

Opportunities and challenges for engineering construction materials as carbon sinks

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Abstract

Population growth and urbanization over the coming decades are anticipated to drive unprecedented demand for infrastructure materials and energy resources. Unfortunately, factors such as the degree of resource consumption, the energy-intensive nature of production, and the chemical-reaction driven emissions make infrastructure materials production industries among the greatest contributors to anthropogenic CO₂ emissions. Yet there is an often-overlooked potential environmental benefit to infrastructure materials: most remain in use for decades and their long service lives can facilitate extended storage of carbon. In this perspective, we present an overview of recent technological advancements that can support infrastructure materials acting as a global, distributed carbon sink and discuss areas for further research and development. We present mechanisms to quantify the extent to which the embodied carbon will be removed from the carbon cycle for a long enough period of time to provide carbon sequestration and climate benefit. We conclude that it is possible to unlock the vast potential to engineer a carbon sequestration system that simultaneously meets societal need for expanding infrastructure systems; however, complexities in how these systems are engineered must be systematically and quantitatively incorporated into materials design.

Keywords: Carbon capture and utilization (CCU); Concrete; Wood; Bioplastics; Greenhouse gas emissions

1 Introduction

Infrastructure materials production and their accumulation in the built environment directly affects our demand for natural resources, energy consumption, and climate impacts [1,2]. There is a particularly high burden associated with continued material consumption to support urbanization [3]. The world population is currently estimated to reach 11 billion by 2100 [4]. This growth will continue to strain the environment [5,6]: anthropogenic material-output has resulted in an accumulated mass output that nearly equates the mass of all living biomass on Earth [7]. Demand for construction materials is particularly high: between 1900 – 2015 their demand has been estimated to be 80% of the magnitude of all food, animal feed, and energy resources combined [8].

This growing demand presents a challenge for curbing environmental impacts from materials production, but it also presents an opportunity if this growing body of mass can be used to sequester greenhouse gases (GHG). To mitigate climate damage, anthropogenic CO₂ emissions must reach net zero by 2050 [9], and society will be reliant on carbon uptake mechanisms that can sequester GHGs to break the current pattern of anthropogenic emissions [10,11]. Carbon capture and storage (CCS) or carbon capture and utilization (CCU) technologies (when referred to simultaneously herein,

abbreviated as CCUS) show great promise for capturing flue gas emissions from the energy sector, but remain underdeveloped for key material decarbonization (e.g., for cement production [12]). Another method to meet near-term emissions goals is the sequestration of CO₂ within infrastructure materials [13]. The large mass and long-lived nature of infrastructure materials could provide means for sequestering GHGs over sufficient time periods to be relevant for climate change mitigation.

In this perspective, we argue that storage of CO₂ within construction materials will be a critical route for meeting net-zero emissions goals. We present sequestration pathways for several common classes of construction materials, note certain challenges that must be overcome, and highlight areas where further research is needed. We then turn to systematic and quantitative approaches to enable robust comparisons and to advance carbon-uptake materials design. We note that CO₂ sequestration has also been presented in fuels and chemicals, among others [13], but are outside the scope of this discussion.

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2 Current state of construction materials and the environment

Conventional production methods for construction materials result in net-GHG emissions that must be overcome to lead to net-CO₂-uptake systems. The two material groups with the largest contributions to global anthropogenic CO₂ emissions are cement (the hydraulic “glue” commonly used in the production of concrete) and iron/steel, both of which are critical for construction: approximately 94 to 100% of cement [14,15] and over 50% of steel [16] produced are used in infrastructure applications. Beyond these materials, almost 20% of the plastics made are used in construction [17]. The production of plastics currently contributes nearly 4% of global GHG emissions [18], and leakages in their production supply chains have shown to emit a more potent GHG, methane [19]; woods, because of CO₂ uptake during cultivation, make up a smaller fraction of GHG emissions. Cumulatively, construction materials result in an excess of 15% of annual anthropogenic GHG emissions (see Figure 1, woods are included in “Other materials”). In this subsequent section, we present several classes of building materials that have been discussed as routes for carbon-uptake, which account for a significant engineered mass entering our civil systems annually (see Table 1).

Table 1. Summary of annual demand of infrastructure materials for which sequestration is commonly discussed.

Material	Approximate quantities used annually in construction	Example applications	Ref
Woods	845 Mm ³ (estimated as sawn wood, plywood, particle board, oriented strand board, and fiberboard)	Framing, flooring, siding	[20]
Cements	4 Gt (assumed all hydraulic cement production is used in construction)	Buildings, bridges, roadways	[21]
Aggregates	20 Gt (based on relative demands for concrete, mortar, and sand in asphalt production)	Buildings, bridges, roadways	[21–24]
Plastics	71 Mt (estimated as percent used in construction multiplied by global production)	Piping, flooring, doors/windows	[17]
Natural fibers	30 Mt (estimated as all plant-based fibers – note: many of these are used in textiles)	Insulation, flooring, composites	[25]

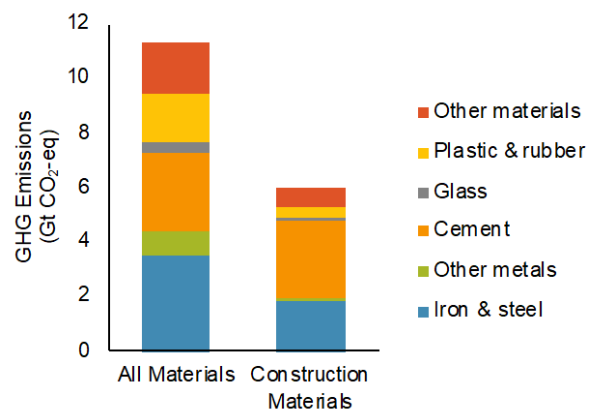


Figure 1. Approximate global greenhouse gas emissions from all materials production and construction materials production in 2016. Emissions from materials production based on data from [14]; fraction of iron and steel in construction based on data from [16]; fraction of cement in construction based on data for US from [15]; fraction of plastics in construction based on data from [17]; all other material fractions used in construction based on data from [14]. Note: emissions from materials production are from [14], and do not reflect all emissions reported by the Intergovernmental Panel on Climate Change (IPCC) [26].

3 Material technologies

3.1 Woods and engineered woods

3.1.1 Opportunity

Woods have been used in construction applications for centuries, and as a biological material for which photosynthesis occurs during cultivation, wooden materials can uptake atmospheric CO₂ [27] (see Table 2). The introduction of engineered woods such as glue-laminated beams (glulam) and cross-laminated timber (CLT), which are composed of multiple layers of smaller boards or lamella glued together [28], has expanded the structural applications of woods. Individual studies have suggested that a concrete framed building may require 80% more energy and result in 100-200% more GHG emissions than a wood-framed building [29]. Further, use of timber rather than steel or concrete has shown to potentially halve the mass of a structural system [27], which could help reduce emissions by requiring smaller foundations. At end-of-life, wooden structures have the potential to be reused, recycled, or used as a bioenergy source, whereas typical mineral structures are demolished and sent to landfills. While the combustion of wood results in GHG emissions, wood components can also be converted into biochar-based materials via pyrolysis and continue to act as a means of carbon sequestration [27].

3.1.2 Challenges and research needs

Although there is carbon uptake from photosynthesis during cultivation, arguments have been made that the feasibility of these resources to contribute meaningfully to carbon sequestration goals is dependent on construction demands, the quantity of wood-resources that can be cultivated, and whether demands and resources are co-located. Pomponi *et al.* [30] evaluated future scenarios, estimating that timber supply would only satisfy 36% of the required timber in 2020-2050 to cover all new floor areas. Additionally, wood

harvesting has become a major driver affecting the age distributions of forests. While shorter lived trees have higher gross photosynthesis, such shifts result in a net reduced carbon storage flux in forests compared to their old-growth counterparts [31]. Although a quarter of global forest area is used for production, only 3% is currently actively managed [30], and intensely managed forests could increase wood biomass production by 2 to 25 times per hectare [32]. Further, noting that in 2015, 50% of roundwood was used for fuel [27], it is possible that re-directing such wood use from short-term energy generation to long-term applications would increase the feasibility of wood as a carbon sink, as well as help meet future demands for timber without having to increase the harvest rate of wood. Attention must also be given to soil destabilization from clear cutting that can return carbon to the atmosphere [33] as well as to vulnerabilities of monoculture tree plantations [34].

3.2 Cement and concrete

3.2.1 Opportunity

Conventional Portland cement typically contributes over 70% of the GHG emissions from concrete production [35]. These emissions are predominately derived from the quantity and type of energy resources used and the decarbonation of limestone during the formation of clinker, a precursor to cement. While there are several mechanisms that could support CCUS in concrete, carbon mineralization and the use of those minerals formed within the cement and concrete industries have been highlighted as a significant potential avenue for GHG-sequestration in the built environment [13,36,37] (select strategies in Table 2). In this process, CO₂ is stored in a mineral, which typically occurs through a reaction of calcium- or magnesium-bearing silicate minerals and CO₂, leading to the formation of carbonate minerals [36]. The inclusion of these minerals in materials like concrete, either as a portion of the cement system or as another constituent (e.g., aggregates), have been proposed as means to sequester CO₂, the most-produced GHG globally [26], in long-lived concrete applications. These concrete applications are responsible for an estimated 30 Gt of material consumption annually [1] in over 160 countries or localities [38]. Such mineralization processes can take place with appropriate alkaline industrial waste, natural or synthetic minerals, as well as hydraulic cement components and their hydration products [39]; there is ongoing research on the most advantageous parameters to drive desirable formation, which is outside the scope of this perspective.

3.2.1.1 Mineralized CO₂ in concrete production

Several pathways for mineralized CO₂ streams to enter concrete production have been investigated. Accelerated carbonation curing and the addition of CO₂ in concrete batching water have been suggested as means to store CO₂ in cement-based materials [36,40]. The use of alternative clinkers that have lower enthalpies of reaction and decarbonation-related emissions has been proposed to reduce GHG emissions from the production of cement [41–43]; certain alternative clinkers can cure through carbonation as opposed to hydration, which could contribute to an uptake

of CO₂ in the production of concrete [42,44]. Engineered carbonate minerals, such as nano-CaCO₃ produced from certain CCUS technologies and carbonate bearing slags, have been shown to improve some concrete properties when used as a filler and could mitigate several environmental impacts [45,46]. It has been suggested that a combination of CO₂ mineralization, direct air capture, and clinker content reduction can sequester 44–85% of the cement production emissions [47]. Among the alkaline waste resources discussed for forming carbonate minerals are cement kiln dust as well as construction and demolition wastes [48]. Recent work has begun to explore potential CCUS through enforced carbonation of cement fines from recycled concrete as an SCM [39,49,50]. Commercialized products have included injecting flux CO₂ into fresh concrete, which has limited direct carbon sequestration potential, but can be used to achieve similar concrete strengths with lower cement contents [40]. Additionally, the formation of synthetic aggregates with mineralized CO₂ coatings has been proposed as a marketable CO₂ storage method (e.g., [51]).

3.2.1.2 Biological sequestration methods

Several biological mechanisms have been explored to support carbon-sequestration in concrete. These have included microbial- and fungal-driven pathways to produce CaCO₃ as bio-cementation routes for reduced GHG emissions [52–54]. There are a variety of methods to produce such bio-cements, and depending on feedstocks, it has been proposed that these cements could lead to a reduction in GHG emissions of more than 70% relative to Portland cement [53]. Distinct from a mineralization process, plant biomass has been proposed as an alternative to mineral aggregates, where photosynthesis during cultivation could contribute to carbon-fixing [55,56] and can lower the embodied energy of the concrete [57]. In addition to carbon-fixing, these plant-based materials can provide better insulation, thus potentially lowering building operation energy demands [55].

3.2.1.3 Carbonation during use and at end-of-life

Carbonation of cement-based materials during their use and at their end-of-life is widely reported in literature [37,48,58,59]. Uptake potential varies based on parameters such as cement chemistry, lifespan, member type and dimensions, as well as end-of-life storage conditions and size of demolition waste [37,59]. While use-phase CO₂ uptake is limited, end-of-life treatments such as decreasing crushed concrete particle size or waste pile sizes, could theoretically lead to sequestering 63–80% of the CO₂ released from limestone decarbonation during production [48,59].

3.2.2 Challenges and research needs

Among the greatest challenges for these technologies are the ability for these materials and practices to meet similar performance as conventional systems and to be cost-competitive. Cement-based materials are used in a wide range of systems that each have varying performance requirements and service lives [60,61]. For mineralized CO₂ applications there are additional challenges. For carbonatable clinkers, achieving desired compressive strengths require

concentrated CO₂ streams (e.g., [62]) and result in cement systems with lower pH, which could affect durability if used in reinforced structures. Further, if the mineral resource used to form carbonatable clinkers are synthetically produced, their formation could lead to greater emissions than their uptake potential, and desirable mineral deposits may be limited [43]. For bio-cements, depending on the application and production method, emissions could be higher than conventional cement [63]. While there has been recent progress in understanding the relationship between input feedstocks for biomineralization and material performance [64], large variability in performance remains [53,64,65]. Additionally, these bio-cements can be quite costly, ranging from ~15 to 600 USD/kg, depending on cultures and

resources used [66], far exceeding the current cost of cement (approximately 0.12 USD/kg in the United States [67]). Although, carbon taxes as a measure to drive emissions reductions (e.g., [68]) could benefit their use if they can provide lower GHG emissions. Similarly, the inclusion of biomass in concrete can lead to challenges: it typically cannot be applied in load-bearing applications [55] and for a cement-based material to reach near-net-zero CO₂ emissions, biomass must constitute a significant volume of the composite [56]. These factors add to the complexity of turning cement-based materials into net-CO₂-uptake systems.

Table 2. CO₂ uptake ranges for example groups of materials (note: for CO₂ uptake, positive values indicate removal of CO₂ from the environment).

Material	CO ₂ uptake range	% Reduction in emissions	Notes	Sources
Woods	1.4 to 1.6 kg/kg	13 to 260% lower emissions than reinforced concrete or structural steel	- fewer uptake benefits noted when building use and end-of-life are taken into account - end-of-life options that consider wood as bioenergy resources lead to high end-of-life emissions, but could still be beneficial relative to other more CO ₂ intensive energy resources	[69–71]
Cement composites				
Alternative clinkers	0 to 0.33 kg/kg	0 to 130% relative to Portland cement	- variation based on clinker composition and raw mineral resources used - improper resource use could lead to greater emissions than Portland cement	[43]
Microbially induced calcium carbonate	0 to 0.44 kg/kg ^a	70 to 83% relative to Portland cement	- variable uptake based on Ca feedstock - many sources use CaCO ₃ as a feedstock, which leads to a process with no net-uptake of CO ₂	[53]
Carbonation	0.04 to 0.69 kg/kg	17 to 80% relative to Portland cement	- includes carbonation in use and at end-of-life - highest uptake potential requires end-of-life management to maximize exposure to CO ₂	[59,72]
Bioplastics	0 to 3.2 kg/kg	0 to 225% relative to petroleum-based plastics	- greater reductions typically noted for bioplastics from entirely bioderived feedstock (as opposed to partially bioderived) - scope of land use can have a significant effect on emissions reported	[73–77]
Natural fiber composites	0 to 5.7 kg/kg	varies	- uptake varies depending on bioplastic matrix, fiber type, and fiber content	[78,79]
CCUS^b process	% Reduction in emissions	Technology readiness ^c	Notes	Sources
Post-combustion	15-89%	commercial projects for power plants	- regeneration of sorbent requires high energy - high volume of flue gas needs to be treated to separate CO ₂	[45,80–82]
Oxy-fuel	10-100%	pilot scale operations	- separation of air to generate pure oxygen requires a large amount of energy	[81–83]
Pre-combustion	35%	full scale plants under construction	- emissions from calcination cannot be captured - regeneration of sorbent requires high energy	[83]

^a assuming a maximum of 1 mole CO₂ sequestered per mole CaCO₃ formed, dependent on Ca feedstock source

^b CCUS = carbon capture and utilization or storage, here focusing on application to the production of Portland cement

^c source for technology readiness: [84]

3.3 Bioplastics

3.3.1 Opportunity

The ease of manufacturing, low density, and typically ductile properties of plastics make them desirable for a wide variety of infrastructure applications, ranging from piping to structural components [85]. Currently, 99% of plastics are made from petroleum resources [86] with polyurethane (PUR), polyvinyl chloride (PVC), high density polyethylene (HDPE) and polyamides (PA) among the most commonly used in construction. The use of bioderived feedstock has been proposed as a means to lead to CO₂-uptake bioplastics [74] (Table 2).

Bioplastics can be formed with structures dissimilar from conventional plastics or they can be formed with either partially or fully bioderived feedstock in the same chemical structure as their petroleum-based counterparts. The most prevalent, commercially available bioplastics are polylactic acid (PLA), thermoplastic starch (TPS) and polyhydroxyalkanoates (PHAs). Cumulatively, these materials make up almost 40% of the current bioplastic market [87]. Notably, PHAs can be formed with methanotrophic bacteria that utilize methane, instead of CO₂, as the primary carbon source [88]. Depending on the feedstock and polymerization process used, studies have suggested production of both PHAs and PLA could lead to net-negative GHG emissions (from -6.06 and -1.7 CO₂e / kg bioplastic, respectively) [88–90]. However, the technical ability of PHAs and PLA to substitute for conventional plastics is uncertain as they have dissimilar properties to the conventional plastics used in construction. Bioplastics with the same structure as petroleum-based plastics, e.g. bio-PE, bio-PVC, bio-PUR and bio-PA, have a higher technical substitution potential: estimated to be roughly 75% of total plastic consumption [91]. Common feedstock resources for these bioplastics include sugarcane or corn stover for bio-PE and bio-PVC, and vegetable oil for bio-PUR [92,93]. Both bio-HDPE and bio-PVC show a possible net uptake of CO₂: theoretically feasible emissions of -1.95 to -0.75 kg CO₂e / kg of bio-HDPE [74–76] and -0.9 to -0.2 CO₂ kg CO₂e / kg of bio-PVC [77].

3.3.2 Challenges and research needs

The most common PLA, TPS, and PHB bioplastics do not typically have properties that are well suited for construction applications. PLA and PHB exhibit brittle behavior [94,95], although efforts are underway to overcome these limitations [95,96]; TPS has high sensitivity to moisture and high affinity for biodegradation [97]. In addition to performance limitations, poor selection of feedstock and polymerization process could result in upwards of 12 kg CO₂e / kg bioplastic [98].

Bio-PE, bio-PVC, bio-PUR and bio-PA that have equivalent chemical structures to their petroleum counterparts will overcome performance-related issues. Yet, the potential for CO₂-uptake with these plastics is sensitive to the scope of assessment, assumptions made (e.g., longevity of plastic use, role of land-use change), feedstock resource, and polymerization method, with several inputs leading to net-GHG emissions as opposed to uptake [74–77]. Further, bio-

PUR and bio-PA still require fossil feedstocks for production and contain as little as 10% and 40% bio-based carbon content [99]. These production methods do not lead to a net-uptake, but could offer a potential 38–75% decrease in GHG emissions for bio-PUR [100] and a 40% reduction in GHG emissions to produce adipic acid (AA), a monomer in PA [101,102]. Further work is needed to select processing alterations to lower production emissions [103], including appropriate selection of energy resources [104], polymerization process [105,106], and farming practices [107]. Such adaptations, in conjunction with appropriate selection of feedstock, will support bioplastic production to act as a carbon-uptake mechanism.

3.4 Natural fiber composites

3.4.1 Opportunity

Natural fiber composites (NFCs), formed from bioplastic matrices and any of a variety of natural fibers, can have mechanical properties similar to engineered woods as well as desirable environmental benefits [108]. Many of the fibers used in NFCs are residues from other systems (e.g., sawdust from sawn lumber [109]) or from annual crops (e.g., hemp, flax, [110]). Due to short cultivation periods, if annual crops are replanted after harvest, they have a greater potential to lead to CO₂ sequestration than longer growth woods [111,112]. Appropriate selection of processing methods for bioplastics and natural fibers could lead to net-negative GHG emissions from NFC production [79].

3.4.2 Challenges and research needs

There are several aspects of NFCs that present challenges, which should be further investigated to overcome their current limitations. Among these issues are other environmental burdens: even when these composites have been modeled as contributing to net-negative GHG emissions, they can lead to other non-negative environmental impacts, such as acidification and eutrophication [79]. Further, while NFCs are commonly discussed for construction applications, they are susceptible to several durability issues, such as those associated with thermal, ultraviolet, moisture, and biological deterioration mechanisms [113–115]. As a result, the ability to implement NFCs in construction remains limited. Methods are being developed to ensure appropriate composite selection while mitigating environmental impacts [116–118], and such research must continue to support the advancement of these materials.

3.5 Other building materials

There are many additional non-structural building components that could act as temporary carbon storage. Incorporation of natural fibers, biochar, or cork into components such as gypsum board or insulation could decrease the net-CO₂ emissions of the building material [119–123]. In some cases, such use could lead to a potential net-uptake material [120–123]. As non-structural components, the acceptance of these materials may occur more readily as performance requirements are less stringent. Additionally, a variety of plant biomass has been shown to decrease the thermal conductivity of the materials and, as a result, could

contribute to a reduction in the energy load during the use of a building [122,124]. Noting variations in carbon storage ability depending on the biomass resource [120,121] and the typically shorter lifespan of non-structural components relative to the building [125,126], research should verify scenarios under which such materials can act as a meaningful CO₂ storage mechanism.

3.6 Other carbon capture and utilization or storage opportunities

CCUS methods for power plants have been more widely researched but less studied for their applications in materials production. Some studies have evaluated adapting power sector applications to the cement sector, which we focus on here due to its non-energy derived emissions. The fraction of CO₂ in flue gas from cement production, ranging from 15 to 30 mol%, is higher than the fraction found in flue gas from power plants [81,127]. Yet, CCUS solutions for power plants are not directly transferrable to cement production due to significant differences in equipment, processes and chemical/thermal reactions [128]. Reports have projected CCUS implementation in cement production plants to begin in 2030, and as such, a rigorous understanding of the technology and environmental impacts is required [129]. Several studies analyzing post-combustion CCUS reported it leading to lower GHG emissions than traditional cement production, but driving harmful increases for human health impacts [45,80,81,130], thus potentially shifting the problem from CO₂ emissions to another impact category. Further, the use of CO₂ captured from power plants in CCUS within concrete has been explored, but recent findings suggest a loss of mechanical strength could result in some of these technologies leading to higher CO₂ emitting systems than conventional concrete [131]. Finally, the upfront and long-term costs remain high for many CCUS technologies. For example, oxyfuel-combustion costs 55-70 USD/tCO₂ avoided and post-combustion costs 90-150 USD/tCO₂ avoided [129]. While we focus our CCUS discussion on cement, we note that some materials, such as steel, do not lend themselves to CO₂ storage. In the case of steel, improved production methods (e.g. lower CO₂ energy sources and/or recycling [132,133]) could lead to a 50-89% reduction in CO₂ emissions from production [133,134], and energy-CCUS can further benefit such materials.

4 Pathways Forward

Systematic and quantitative methods are necessary to determine carbon-sequestration viability of alternative construction materials. Here we outline three critical areas in such analyses, namely, (1) environmental impact assessments, (2) materials performance and design techniques, and (3) consideration of co-benefits and unintended consequences. We highlight aspects of each of these approaches that are necessary to ensure robust analysis, and we outline key takeaways from these sections in Figure 2.

4.1 Environmental impact assessment

Environmental impact assessment methods are the most robust way to quantitatively assess the potential of CO₂-uptake materials. Forms of environmental impact assessment are frequently applied to examine the potential for new technologies to contribute to GHG emissions mitigation (e.g., [135–138]). For such assessments, it is crucial that consistent scoping, accounting methods, consideration of uptake time horizons, carbon-storage periods, and emissions during life cycle stages be considered to ensure net-sequestration. Variations in scope of analysis can lead to biases in quantified GHG emissions, double-counting, and/or under-estimated emissions [139]. Inherent sources of data variability and uncertainty that could directly influence the likelihood of achieving lower emissions should be considered [140–142]. This is particularly pertinent to new technologies that are based on laboratory scale production, which can have greater uncertainty in several material, energy, and waste flows as industrial-scale production is typically more efficient [143]. Allocation of emissions to products and processes and the time-dependent effects of global warming potentials can alter outcomes in assessing how CO₂ is stored [144,145]. To mitigate undue burdens, potential co-benefits and unintended consequences of measures used to lower GHG emissions from systems must be considered [130,146].

Importantly, analysis of sequestration potential has conventionally left out evaluation of time-dependent effects. This factor is an issue of particular concern for carbon-sequestration in the built environment as GHG fluxes and material in-use longevity can affect benefits in the goal of mitigating climate impacts (e.g., [147]). As examples: (a) during the production stage, the rate of CO₂ uptake for annual crops is quicker than that of old growth forests [111]; (b) in terms of longevity, CO₂ storage in interior floorings, such as carpeting, could last less than 20% as long as a foundation or frame [126]; (c) at end-of-life, differences between GHG emissions from bioplastic anaerobic decomposition, thermomechanical recycling, and combustion can be substantial [148–151]. Additionally, elongating the service-period of a material by using it longer than its original design life, as is common in structural systems, would shift the in-use carbon storage within that element.

Simply summing GHG fluxes can distort actual global warming effects [145]. The impacts due to radiative forcing of a specific GHG (in this case shown, CO₂) are dependent on the year in which the emissions occur, as seen in equations 1 and 2 below:

$$Total\ impact = C_u * k_u + C_p * k_p + C_e * k_e \quad (1)$$

$$k_{u,p,e} = \int_0^{AT-y} RF_{CO_2} dt \quad (2)$$

where $C_{u,p,e}$ is the quantity of CO₂ emissions associated with uptake, production and end-of-life, respectively, $k_{u,p,e}$ is the time-adjusted warming potential constant associated with uptake, production and end-of-life, respectively, AT is the analytical time horizon, y is the year in which the emissions occur, and RF_{CO_2} is the radiative forcing of CO₂. A preliminary study by the authors shows that using bio-HDPE

for 40 years would lead to 80% lower CO₂ emissions than traditional global warming potential accounting. Inversely, using bio-HDPE for 1 year increases net-CO₂ emissions by 4-fold relative to the 40-year use; yet in both scenarios, conventional accounting methods would inaccurately assume equivalent emissions. Similar trends have been found for woods. Guest *et al.* [152] found that tree harvest rotation periods and use-periods would lead to net-GHG emissions varying from roughly -1 kg CO₂e / kg wood to 0.44 kg CO₂e / kg wood.

In the examination of intended CO₂-uptake materials, it is necessary to systematically quantify net-sequestration potential, and consideration must be given to when sequestration will occur relative to production-related emissions as well as to the time-horizons over which uptake and emissions take place. Such work reflects the significance of both use of materials for long-term applications and use of appropriate accounting methods.

4.2 Material performance and design

The benefit of material long-use is contingent upon engineered CO₂-uptake alternatives being able to maintain or improve material performance relative to the conventional materials they would replace. Construction materials are critical to many facets of society, including transportation systems, dwellings, energy infrastructure, water and wastewater utilities, among others; the materials used in these systems are often required to maintain performance under prolonged loading conditions in various environmental exposures and under a multitude of potential hazards [153]. Poor functionality could be hazardous as well as lead to greater maintenance or replacement, which could increase burdens [154–156], or reduce the ability to act as a means for sequestration.

Material performance should be addressed in environmental impact comparisons where applicable and appropriate [156]. Typical functional units of comparison in such assessments are based on a unit volume of material produced, tracking cradle-to-gate impacts (from raw materials acquisition, through processing and manufacture, but not including installation, use, or disposal) (e.g., [157,158]). However, CO₂-uptake material alternatives can behave differently from

conventional ones, and differences in performance could alter the amount of material, maintenance, and/or replacement necessary, which in turn can drive changes in environmental impacts [116,155,159,160]. Therefore, these units of comparison should incorporate mechanical properties [161], the influence of constituent and process selection [109], as well as durability characteristics [162,163].

Beyond more robust functional units, several multi-objective design and optimization methods have been derived to concurrently weigh environmental impacts and material performance [164] – such tools can be advanced to drive strategic engineering of carbon sequestering materials. To date, work in developing these tools has included simultaneous examination of concrete strength development and GHG emissions (e.g., [165,166]), materials and composite constituent selection methods (e.g., [117,167]), and material properties that drive different use-phase impacts alongside environmental impacts (e.g., [168]). Often, such methods examine a single class of materials or a specific material application. Extending their application to assess the carbon sequestration potential of multiple material alternatives and applications will advance our ability to systematically design a carbon-uptake built environment.

While not currently well suited for carbon uptake materials, eventual use of robust data structuring and machine learning methods could support structured discovery of these materials. Data processing and extraction for structured databases can support such research [169] and be used with advanced data processing and machine learning methods to guide environmentally sustainable materials development and selection [170,171]. However, for carbon-uptake materials, there is a need to build-up training dataset information before such modeling efforts can be employed. Further, there is the challenge of addressing the complexity of modeling local resources, production methods, environmental exposures, and loading requirements, which could impact data availability and may require additional research.

Figure 2. Simplified framework of considerations to be made as CO₂-uptake materials are engineered

Key considerations for designing carbon-sequestering materials		
<u>Environmental impact assessments</u> • Critical to quantitatively address uptake • Need consistent scope, accounting • Should address uncertainty and variability • Must consider time-dependent effects of GHG fluxes	<u>Material performance and design</u> • Must consider changes in performance relative to conventional equivalent • Multi-objective design can be used to guide sustainable constituent and process selection • Leverage data science methods when applicable	<u>Co-benefits</u> • Engineer new materials to mitigate other environmental impacts • Regionally diverse approach to minimize resource scarcity • Support equity in access to requisite infrastructure systems while minimizing disproportionate impact

4.3 Co-benefits, unintended consequences, and sustainable systems

Shifting how we produce construction materials presents a significant opportunity to create consumption chains that lead to co-benefits for society and the environment. For many construction materials, the supply chains that support their production are well established, and there are often high sunken costs in production facilities designed to last several decades [172]. Additionally, the use of certain long-lived materials creates long-term path dependencies, in which society becomes “locked-in” to continued use of similar materials after their initial use is established [2]. However, changes in materials used could open up mechanisms to concurrently mitigate other environmental impacts as well. A key example of how this could occur has been shown in the adaptations of fuels: most fuel decarbonation strategies have resulted in significantly lower air pollutant emissions [146]. There is not a direct corollary for the production of materials as formation of air pollutants from minerals and processes make such co-benefits sometimes more difficult to address [130]. And, in the case of CCUS technologies that recover GHGs from flue gas, the high energy input could lead to other emissions if inputs are not appropriately selected [173].

Yet, the challenge in producing CO₂-uptake materials also presents an opportunity to overcome the barriers to reducing both emissions and inequities associated with conventional materials. Industrial production PM_{2.5} emissions, which lead to substantial health burdens, have been shown to disproportionately affect underrepresented populations [174]. Similarly, resource extraction has disproportionately affected indigenous peoples [175] and has led to violent conflicts [176]. To produce infrastructure materials, there is a need for large resource availability, which could require a regionally diverse approach with solutions that vary by location. New material supply chains can be engineered to overcome unequal distribution of resources and break dependencies on inefficient long-lived industrial facilities. To support such shifts in consumption, policies will be needed that support the transition to using CO₂-uptake materials with co-benefits. Measures, such as government procurement of novel materials or economic incentives, that overcome self-perpetuating stock dynamics [2] can facilitate such change and instigate regionally appropriate technologies that support local populations and limit resource scarcity. Industrialization of production methods can limit waste of resources [177], and standardization can support the acquisition of materials that meet certain design thresholds; however, it must be noted that such measures could limit adoption of breakthrough technologies that do not easily fit into those conventions.

5 Conclusions

The high levels of material consumption and the long-lived nature of material use for infrastructure systems presents a unique opportunity to create value-added systems that both support continued material demand from growing populations and sequester CO₂. In this work, we present several material classifications and technologies with the

potential to act as significant routes for CO₂ sequestration in the built environment. These sequestering materials need continued research and development to ensure net-uptake pathways that can contribute to emissions goals, meet desired performance, and support equitable utilization. As such, a systematic approach to how these materials are engineered, accounting for desired application, location of use, and quantitative environmental impact assessments must be incorporated. Here, we argue that such measures will facilitate breakthroughs in materials development that allow our built environment to disrupt the current anthropogenic GHG emissions cycle. Policies that support dissemination of these materials will both trigger continued research efforts as well as disrupt current materials consumption pathways. Society is poised to take advantage of this significant opportunity to create sequestration pathways while improving the built environment to support current and future generations’ needs.

Conflict of interest

The authors declare no competing financial interest.

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SAM: Conceptualization, Data curation, Writing – original draft, Writing – review and editing, Visualization, Supervision, Funding acquisition

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