersulfated cement

For the clinkered and calcined cement alternatives, a process must still be undergone to kiln and quench mineral inputs to create solid precursors for cements. Permutations of these cements include only moderate changes from Portland cement, such as Reactive Belite Portland Cement, which has similar minerology to Portland cement, but it has a higher relative fraction of belite to alite than Portland cement. As a result, the lower calcium-content and lower enthalpy of formation belite allows for lower emissions in production, and these cements are used in practice in some areas (131). There are also calcium sulfoaluminate (CSA) cements and belite-ye'elimite-ferrite (BYF) cements. The principal phase for CSA cements is ye'elimite, and these cements are an already established technology with primarily specialty applications (131). BYF cements contain three main phases, belite, ye'elimite, and ferrite, as well as lower levels of other phases, and these clinkers should be able to be produced in a conventional cement kiln (131). In the case of both CSA and BYF, the composition of the cements leads to both lower limestone decarbonation emissions and lower enthalpy of formation, the latter of which suggests the potential to drive down energy-related demands and emissions (127). There are also cements that are MgO-based, such as Sorel cements and magnesium phosphate cements; the production of these cements can have lower CO_2 emissions (5), but because depending on the MgO source, there could be notable CO_2 emissions from magnesite decarbonation through a calcining process (131). Sourcing of magnesium from seawater has been proposed (132). Further, market demand for phosphorous is cyclical, with agricultural markets, which has a strong influence on cost and availability. In all cases, life cycle assessments must be performed to ensure lower CO_2 emissions are achieved with these cements and adequate availability of resources must be considered. Noting the immense scale at which we consume Portland cement and the demands for constructability and long-term performance, not all technologies are well-suited to be replacements (127, 133).

Beyond these cement alternatives, there is also the potential to use alkali-activated materials (AAMs), which is among the most broadly discussed non-clinkered cement alternative to Portland cement. AAMs use an alkaline resource, conventionally in a solution, to "activate" solid precursors to form a highly cross-linked network that can act as a hardened matrix holding together aggregates (not unlike how hydrated cement paste binds aggregates) (134). Alkaline activators are commonly sodium- or potassium-based (e.g., sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), potassium hydroxide (KOH)) (129). Solid precursors commonly used have been aluminosilicates, such as the ones used as SCMs (129). Because there are a range of activator types, activator concentrations, solid precursor types, solid precursor morphology and because characteristics such as aggregate properties, chemical admixtures, pigments, fibers, as well as other additives can alter the material performance of AAM-based concrete, these materials can be tuned to a wide spectrum of desired performance (134). For certain characteristics (e.g., some durability properties) and/or compositions (e.g., some unconventional solid precursors) would benefit from additional exploration (129). However, AAMs have been used in several applications around the world (130). As with other resource alternatives, the availability of materials that can be used at scale can be an issue with AAMs, particularly if they utilize byproducts from other industries (e.g., coal fly ash); but if the wider range of alternative SCMs is considered for potential as solid precursors in AAMs, then the correct order of magnitude of resources is available to replace cement (121).

4.3. Alternatives for non-cement constituents

In response to localized resources of water and sand resources, there has been growing interest in expanding the material sources used for concrete mixing water and fine aggregate. This is particularly important given that much of the growth in concrete construction occurs in regions that are water stressed (16), and climate change makes these challenges even more severe. Appropriate rock and sand deposits are necessary for concrete aggregates and conventionally freshwater resources are necessary for water as a concrete constituent, as contaminants in water and undesirable physiochemical properties of aggregates can lead to deleterious effects on concrete properties (49, 135). Interest in using seawater and brines from industrial sources is increasing (136), as is interest in sea-sand substitutes without additional processing (in the past they have typically been de-salted prior to use) (137). While chloride-contaminated materials can cause differences in concrete microstructure and properties, the primary concern in the impact on reinforcement. Adoption of seawater and sea sand necessitates the use of non-corrosive reinforcement, such as fiber reinforced polymer (FRP) bars and subsequent adjustments to structural design (138).

The use of sea sand as a replacement of river sand is a choice made based on geographic availability. Another common substitute for river sand is manufactured sand, or the fines from crushed stone. Manufactured sand has a different particle shape than river sand; the particles are angular from the crushing process while river sand particles are generally rounded from weathering. Manufactured sand also has a different particle size distribution than river sand, with more fine particles. Both of these factors affect the water demand and workability of concrete mixtures, which necessitates changes in mixture design (139). While sea sand and manufactured sand are the most available substitutes for river sand, there are other options that can be explored based on regional availability including wastes from mining (140) and concrete construction (141). Other resources have been investigated to mitigate resource scarcities and improve circularity for both water and aggregates, including a variety of what are conventionally considered waste flows. Chemical contamination can be a concern with these materials, in addition to water demand and mechanical properties. The use of such alternative resources must be conducted in a way that does not compromise material performance.

4.4. Biogenic resources and carbon uptake pathways

Resources that are renewable on short timescales and resources that are capable of uptake of atmospheric CO_2 have been explored for application in concrete. These resources can be considered in predominantly two categories, with some overlap. The first is biogenic materials, which can be generated on short timescales and, if they are both processed appropriately and used in large enough quantities, may lead to the CO_2 taken up during photosynthesis being stored in concrete. The second is using accelerated carbon mineralization pathways to synthesize resource alternatives to the conventional constituents in concrete.

The use of biogenic materials as constituents in concrete has spanned from low-level additives to the replacement of the largest constituent in concrete, aggregates. Microbial and fungal-driven pathways for precipitating $CaCO_3$ are being studied both as means for bio-cementation as well as for a source of $CaCO_3$ that is not reliant on fossil limestone deposits (142, 143). Work is underway to determine environmental benefits and feedstock requirements for these synthesis routes, as the source of Ca and compounds used in production may have high impact. As noted, use of agricultural biomass that has been fully combusted can leave an ash that may be useful as an SCM, depending on physical and chemical characteristics (121, 144).

Other residues that can be byproducts of energy generation have also been studied for use in concrete. Among these is biochar, which has higher carbon-content than ash (noting, this carbon comes from photosynthesis) and can be formed as a byproduct of certain energy-generation pathways. The use of some biochar as a constituent in concrete has been suggested to lower GHG emissions from the system (145); however, there can be notable changes to material performance based on factors such as degree of use, biochar characteristics, and other drivers for concrete performance (146). Flammability of biochar varies with processing and composition and should be considered during its storage and during mixing (147). The inclusion of low-levels of performance enhancing additives, such as biogenic carbon-based nanocrystals, is being explored to improve the behavior of concrete such that less is specified in designs and the material can last longer without maintenance or replacement (148). Further, the use of biomass directly in concrete has been explored through pathways such as direct inclusion of biomass to replace or partially replace mineral aggregates, which has been proposed as a means to store atmospheric carbon recovered from photosynthesis directly in concrete (149). While this use of biomass can improve some properties, such as lowering thermal conductivity, other material properties, such as strength, are often compromised, and high levels of use may be needed to reach net-zero GHG emissions for the cementitious composite (149).

Another line of research is converting concrete into an atmospheric CO_2 storage mechanism via carbon mineralization pathways (25, 150). There are several carbon mineralization pathways that have been discussed in the context of producing concrete, including the carbonation of concrete during its use and through carbonation of recovered hydrated cement, as discussed in Section 3.6. Additionally, there are types of cementing clinkers that instead of reacting with water to solidify, can react with CO_2 to form carbonate minerals that can bind together aggregates (131, 151). Examples of these types of cement capable of carbonating include MgO cements (e.g., (152)) and carbonatable calcium silicate cements (e.g., (153)). The use of these types of cements typically requires concentrated CO_2 streams to achieve desired strength (152); however, if inappropriate mineral resources are selected (e.g., magnesite), then there could be substantial CO_2 emissions in the production of cement that do not necessarily outweigh uptake during carbonation, and a net-emissions system can result (127). Carbonating SCMs, by exposing the SCMs to CO_2 streams such as flue gas and appropriate processing conditions prior to their inclusion in concrete, has also been proposed as a means to store CO_2 in concrete (154). Engineering relatively inert fillers, such as nano-$CaCO_3$ produced from certain carbon capture technologies (155) and the formation of synthetic aggregates containing mineralized CO_2 (150) have all been proposed as means to utilize and store CO_2 in concrete. Combinations of CO_2 mineralization, reducing clinker content in cement, and direct air capture have been proposed to cumulatively be able to negate up to 85% of CO_2 emissions from concrete (156). However, more work is needed to verify material performance of some of these mineralized carbon alternatives as well as to systematically quantify environmental benefits as scopes of assessment may not address factors such as resource availability, upstream impacts, or other environmental burdens beyond CO_2 emissions.

4.5. Summary

Although there are various strategies to mitigate CO_2 emissions across the concrete value chain, these methods alone will not lead to net-zero emissions necessary to meet climate goals and technological advancements will be needed. Enhancing the efficiency of clinker utilization in concrete, such as by incorporating higher amounts of pozzolanic substances, can contribute to lowering emissions. Despite the widespread use of Portland cement globally, there are also alternative types of cement available that can lead to lower GHG emissions than Portland cement. These include clinkered and calcined alternative cements, which can offer lower limestone decarbonation and energy-related emissions, although they still require kilning and quenching of minerals to form cement precursors. There are other cement alternatives that do not require a kilning phase (e.g., AAMs). For other constituents in concrete, the diversification of materials for batching water and fine aggregates is gaining attention due to the localized scarcities of water and sand. Resources that are renewable on a short time scale and can capture atmospheric CO_2 are also being considered for concrete production. These resources include materials derived from biological sources and those that can be created through accelerated carbon mineralization processes.

5. Conclusions

Cement is commonly considered to be a difficult-to-decarbonize material that is limiting our ability to meet climate-change goals. However, via appropriate engineering throughout the cement value chain and use of alternative resources, this material can be converted to a mechanism to both meet societal infrastructure demands, while mitigating emissions of, or even sequestering, atmospheric CO_2. By overcoming limitations associated with the need to meet prescriptive design and by leveraging other methods to achieve desired performance without high clinker content, notable GHG emissions from concrete can be mitigated. Such measures can occur throughout the life cycle, from improved concrete mixture proportioning, better construction practice, shifts to accommodate CO_2 accounting in the structural design stage, elongating material use, and improved recovery or disposal. These methods, used in concert with alternative resources, can further drive down emissions. In this work, we have highlighted some of these alternative methods. The largest opportunities that can be implemented readily include reducing clinker content in cement or cement content in concrete through use of mineral additives, as well as improving material efficiency through improved design (e.g., of structures) and use (e.g., repurposing in-use materials). Areas with great future potential, but requiring additional research and development, include altering clinker production to lower emissions from limestone decarbonation and energy demand, and using unconventional resources to attain more desirable carbon fluxes (e.g., carbon uptake). We also highlight, though, that solutions must also address the magnitude of resources needed to scale, as well as not compromise either other environmental impacts or material performance.

Summary Points

1. Because clinker production is the main cause of GHG emissions from concrete production, reducing clinker consumption is as a key strategy for decarbonization.
2. Improving concrete mixture proportioning, properly designing structures to reduce material demand, and maximizing the longevity of concrete elements can significantly enhance material efficiency, leading to substantial cuts in CO_2 emissions.
3. Though various strategies exist to mitigate GHG emissions throughout the concrete value chain, achieving net-zero emissions will require technological innovations beyond these methods alone.
4. Mitigating emissions from cement directly can include improved use of SCMs, which are widely used, well-understood, and scalable. But emissions from cement can also be achieved through use of alternative cements, including those that still need kilning and quenching of minerals and those that do not, like AAMs.
5. Use of resources that are rapidly renewable and those that can absorb atmospheric CO_2 are being investigated for use in concrete. However, these alternatives are generally less developed relative to other established emissions reduction strategies.

Future Issues

1. New material alternatives should continue to be explored, and with that exploration robust assessment of their performance (e.g., through experimental analysis and modeling) must be considered. This exploration could include the use of advanced computing methods, such as artificial intelligence, as routes for accelerating study.
2. Future research should systematically quantifying environmental impacts of conventional and alternative materials (e.g., through life cycle assessment methods). Such assessments should address factors such as appropriate benchmarks, methods to improve comparisons across materials, and addressing tradeoffs between multiple materials when used together in a system.
3. Attention should be given to investigating barriers to innovation at the policy and implementation levels — this may include improving understanding for contractor involvement and industry involvement, mechanisms for education/training (practitioners, stakeholders, policy makers) and modernization of standards and specifications.
4. Further efforts should also address quantifying and understanding pathways to mitigate issues beyond CO_2 emissions – e.g., resource scarcities, human health impacts, and ecosystem damages. It should be noted, material efficiency can contribute to reducing multiple impacts by lowering overall consumption and waste,

and additional research should be conducted into the most effective ways of implementing such strategies.

5. Efforts should also be made to understand where infrastructure demands will be growing, appropriate policies to target new material production or material maintenance/replacement, cost of resources, social perception of materials, and social justice concerns for local communities.

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