Life Cycle Assessment (LCA) and Cost-Benefit Analysis for Low Carbon Concrete and Cement Mix Designs

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Author: Delaney Khung (Research Associate at the United Nations (UN) Sustainable Development Solutions Network (SDSN); Associate at Saoradh Enterprise Partners)

Contributor: Elena Crete (Head of the Climate and Energy Program at the UN SDSN)

Editorial Support: Sonja Neve (Program and Outreach Coordinator at the UN SDSN) and **Cheyenne Maddox** (Outreach and Events Manager at the UN SDSN)

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About the SDSN

The UN Sustainable Development Solutions Network (SDSN) mobilizes scientific and technical expertise from academia, civil society, and the private sector to support practical problem solving for sustainable development at local, national, and global scales. The SDSN has been operating since 2012 under the auspices of the UN Secretary-General. The SDSN is building national and regional networks of knowledge institutions, solution-focused thematic networks, and the SDG Academy, an online university for sustainable development.

About SEP

Saoradh Enterprise Partners (SEP) is a venture capital and research firm focused on technologies for disruptive sustainability across the nine sectors that comprise the cleantech ecosystem. SEP's approach is unique, leveraging its innovative market and technology research platform to identify sustainable technology opportunities in emerging cleantech hubs in the US for its investment funds and corporate clients. The SEP team partners with entrepreneurs, innovators such as universities and national labs, and leading corporations to build companies that disrupt valuable segments of supply chains for products that mitigate climate change and other environmental impacts.

Two reports accompany this whitepaper:

An ArcGIS StoryMap that reviews the material in a quick, interactive format (published on SDSN's website).

A Topic Report that expands on the market, green metrics, cost metrics, technologies, policy, 87 global startup and growth companies, and researchers (available for purchase at SEP's marketplace).

ABSTRACT

Concrete accounts for 8% of global CO_2e emissions and is a notoriously hard-to-abate sector. 80% of those emissions come from concrete's key ingredient, cement, and 50% to 40% are from the calcination of calcium carbonates. These emissions cannot be addressed through renewables, electrification, etc. Reducing cement content through low carbon mix designs is a key solution. This study uses a cost-benefit analysis and life cycle assessments (LCA) to determine which low carbon mix designs reduce CO_2e footprints, are profitable to concrete batching plants, and are most advantageous to society. These ready mix, mix designs replace traditional cement with ground granulated blast furnace slag (GGBS), fly ash, biochar, recycled concrete aggregate (RCA), portland-limestone cement, limestone calcined clay cement (LC3), and early stage carbon curing. The LCAs demonstrate that GGBS, LC3, fly ash, and portland-limestone cement reduce the most CO_2e emissions: 43%, 37%, 27%, and 9% (respectively). All four are more profitable for batching plants than traditional ready mix concrete by 3% to 21%. Biochar and carbon curing offers negligible CO_2e reductions of 2% and 0% (respectively), and RCA may increase overall emissions. These are not more profitable for batching plants, although all mix designs are more advantageous if social carbon costs and waste aversion benefits are considered.

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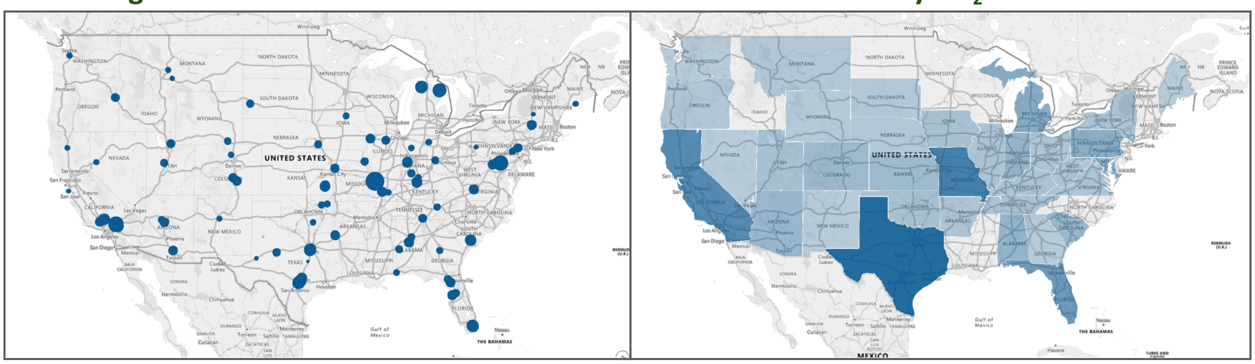
I. INTRODUCTION

Concrete, the second most consumed material in the world after water[106], accounts for about 8% of global carbon dioxide (CO_2) emissions[17]. If the cement industry were a country, it would emit the third largest amount of CO_2 behind China and the US[107]. Furthermore, US waste from construction, reconstruction, expansion, alteration, conservation, and demolition equated to almost 550 metric tonnes (mt) in 2018–twice the amount of municipal solid waste[101].

Yet, projections indicate continued growth in the concrete market. As of 2020, the global concrete market stands at $617 billion and is growing[102]. There are 98 cement plants and more than 8,500 concrete plants in the US today[9], employing 12.3 million people[32]. Figures 1 and 2 provided by SEP represent the cement production facilities and the cumulative CO_2 emissions from cement production in the US[103].

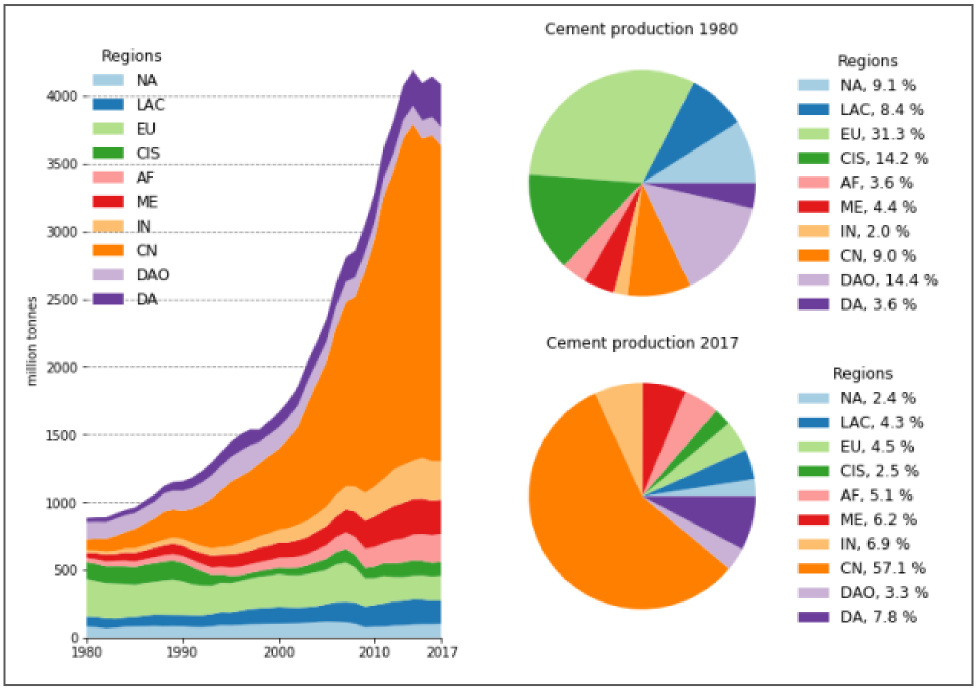
Figures 1 and 2: Cement Production Facilities Characterized by CO_2 Emissions[103]



Note: Figure 1 (left) represents the cement production facilities in the US sized by CO_2 emissions, and Figure 2 (right) represents the cumulative CO_2 emissions from cement production within a state. Texas, Missouri, California, Florida, and Michigan have the highest cumulative emissions.

By 2050, the International Energy Agency (IEA) estimates a global growth of 12 to 23% for cement, and Chatham House estimates a growth of 25%[15]. The biggest growth is expected in rapidly developing economies still in major construction phases[14]. Figure 3 represents previous growth in cement production, as characterized by the Climateworks Foundation[8].

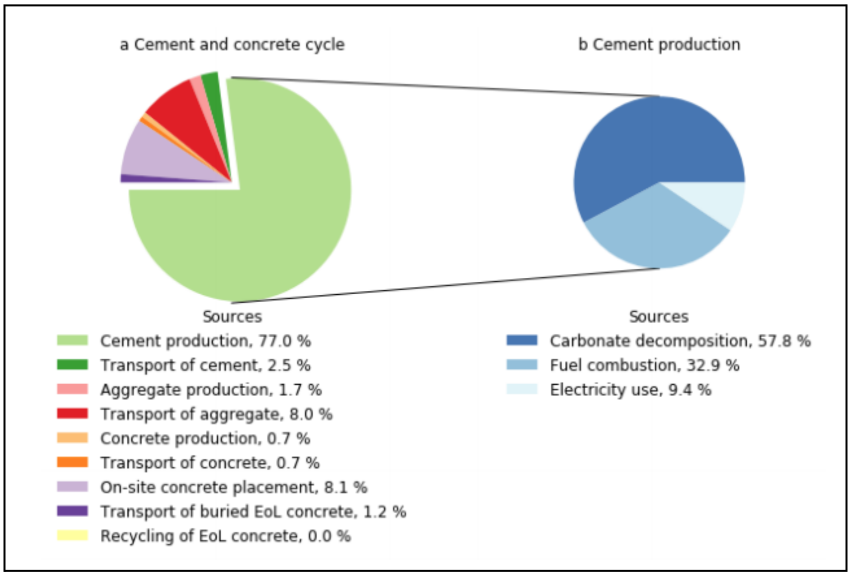
Figure 3: Cement Production by Region from 1980 to 2017[8]



Note: Climateworks sourced their data from the United States Geological Survey (USGS) Mineral Yearbooks. NA=North America, LAC=Latin America and Caribbean, EU=Europe, CIS=Commonwealth of Independent States, AF=Africa, ME=Middle East, IN=India, CN=China, DAO=Developed Asia and Oceana, and DA=Developing Asia.

The science community reports that we already met the carbon budget for a 1.5℃ warming scenario, so the concrete industry requires low carbon solutions[2]. However, concrete is a hard-to-abate sector. About 80% of concrete's emissions come from cement, and 50% to 60% of cement's emissions come from calcination of calcium carbonate[9,78]. Calcination cannot be decarbonized using commonly cited solutions such as electrification, kiln efficiency, and more. Figure 4 from Climateworks Foundation illustrates the breakdown of CO_2 emissions by production phase from the cement and concrete industry in China[8].

Figure 4: Breakdown of CO_2 Emissions in Concrete Production[8]



Note: This figure breaks down the 2017 CO_2 emissions for China's cement and concrete industry.

Emission reduction solutions in current literature focus on difficult process and grid improvements, building improvements and cement content reduction[2,8,12,15,80,90,98]. Process improvements include plant efficiency; electrifying kilns; low carbon fuels; renewables; replacing natural gas or coal with blue or green hydrogen; implementing state-of-the-art technologies; and carbon capture, utilization, and storage (CCUS). CCUS at cement plants is expected to grow from 5% in 2030 to 50% in 2050[2]. Building improvements include material substitution, design optimization, lifetime extension, recycling, smart buildings, and sustainable construction.

Low carbon concrete and cement mixes reduce cement content, the highest source of carbon dioxide equivalent (CO_2e). In 2017, the clinker[I] ratio in cement was 78.9% in China, 89.6% in the US, and 69.3% in India; some estimate that the ratio can drop to 60% without sacrificing performance[8].

[I]Clinker is the result of calcination where calcium oxide reacts with silicate, alumina, and ferrite. It is the size of a golf ball and is ground up and combined with gypsum and uncalcined limestone to form cement.

A publication search on Web of Science concerning low carbon concrete and cement mixes from 2010 to 2021 found 18,588 publications regarding fly ash, 1,880 publications regarding ground granulated blast furnace slag (GGBS), 1,712 publications regarding recycled concrete aggregate (RCA), 199 publications regarding biochar, 159 publications regarding portland-limestone cement, 153 publications regarding limestone calcined clay cement (LC3), and 119 publications regarding carbon curing.

The most controversy in this field surrounds carbon curing. Some research finds concrete performance improvements and net CO_2 benefits with carbon curing[7] while others find no net CO_2 benefits. A 2021 paper by Ravikumar et al. that reviewed 99 experimental datasets found evidence for lower compressive strength and found that 56 to 68 of the datasets showed a net increase in CO_2 emissions[6].

Literature also argues that cement decarbonization may increase cement prices. The World Resources Institute posits that decarbonizing the concrete industry by mid century may increase concrete costs by 30%[9]. The Energy Transitions Commission posits that decarbonizing the cement industry accounts for 60% of costs needed to decarbonize all global harder-to-abate sectors including steel, plastics, trucking, shipping, and aviation[14].

This study posed the question “how do low carbon concrete and cement mix designs differ in costs, benefits, and LCAs?” Cost-benefit analyses and LCAs were calculated for a baseline ready mix concrete mix design, two low carbon cement mix designs, and five low carbon concrete mix designs. This study finds that all low carbon mix designs except for RCA, offer 2% to 43% CO_2e reductions. Four low carbon mix designs offer production cost advantages: GGBS, LC3, fly ash, and portland-limestone cement. The inclusion of waste aversion and social carbon costs makes all low carbon mix designs preferable from a cost standpoint. The study also addressed the carbon curing controversy, and found little evidence for its benefits.

II. METHODOLOGY

This study developed a cost-benefit analysis that included a LCA. The analysis considered one baseline scenario and seven low carbon mid designs. The mix designs incorporate GGBS, fly ash, biochar, RCA, portland-limestone cement, LC3, and early stage carbon curing. This study summed costs and benefits from 2022 to 2050 and applied a 7% discount rate. 2050 was used because the price projection of CO_2 costs, carbon offsets, carbon social costs, and carbon tax credits end in 2050. The analysis assumes a medium to large concrete batching plant that produces 100,000 cubic meters (m^3) of concrete annually. Inputs are based on US national averages.

18 sources were reviewed in a literature review prior to the analysis, and 17 experts were consulted during and after the analysis development. Appendix A lists all experts. The literature review and data sources expanded to 108 sources upon completion of the study. SEP

visited a Holcim ready mix plant May 2022 in Denver, CO, to solidify an understanding of processes. Appendix B depicts images from the visit.

All scenarios modeled ready mix concrete. Ready mix concrete–concrete produced and mixed at a batching plant, delivered to a site, and poured on site–accounts for 70% to 75% of concrete sales in the US in 2021[3]. This study originally considered, but ultimately excluded, precast concrete due to a lack of data and a difficulty in converting data to comparable units; precast concrete products often include pipes, walls, slabs, and more and contain other materials beyond concrete such as steel rebar. This study designed mixes using Union College's Concrete Mix Design Tool[37] based on American Concrete Institute's (ACI) standards as well as other resources. Mix design results for curing were manually adjusted due to the tool's limited scope. The mix designs were compared to mix designs outlined by the National Ready Mixed Concrete Association (NRMCA). Appendix C outlines mix design assumptions, and Appendix E compares the designs with the NRMCA's. Table I depicts the mix design compositions for the eight scenarios.

Table 1: Mix Design Specifications for Eight Scenarios

Scenario	Material Content (kg/m^3)											
	Water	Type I/II Cement	Portland-Limestone Cement	LC3	Coarse Aggregate	Recycled Coarse Aggregate	Fine Aggregate	Recycled Fine Aggregate	GGBS	Fly Ash	Biochar	Liquid CO_2
Baseline[a]	169	365			1054		807					
GGBS[b]	286	183			1054		793		183			
LC3[c]	170			365	1054		780					
Fly Ash[d]	170	256			1054		787			110		
Portland-Limestone Cement[e]	169		365		1054		807					
Biochar[f]	169	358			1054		796				7	
Curing[g]	169	347			1054		823					1
RCA[h]	208	406				1054		590				

Note: Concrete is a mixture of cement, fine aggregate, coarse aggregate, water and admixtures. [a]The baseline mix design is a traditional ready mix concrete. [b]The GGBS mix design replaces 50% of cement with GGBS. [c]The LC3 mix design replaces all cement with LC3: a blend of 30% calcined clay, 15% limestone, 5% gypsum, and 50% clinker. [d]The fly ash mix design replaces 30% of cement with fly ash. [e]The portland-limestone cement mix design replaces all cement with portland-limestone cement: a cement with 15% uncalcined clay as opposed to 5% in the baseline. [f]The biochar mix design replaces 2% of cement with biochar: a net negative material developed from biomass. [g]The curing mix design pumps 0.15% liquid CO_2 into the concrete when poured as a cement replacement. Cement content is cited to decrease 5%. [h]The RCA mix design replaces 100% of the fine and traditional aggregates with recycled concrete aggregates. Cement content increases in this mix.

Each cost-benefit analysis accounted for a LCA. This study only considered CO_2e and waste avoided in the final cost-benefit analysis. However, concrete production also generates carbon monoxide, lead, nitrous oxide, particulate matter, sulfur dioxide, and volatile organic compounds. This study excluded these emissions from evaluation due to a lack of available data. CO_2e was monetized using social costs outlined by the United States Government's Interagency Working Group on Social Cost of Greenhouse Gasses, carbon offsets were outlined by Bloomberg, and tax credits were based on 45Q. Note, this study was conducted prior to the Inflation Reduction Act–an act that significantly altered 45Q. Social costs include the net harm to society from human health impacts, net agriculture productivity changes, property damages, natural disasters, disruption of energy systems, environmental migration, conflict risk, and the value of ecosystem services. It does not include the physical, ecological, and economic impacts of climate change supported by literature. The United States Government valued the social cost of carbon at $51 per mt CO_2 in 2020 and at $85 per mt CO_2 in 2050 (in 2020 dollars). Waste avoided was monetized using a KPMG[61] estimate for the average city spending to divert waste. Waste is valued at $210 per mt waste in 2017 dollars.

LCA calculations accounted for the input of resources, primary energy use (fuel pre-combustion, fuel combustion, and electricity generation), process-specific emissions (calcination), and transportation of materials. LCA calculations used University of California, Berkeley's Green Concrete LCA Web Tool[95] last modified in 2012 as well as other resources. The study chose this tool partially because it broke emissions down by production phase. LCA results for biochar, RCA, portland-limestone cement, LC3, and curing were manually adjusted due to the tool's limited scope. LCA results were compared to reports from the NRMCA. Appendix D outlines LCA assumptions, and Appendix E compares this study's LCAs with the NRMCA's.

The analysis includes four time series datasets: the cost of CO_2 gas, carbon offset prices, social carbon costs, and carbon tax credit values. Some datasets provided step increases for only a few years and in intervals. Values were calculated for the years not provided by assuming linear trends.

The cost and benefit inputs are segmented into three silos: 1) the inputs relevant to producers (producer case), 2) the inputs relevant to producers and carbon revenues (carbon case), 3) the inputs relevant to producers, carbon revenues, and social costs (social case). Segmenting these illustrates the net benefits from the perspectives of multiple stakeholders. Table 2 depicts the costs and benefits included in each case, and Appendix F outlines all assumptions and sources for each input.

Table 2: The Costs and Benefits Included in Each of the Three Silos

Producer Case	Carbon Case	Social Case
Costs		
Operating Costs[a,b]	Operating Costs[a,b]	Operating Costs[a,b]
Cement Costs[a,c]	Cement Costs[a,c]	Cement Costs[a,c]
Coarse Aggregate Costs[a]	Coarse Aggregate Costs[a]	Coarse Aggregate Costs[a]
Recycled Coarse Aggregate Costs[a]	Recycled Coarse Aggregate Costs[a]	Recycled Coarse Aggregate Costs[a]
Recycled Fine Aggregate Costs[a]	Recycled Fine Aggregate Costs[a]	Recycled Fine Aggregate Costs[a]
Other Pozzolanic Material Costs[a,d]	Other Pozzolanic Material Costs[a,d]	Other Pozzolanic Material Costs[a,d]
Liquid CO_2 Cost[a]	Liquid CO_2 Cost[a]	Liquid CO_2 Cost[a]
Final Product Transportation Costs	Final Product Transportation Costs	Final Product Transportation Costs
		Social Carbon Costs
Benefits		
Final Product Revenue	Final Product Revenue	Final Product Revenue
	Carbon Credit Revenue	Carbon Credit Revenue
	Carbon Tax Credit Revenue	Carbon Tax Credit Revenue
		Avoided Waste

Notes: [a]Costs include transportation and material costs. [b]Operating costs include water, salary, early stage curing equipment (differs by mix design), and more; provided largely by Holcim. [c]Cement may be type I/II, portland-limestone cement, or LC3 depending on the scenario. [d]Pozzolanic material may be GGBS, fly ash, or biochar depending on the scenario.

This paper reports six results: net CO_2e production, percent reduction CO_2e compared to the baseline ready mix (Equation 1), net benefits (Equation 2), percent change of net benefits compared to the baseline (Equation 3), dollar change compared to the baseline (Equation 4), and benefit/cost ratios (Equation 5). All results report net present values.

$$\frac{CO_2e\ of\ Low\ Carbon\ Mix\ Design}{CO_2e\ of\ Baseline\ Mix\ Design} - 100 \quad \text{Equation 1}$$

$$Benefits - Costs \quad \text{Equation 2}$$

$$\frac{Net\ Benefit\ of\ Low\ Carbon\ Mix\ Design}{Net\ Benefit\ of\ Baseline\ Mix\ Design} - 100 \quad \text{Equation 3}$$

$$Net\ Benefit\ of\ Low\ Carbon\ Mix\ Design - Net\ Benefit\ of\ Baseline\ Mix\ Design \quad \text{Equation 4}$$

$$\frac{Benefits}{Costs} \quad \text{Equation 5}$$

III. RESULTS

LCA Results

Table 3 shows the kilograms (kg) CO_2e per m^3 of concrete and the percent reduction CO_2e compared to the baseline ready mix:

Table 3: LCA Results

CO_2e in kg/m^3 for Eight Scenarios		
Mix Design	**CO_2e (kg/m^3)**	**% Reduction CO_2e Compared to Baseline Ready Mix**
GGBS	232	-43%
LC3	255	-37%
Fly Ash	295	-27%
Portland-Limestone Cement	369	-9%
Biochar	385	-6%
Curing	397	-2%
Baseline	407	-
RCA	446	9%

Note: Green text indicates the mix design produces less CO_2e than the baseline and red indicates the mix design produces more CO_2e than the baseline.

GGBS, LC3, and fly ash produce much less CO_2e compared to the baseline ready mix design primarily due to cement reductions of 50%, 40%, and 30% respectively. Reducing cement results in notably smaller CO_2 footprints. For example, GGBS has a CO_2e footprint about 11.5 times smaller than cement.

Portland-limestone cement, biochar, and curing offer small CO_2e savings due to smaller cement reductions of 10%, 4%, and 5% respectively. Biochar, a net negative material, sequesters 2.2 mt CO_2 for every mt biochar; this offers additional carbon reductions. Curing's carbon small benefit is solely from the 5% cement reduction. The liquid CO_2 used for curing adds to the total CO_2 footprint. The CO_2e emissions from the use of liquid CO_2 is 9.36 kg CO_2e per m^3 of cement. This accounts for liquified CO_2 production, transport, and the production, transport, and operation of equipment. Only 60% of the CO_2 pumped into the mix gets absorbed, meaning that only 0.312 kg of CO_2 per m^3 of concrete is sequestered[80].

Given that RCA mix designs require a lower water-cement ratio (0.45 compared to the baseline 0.5), CO_2e increases; RCA's carbon footprint is also 2.05 times that of traditional fine and coarse aggregate[67].

In 2019, the NRMCA found that the US produced 23,257,054 m^3 of ready mix concrete[52]. Table 4 shows the amount of emissions saved if all of 2019 ready mix concrete was produced using each low carbon mix design.

Table 4: Projection of Possible CO_2e Saved Annually in the US per Mix Design

CO_2e for Eight Scenarios			
Mix Design	**CO_2e (kg/m^3)**	**Total US CO_2e (kg)**	**Total US CO_2e Saved (mt)**
GGBS	232	5,386,729,076	4,082,590
LC3	255	5,919,622,606	3,549,696
Fly Ash	295	6,866,761,479	2,602,557
Portland-Limestone Cement	369	8,583,673,953	885,645
Biochar	385	8,946,868,304	522,451
Curing	397	9,234,317,355	235,001
Baseline	407	9,469,318,850	0
RCA	446	10,365,761,413	-896,443

Note: Green text indicates CO_2e savings compared to the baseline and red indicates more CO_2e production than the baseline.

Table 4's CO_2e savings show potential but are not feasible in practice for all mix designs. For example, fly ash and GGBS have limited supply and currently, can only replace 15% of cement production. They are byproducts of industrial processes that decrease in a decarbonizing world; in the future, only 10% of cement can be replaced with fly ash and GGBS[98].

For reference, in 2020, the US produced 5,222 million mt of CO_2e after accounting for sequestration from the land sector[99].

Appendix G breaks down emissions by phase of concrete and cement production.

Cost Metric Results

All cost metrics aggregate costs and benefits for the years 2022 through 2050 for a typical concrete production batch plant (that produces 100,000 m^3 per year).

All cost metrics rely on US averages. The results likely vary by region. Appendix H contains a regional sensitivity analysis that shows the difference in total cost of coarse aggregates, fine aggregates, and cement for the baseline mix design by location.

Table 5 shows results for the producer case: the case that considers only inputs relevant to producers.

Table 5: Cost Metric Results for the Producer Case

Benefit/Cost Comparisons for Eight Scenarios - Producer Case				
Mix Design	**Net Benefits**	**% Change Benefit Compared to Traditional Ready Mix**	**$ Change Benefit Compared to Traditional Ready Mix**	**Benefit/Cost Ratio**
GGBS	$82,307,647	7%	$5,304,758	1.492
LC3	$92,893,642	21%	$15,890,754	1.593
Fly Ash	$82,358,407	7%	$5,355,519	1.492
Portland-Limestone Cement	$79,238,767	3%	$2,235,879	1.465
Biochar	$70,840,160	-8%	-$6,162,728	1.396
Curing	$76,180,217	-1%	-$822,671	1.439
Baseline	$77,002,888	0%	$0	1.446
RCA	$74,024,883	-4%	-$2,978,005	1.422

Note: Green text indicates the low carbon mix design is more profitable than the baseline, and red text indicates the low carbon mix design is less profitable than the baseline.

Concrete producers have the incentive to implement LC3, fly ash, GGBS, and portland-limestone cement. This aligns with the current market. In 2019, fly ash and GGBS accounted for about 9.74% of the mineral components used to produce clinker-based Portland cement[100]. The transition to portland-limestone cement is also already underway; Holcim will use 100% portland-limestone cement at all US plants by 2023. LC3 is early in development, but the limited supply of fly ash and GGBS exacerbates the push towards alternatives like LC3. Concrete producers are disincentivized to implement biochar, early stage carbon curing, or RCA under these conditions.

Table 6 shows the results for the carbon case: the case that considers inputs relevant to producers, carbon credit revenues, and carbon tax revenues.

Table 6: Cost Metric Results for the Carbon Case

Benefit/Cost Comparisons for Eight Scenarios - Carbon Case				
Mix Design	**Net Benefits**	**% Benefit Change Compared to Traditional Ready Mix**	**$ Benefit Change Compared to Traditional Ready Mix**	**Benefit/ Cost Ratio**
GGBS	$82,307,647	7%	$5,304,758	1.492
LC3	$92,893,642	21%	$15,890,754	1.593
Fly Ash	$82,358,407	7%	$5,355,519	1.492
Portland-Limestone Cement	$79,238,767	3%	$2,235,879	1.465
Biochar	$73,937,582	-4%	-$3,065,306	1.414
Curing	$76,240,406	-1%	-$762,482	1.440
Baseline	$77,002,888	0%	$0	1.446
RCA	$74,024,883	-4%	-$2,978,005	1.422

Note: Green text indicates the low carbon mix design is more profitable than the baseline, and red text indicates the low carbon mix design is less profitable than the baseline.

Under current carbon tax programs, such as 45Q, batching plants qualify for credits if captured CO_2 is converted to a material or compound that is securely stored in products. The minimum threshold is 25,000 mt CO_2 per year[28, ll]. This study assumes that the curing and biochar mix designs qualify for tax programs and carbon credits due to the materials being carbon negative processes and materials. This study assumes qualification despite a concrete plant producing 100,000 m^3 of concrete annually only sequesters 31 and 1,608 mt CO_2 per year respectively. Under current regulations, a company must operate many batching plants to meet the minimum threshold. Even so, curing and biochar are not more profitable than the baseline with the inclusion of these tax and credit benefits.

[ll]This study was conducted prior to the Inflation Reduction Act of 2022. The Inflation Reduction Act increased the value of CO_2 used in concrete from up to $50 per mt CO_2 to $130 per mt CO_2 if the CO_2 is sourced from direct air capture or $60 per mt CO_2 if the CO_2 is sourced elsewhere. If low carbon mix designs qualify for 45Q, the profitability will increase. The Act also reduced the minimum capture threshold to 12,500 (this threshold is still not possible to meet at a single batching plant with a capacity of 100,000 m^3).

Table 7 shows results for the social case: the case that considers inputs relevant to producers, carbon credit revenues, carbon tax revenues, social costs of carbon, and the benefits of waste disposal avoidance.

Table 7: Cost Metric Results for the Social Case

Benefit/Cost Comparisons for Eight Scenarios - Social Case				
Mix Design	**Net Benefits**	**% Benefit Change Compared to Traditional Ready Mix**	**$ Benefit Change Compared to Traditional Ready Mix**	**Benefit/Cost Ratio**
GGBS	$116,800,307	192%	$76,847,121	1.620
LC3	$69,732,499	75%	$29,779,312	1.388
Fly Ash	$88,832,765	122%	$48,879,578	1.458
Portland-Limestone Cement	$56,077,624	40%	$16,124,438	1.290
Biochar	$41,154,774	3%	$1,201,588	1.192
Curing	$40,110,172	0%	$156,986	1.191
Baseline	$39,953,186	0%	$0	1.191
RCA	$533,403,670	1235%	$493,450,484	3.468

Note: Green text indicates the low carbon mix design is more profitable than the baseline, and red text indicates the low carbon mix design is less profitable than the baseline. These results are only true if social carbon costs and waste avoided becomes monetized.

When considering social carbon costs and waste avoidance costs, all mix designs become largely favorable to the baseline. Waste diversion plays a significant role in this favorability, as GGBS diverts 18,273 mt waste annually, fly ash diverts 10,964 mt waste annually, biochar diverts 731 mt waste annually, and RCA diverts 164,396 mt waste annually in a 100,000 m^3 per year batching plant. Subsequently, RCA yields the largest net benefit. Biochar and curing's favorability is negligible.

IV. DISCUSSION

The following section discusses key takeaways for each of the seven low carbon mix designs aimed to inform producers, researchers, and policy makers; limitations to the study; and policy implications. The seven low carbon mix designs are ordered from most to least CO_2 reduction.

GGBS

GGBS offers the largest CO_2e reduction (43%), a 7% cost benefit in the base case, and a 192% cost benefit in the social case. GGBS not only has a CO_2e footprint 11.5 times smaller than cement, it is also cheaper than cement. GGBS is used today. The mix design assumes 50% replacement of cement with GGBS but research finds that GGBS can replace 20% to 95% of cement[42]. Therefore, the 43% CO_2e reductions are conservative.

GGBS derives from the melting of metal in blast furnaces. The supply of GGBS will likely decrease as metal production, such as steel, decreases. Other alternatives should be considered long-term.

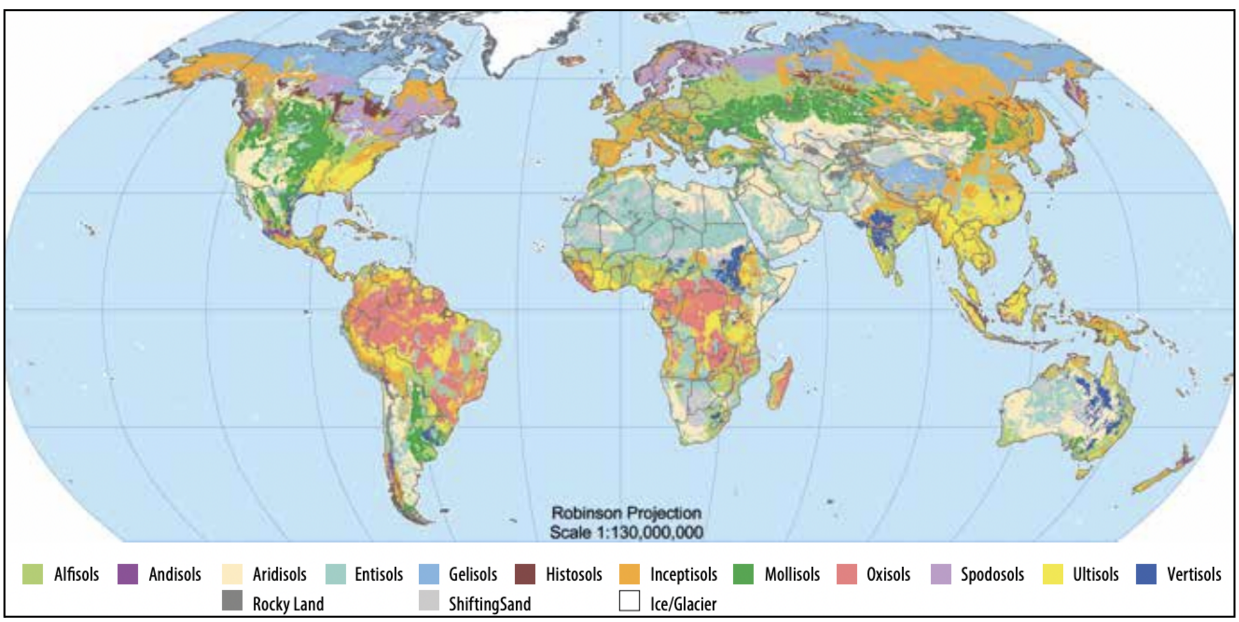
Some GGBS emissions may be double counted. Some metal producers classify GGBS as a coproduct and allocate emissions to the GGBS instead of the final metal product. If a concrete producer buys this GGBS and classifies the GGBS as a waste product with no allocated emissions, the metal and concrete producers double count their emission reductions.

LC3

LC3 offers the second largest CO_2e reduction (37%), a 21% cost benefit in the base case (the highest benefit of all mixes), and a 75% cost benefit in the social case. The mix design assumes 100% cement replacement with LC3. LC3 is a blend of 30% calcined clay, 15% limestone, 5% gypsum, and 50% clinker.

Unlike other low carbon mix designs, the contents of LC3 are not limited in supply. Figure 4 illustrates widely available clay, as seen in yellow and green regions.

Figure 5: Geographical Distribution of Available Clay Supplies[64]



LC3 may offer performance benefits such as compressive strength increases. However, it takes longer than traditional concrete to reach these strengths. This makes it a poor alternative to high early strength concrete.

Fly Ash

Fly ash offers the third largest CO_2e reduction (27%), a 7% cost benefit in the base case, and a 122% cost benefit in the social case. The mix design assumes 30% replacement of cement with fly ash as this composition retains satisfactory performance levels[44,45]. It is in use today.

Fly ash is a by-product of coal-fired electric and steam generation plants. Supply may likely see an even larger decrease compared to GGBS as renewable power plants replace coal plants. As supply decreases, prices will likely increase due to higher logistical costs and will be felt strongly within the US. Some fly ash may be produced from pozzolan, but the LCA is unknown. In the future, fly ash and GGBS will only feasibly replace less than 10% of cement due to these barriers[98].

Fly ash also faces double counting problems similar to GGBS.

Portland-Limestone Cement

Portland-limestone cement offers the largest most CO_2e reduction (9%), a 3% cost benefit in the base case, and a 40% cost benefit in the social case. Batching plants are currently implementing this one-to-one drop-in replacement. Portland-limestone cement incorporates 15% uncalcined limestone compared to traditional cement's 5%. ASTM, an international standards organization, and the American Association of State Highway and Transportation Officials (AASHTO) increased the allowable uncalcined limestone content from 5% to 15% in 2012 under the standards ASTM C595 and AASHTO M240.

Research and foreign markets, such as that of Europe and Mexico, demonstrate that the uncalcined limestone content can increase to 35% without sacrificing performance, and have been demonstrating this for more than 40 years[86]. Portland-limestone cement therefore faces the most stringent policy barriers.

Biochar

Biochar offers a 6% CO_2e reduction, an 8% increase in costs in the base case, and a 3% cost benefit in the social case. This mix design uses a conservative 2% biochar loading as currently researched by the National Renewable Energy Laboratory (NREL). Current research explores greater loading.

Biochar is a net negative material that may utilize biomass that otherwise acts as fuel loads in forests–specifically forests highly susceptible to fires due to increased tree mortality from disease, invasive insects, changing climates, fire suppression, and more. Waste streams are another source of biomass. One mt of biochar sequesters 2.2 mt of CO_2. It is one of five net negative technologies recognized by the Intergovernmental Panel on Climate Change (IPCC) and sequesters carbon for centuries[47]. This allows biochar to qualify for carbon tax credits, carbon credits, and waste avoidance costs.

The inclusion of biochar in concrete may improve performance of concrete as well. Due to its high water absorptive capacity, biochar releases water into the concrete mix slowly which increases internal curing.

Currently, the biochar market is underdeveloped and faces high transportation costs and emissions. Of the roughly 150 US biochar producers, 5% sell to the designed environment[108]. Considering 98 cement plants exist, transportation distances for biochar significantly exceed cement. If the concrete industry creates demand, biochar producers will likely establish themselves 30 miles from the concrete facility to improve profitability. Biochar may also be easily produced onsite.

Researchers question biochar's impact on concrete recyclability, but biochar's non-toxic and easy-to-handle qualities make recycling safe.

Carbon Curing

Carbon curing offers negligible carbon reductions (2%), a 1% cost increase in the base case, and no change in cost benefits in the social case. Any carbon reductions are solely from reduced cement content; the transportation, production, and process of incorporating liquid CO_2 into concrete produces net CO_2 detriments. Results lack a robust scientific research backing because carbon curing has the least publications of all low carbon mix designs. All mix design and emission data were sourced from CarbonCure, a leading company in this space. Concern for carbon curing's scientific integrity was voiced by a large portion of the industry. A deeper analysis of natural carbonation and early stage carbon curing gives reason to this concern.

Natural carbonation occurs when concrete contacts air, and CO_2 diffuses through the concrete's pores. The calcium-rich hydration materials in concrete react with this CO_2 to form calcium carbonate and sequester carbon. Of the CO_2 emitted during calcination, 5% to 20% is reabsorbed in concrete's lifetime[16,78,79]. Surface area, compressive strength, mineral admixtures, atmospheric CO_2, relative humidity, and pore structures impact natural carbonation rates.

Current literature rarely considers natural carbonation in LCAs, and neither does this study. If carbonation is not accounted for, emissions may be overestimated by 13% to 48%. However, a 2018 study found that while CO_2 sequestration by carbonation is non-trivial, low carbon mix designs, such as those with fly ash and GGBS, still reduce CO_2e footprints compared to the baseline[78].

Some research posits that early stage carbon curing increases the amount of CO_2 fixated in the concrete over time. CO_2 fixation has a ceiling, though. The same 2018 study replicated curing over an infinite time exposure and found that only 19% of CO_2 can be reabsorbed[78]. A one-to-one reabsorption level is not possible. The 50% to 60% of emissions produced during cement calcination cannot be fully refixated. Therefore, carbon curing likely offers no net CO_2 benefits, creates an opportunity for CO_2 leakage, and is difficult to quantify.

Despite the skepticism of curing's scientific integrity, this study analyzed CarbonCures' statistics. Even so, carbon curing offers negligible and much less CO_2e reductions compared to other low carbon mix designs.

RCA

RCA increases CO_2e by 9%, increases costs 4% in the base case, and decreases costs 1235% in the social case. This mix design assumes 100% replacement of fine and coarse aggregate with RCA. The increases in cement that may be necessary to maintain concrete performance and the reprocessing of concrete waste causes the CO_2e increase. The large decrease in costs in the social case results from the great amount of expensive waste diverted from the landfill.

This study only considered the demolition of concrete to produce RCA as a substitution for aggregates. However, RCA can be recycled into new cement. This study focused on aggregate substitution because a 2004 study found that 38 states recycled concrete as an aggregate, and only 11 states recycled concrete into new cement[51].

RCA's other benefits include reduced transportation, reduced acidification, and reduced smog[52,68]. RCA may increase rebar corrosion in precast concrete as the material contains higher chloride contents–a chemical that causes metal corrosion–than traditional aggregates.

Limitations

The classified nature of the concrete and cement industry creates the majority of limitations. Due to the concrete market's competitive nature, information is often confidential, unavailable, and protected by antitrust laws. This includes product prices, operating costs, transportation costs, and transportation mileage. Using only one or a few sources for each data point made it difficult to audit the data.

This study lacks data concerning natural carbonation. As stated, refixation of CO_2 likely does not change which low carbon mix designs offer CO_2 benefits[78]. The following discusses how carbonation impacts different mix designs. Fly ash, GGBS, portland-limestone cement, and LC3 reduce the alkaline reserves of concrete and lower carbon fixation in concrete[75,78]. RCA contains cement-based alkaline reserves and likely increases carbon fixation; the increase in cement content in RCA mixes may also increase alkaline reserves[75]. This increases CO_2 fixation. Biochar may increase the porosity of concrete which improves CO_2 diffusion mechanisms and carbon fixation[94]. Carbon curing may accelerate the sequestration but the lifetime fixation potential likely remains the same. In fact, since some companies report lower cement use, alkaline reserves may decrease and lower carbon fixation. Research needs to confirm these hypotheses, address how mix designs impact carbonation, and identify the differences between natural carbonation and early stage carbon curing.

This study also lacks data concerning the social costs and production levels of carbon monoxide, lead, nitrous oxide, particulate matter, sulfur dioxide, and volatile organic compounds. The study excluded these emissions from consideration.

LCA calculations used University of California, Berkeley's Green Concrete LCA Web Tool[95], last modified in 2012. Some assumptions may be outdated. For example, the mode of transportation assumes a class 8b truck, model 2005.

Time series data also pose limitations as the cost of CO_2 and social carbon costs were provided at intervals of time. Values were calculated for all years using linear trends.

Policy Implications

This study pointed towards six policy recommendations. This study identified 68 embodied carbon or low carbon concrete and cement policies in the US: 45 approved, 14 proposed, seven not approved, one on hold, and one that provides policy recommendations. Figure 6 represents these policies.

Figure 6: Embodied Carbon and Low Carbon Concrete Policy Map

Note: Embodied carbon policies regulate the CO_2e footprint of building materials. Not all mention concrete and cement specifically. Policies often regulate and promote the use of sustainable building materials, lower cement contents, maximum global warming potentials, the priority or low carbon concrete in biddings, etc.

The policy recommendations stemming from this study are as follows:

1. *Regulate the bidding of low carbon concrete.* Due to greater data availability and fewer facilities, policy makers often advocate for cement regulation. The lack of data, antitrust laws, and large amount of concrete batching plants makes regulating concrete difficult. However, five of the seven low carbon mix designs are low carbon concrete solutions. Regulating cement disincentivizes low carbon concrete solutions. Therefore, regulating biddings and end devices may be best.
2. *Increase the allowable uncalcined limestone contents.* Foreign markets demonstrate unaffected concrete performance with uncalcined limestone contents up to 35%.
3. *Adjust minimum carbon tax and credit thresholds.* For example, 45Q's minimum threshold requirement of capturing 25,000 mt CO_2 annually prevents individual small to large concrete plants from qualifying. Clarifying whether CO_2 sequestration and/or reduction qualifies for taxes and credits may help clarify regulations as well.
4. *Monetize social carbon costs and waste aversion.* Table 8 represents the difference in benefits when social carbon costs and waste aversion costs are not and are considered. The incentives to implement low carbon mix designs significantly increase when social carbon costs and waste aversion costs.

Table 8: Comparison of Benefits in the Base Case and Social Case

% Benefit Increase Compared to Traditional Ready Mix in a 100,000 m^3/yr Plant		
Mix Design	**% Net Benefit Increase Compared to Traditional Ready Mix When ONLY Considering Product Revenue Benefit and Business Costs**	**% Net Benefit Increase Compared to Traditional Ready Mix When Considering all Benefits and Costs**
GGBS	7%	192%
LC3	21%	75%
Fly Ash	7%	122%
Portland-Limestone Cement	3%	40%
Biochar	-8%	3%
Curing	-1%	0%
Baseline	0%	0%
RCA	-4%	1235%

5. *Eliminate prescriptive requirements such as minimum or maximum cement or additive content; instead, only specify performance requirements.*
6. *Specify 56-day strengths instead of 28-day strength* unless projects require high early strength. Some low carbon mix designs cure over longer periods of time (such as fly ash

and LC3) but develop higher compressive strengths than traditional concrete over time. Traditional concrete often reaches a steady compressive strength. SCMs continue to increase in strength over time.

V. CONCLUSION

This study posed the question “how do low carbon concrete and cement mix designs differ in costs, benefits, and LCAs”. Using LCAs, this study found that ready mix concrete mix designs with GGBS offers a 43% CO_2e reduction compared to a baseline ready mix concrete. LC3 offers a 37% reduction, fly ash offers a 27% reduction, portland-limestone cement offers a 9% reduction, and biochar offers a 2% reduction. Curing offers no CO_2e benefits, and RCA may increase CO_2e emissions but offers significant waste diversion.

Using a cost benefit analysis, this study found that producers are incentivized to implement mix designs with GGBS, LC3, fly ash, and portland-limestone cement because these mix designs offer a 3% to 21% cost advantage over baseline ready mix concrete. If social carbon costs and waste diversion are monetized, all mix designs offer cost incentives except carbon curing.

The incentives and CO_2e benefits for GGBS, fly ash, and portland-limestone concrete align with the current market as GGBS and fly ash are commonly used and batching plants are currently implementing portland-limestone cement. The lack of evident benefits for curing opposes the current market as early stage carbon curing is currently backed by high profile investors. The science needed to differentiate early stage carbon curing from natural carbonation does not exist, the science community is skeptical of the technology, and even if carbon curing’s science is legitimate, the mix design renders negligible cost and CO_2 benefits compared to other alternatives.

This study posits that low carbon mix designs provide significant CO_2 savings and increase profit, contradicting some of the arguments of previous research. This study finds that low carbon mix designs can reduce up to 43% CO_2 emissions. While this indicates that low carbon mix designs must be paired with other solutions–such as CCUS--the designs promise a pathway to partial decarbonization without necessitating difficult system or grid alterations. This pathway is already being explored by industry as demonstrated by increases in policy, research, and a global startup and growth company ecosystem striving to develop decarbonization solutions.

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APPENDIX A. Expert List

Table 9: List of 17 Experts Consulted

Expert List		
Name	**Organization**	**Title**
Alainna Lynch	SDSN	Senior Research Manager
Brennan Pecha	NREL	Researcher III-Computational Science
Brent Constantz	Blue Planet	Chief Executive Officer
Cecile Vaudevire Roman	Holcim	Commercial Innovation and Sustainable Solutions Manager
Edna Possan	Federal University for Latin American Integration	Professor
Fred Grubbe	National Precast Concrete Association (NPCA)	President
Gaurav Sant	University of California, Los Angeles (UCLA)	Professor and Pritzker Endowed Chair in Sustainability
Karen Scrivener	Laboratory of Construction Materials, Cement and Concrete Research Journal	Material Chemist
Katie Lebling	World Resources Institute's (WRI) Climate Program	Associate II
Lionel Lemay	NRMCA	Executive Vice President
Rahul Shendure	CarbonBuilt	Chief Executive Officer, Director
Robert Niven	CarbonCure Technologies	Founder, Chief Executive Officer, Chair
Sean McCoy	University of Calgary	Assistant Professor
Stephen Herald	Holcim	Quality Control Manager
Tien Peng	NRMCA	Senior Vice President of Sustainability
Volcker Sick	University of Michigan	Professor
Will Srubar	AureusEarth	Founder, Director

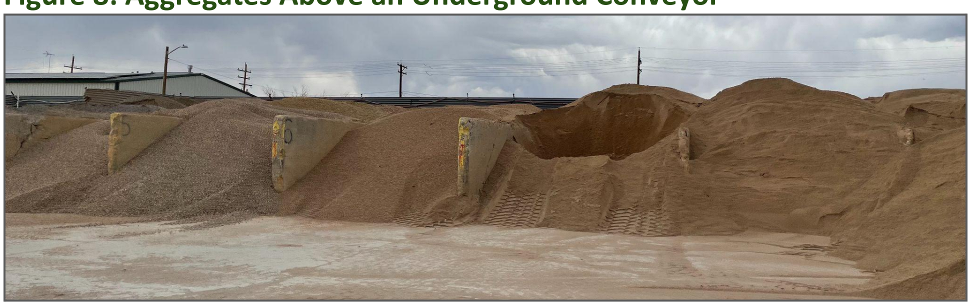
Notes: Experts provided information via video calls, phone calls, in-person meetings, and emails.

APPENDIX B. Site Visit Photos

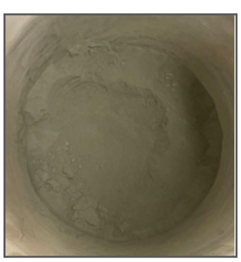
Figures 7- 17: Site Visit at a Holcim Ready Mix - Batching Plant

Figure 7: Ready Mix Batching Plant

Figure 8: Aggregates Above an Underground Conveyor



(From Left to Right) Figure 9: Cement (Portland-Limestone Cement), Figure 10: SCM (Fly Ash), Figure 11: Fine Aggregate, Figure 12: Coarse Aggregate



SEP visited a Holcim ready mix batching plant and a lab in Denver, CO, during May.

Aggregates in Figure 7 are dropped underground and fed through a long conveyor on the right side of the batching plant in Figure 6.

Cement, aggregates, and admixtures are held in tanks in and out of the plant. All material gets dropped onto scales and poured into trucks to be mixed during transport to the site. Mix designs are specified by a computer system and monitored.

Figure 13: Holcim Ready Mix Lab

The Holcim ready mix lab tests concrete mixes. All new concrete mixes must be tested for compressive strength, shrinkage, flexibility, etc. Mixes must be certified by a 3rd party, and certifications must be reaproved every 2 years.

(From Left to Right) Figure 14: Compressive Strength Test, Figure 15: Humidity Chambers

The humidity chamber in Figure 14 is where concrete test samples are stored for 28 days in 73 degrees Fahrenheit and 100% humidity.

(From Left to Right) Figure 16: 6” by 12” Testing Molds, Figure 17: Concrete Samples After Compressive Strength Test

APPENDIX C. Mix Design Assumptions

Table 10: List of Mix Design Assumptions

Assumption	Units	Mix Designs							
		Baseline	GGBS	LC3	Fly Ash	Portland-Limestone Cement	Biochar	Curing[a]	RCA
Maximum Slump	in	3	3	3	3	3	3	3	3
Minimum Slump	in	1	1	1	1	1	1	1	1
Maximum Coarse Aggregate Size[96]	in	1	1	1	1	1	1	1	1
Water Weight for Non-Air-Entrained Concrete	lb/yd^3	308	308	308	308	308	308	308	308
Amount of Entrapped Air	%	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Volume of Water	ft^3	4.936	4.936	4.936	4.936	4.936	4.936	4.936	4.936
Volume of Air	ft^3	0.405	0.405	0.405	0.405	0.405	0.405	0.405	0.405
Compressive Strength at 28 days[52]	psi	4000	4000	4000	4000	4000	4000	4000	4000
Water-Cement Ratio		0.5	0.5	0.5	0.48	0.5	0.5	0.5	0.45
Specific Gravity of Cement		3.15	3.15	2.9	3.15	3.15	3.15	3.15	3.15
Weight of Cement	lb/yd^3	616	616	616	641.667	616	616	616	684.44
Solid Volume of Cement	ft^3	3.134	3.134	3.404	3.264	3.134	3.134	3.134	3.482
Are pozzolanic materials used		No	Yes	No	Yes	No	Yes	No	No
Weight Equivalency - Pozzolanic Material Percentage of weight of cementitious material	%		50[41, 42]		30[44, 45]		2[47]		
Weight Equivalency - Pozzolanic Material Percentage of volume of cementitious material	%								
Volume Equivalency - Pozzolanic Material Percentage of weight of cementitious material	%								
Volume Equivalency - Pozzolanic Material Percentage of volume of cementitious material	%								
Specific Gravity of Pozzolanic Material			2.9[43]		2.6[43]		1.14[48]		
Adjusted Water-Cementitious Material Ratio			0.5		0.5		0.5		

Weight of Pozzolanic Materials	lb/yd^3		308		184.8		12.32		
Weight of Cement	lb/yd^3		308		431.2		603.68		
Solid Volume of Cement plus Pozzolanic Material	ft^3		3.269		3.333		3.244		
Nominal Maximum Size of Aggregate	in	1	1	1	1	1	1	1	1
Weight of Coarse Aggregate[39]	lb/ft^3	100	100	100	100	100	100	100	100
Fineness Modulus of Fine Aggregate[39]		2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Volume of Coarse Aggregate per Unit Volume of Concrete		0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Specific Gravity of Coarse Aggregate		2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.39[69]
Weight of Coarse Aggregate	lb/yd^3	1755	1755	1755	1755	1755	1755	1755	1755
Solid Volume of Coarse Aggregate	ft^3	10.613	10.613	10.613	10.613	10.613	10.613	10.613	11.768
Specific Gravity of Fine Aggregate		2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.39
Weight of Fine Aggregate	lb/yd^3	1308.328	1286.005	1263.681	1275.422	1308.328	1290.139	1308.328	955.813
Solid Volume of Fine Aggregate	ft^3	7.912	7.777	7.642	7.713	7.912	7.802	7.912	6.409
Design Mix Water	lb/yd^3	308	308	308	308	308	308	308	308
Total Moisture Content of Coarse Aggregate[39]	%	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Total Moisture Content in Fine Aggregate[39]	%	4	4	4	4	4	4	4	4
Degree of Moisture Absorption in Coarse Aggregate[39]	%	2.1	2.1	2.1	2.1	2.1	2.1	2.1	3.8[67]
Degree Moisture Absorption in Fine Aggregate[39]	%	1.1	1.1	1.1	1.1	1.1	1.1	1.1	3.8[67]
Net Mix Water	lb/yd^3	284.976	285.623	286.271	285.93	284.976	285.503	284.976	350.841
Wet Weight of Coarse Aggregate	lb/yd^3	1776.938	1776.938	1776.938	1776.938	1776.938	1776.938	1776.938	1776.938
Wet Weight of Fine Aggregate	lb/yd^3	1360.661	1337.445	1314.228	1326.439	1360.661	1341.745	1360.661	994.046
Is water reducer used in mix		no	no	no	no	no	no	no	no

Notes: This table represents the inputs into the Union College's Concrete Mix Design Tool to generate mix designs. [a]Curing's mix design started with the baseline assumptions and was manually changed by reducing the cement content by 5%, increasing fine aggregate content to ensure the concrete's absolute volume is 27 ft^3, and adding 0.15% of cement's mass per unit volume in liquid CO_2.

APPENDIX D. LCA Assumptions

Table 11: List of LCA Assumptions

Assumption	Units	Mix Designs							
		Baseline	GGBS	LC3[a]	Fly Ash	Portland-Limestone Cement[b]	Biochar[c]	Curing[d]	RCA[e]
Total Weight of Concrete	kg/m^3	2396	2383	2369	2376	2396	2385	2393	2258
Total Cementitious Materials	kg/m^3	365	365	365	365	365	365	347	406
Water/Binder Ratio		0.46	0.46	0.46	0.46	0.46	0.46	0.487	0.51
Material Quantities									
Cement	kg/m^3	365	183	365	256	365	358	347	406
Water	kg/m^3	169	169	170	170	170	169	169	208
Fine Aggregate	kg/m^3	807	793	780	787	780	796	823	590
Coarse Aggregate	kg/m^3	1054	1054	1054	1054	1054	1054	1054	1054
Fly Ash	kg/m^3	0	0	0	110	0	0	0	0
GGBS	kg/m^3	0	183	0	0	0	0	0	0
Natural Pozzolan	kg/m^3	0	0	0	0	0	7	0	0
Limestone	kg/m^3	0	0	0	0	0	0	0	0
Total Cementitious Materials	kg/m^3	365	365	365	365	365	365	347	406
Plasticiser	kg/m^3	0	0	0	0	0	0	0	0
Superplasticiser	kg/m^3	0	0	0	0	0	0	0	0
Retarder	kg/m^3	0	0	0	0	0	0	0	0
Accelerating Admixture	kg/m^3	0	0	0	0	0	0	0	0
Air Entraining Admixture	kg/m^3	0	0	0	0	0	0	0	0
Waterproofing	kg/m^3	0	0	0	0	0	0	0	0
Cement Raw Materials									
Cement Clinker	kg/m^3	347	174	347	243	347	340	380	386
Cement Gypsum	kg/m^3	18	9	18	13	18	18	17	20
Cement Kiln Dust	kg/m^3	0	0	0	0	0	0	0	0
Fly Ash, Blended in Cement	kg/m^3	0	0	0	0	0	0	0	0
GGBS, Blended in Cement	kg/m^3	0	0	0	0	0	0	0	0
Limestone	kg/m^3	0	0	0	0	0	0	0	0
Quarry and Plant Location, Grid Mix Information									
Electricity Mix for Raw Material Mining (Quarry), Cement Plant, Gypsum Quarrying and Processing,	N/A	US Average							

Fine Aggregates Quarrying and Processing, Coarse Aggregates Quarrying and Processing, Limestone Quarrying and Processing, Natural Pozzolan Quarrying and Processing, Fly Ash Processing Plant, GGBS Processing Plant, Concrete Batching Plant		
Grid Mix: Contribution of Electricity Source		
Bituminous Coal	%	21.8
Natural Gas	%	38.3
Residual (Heavy) Oil	%	0.5
Distillate (Diesel or Light) fuel oil	%	0.2
Petroleum Coke	%	0.2
Nuclear (Uranium)	%	18.9
Hydro	%	6.3
Biomass	%	1.4
Geothermal	%	0.4
Solar	%	2.8
Wind	%	9.2
Lignite Coal	%	0
Transportation Input (Assume Truck Class 8b (Model 2005))		
Cement Raw Materials to Cement Plant	km	1
Gypsum to Cement Plant	km	200
Fly Ash to Cement Plant (if Blended cement)	km	500
GGBS to Cement Plant (if Blended cement)	km	1000
Cement to Concrete Plant	km	121
Fine Aggregates to Concrete Plant	km	64
Coarse Aggregates to Concrete Plant	km	35
Admixture to Concrete Plant	km	1000
Fly Ash to Concrete Plant	km	99
GGBS to Concrete Plant	km	54
Natural Pozzolan to Concrete Plant	km	1571

Limestone to Concrete Plant	km	500						
Cement Production Technology (Production Phase; Product of Phase)								
Raw Materials Prehomogenization; Raw Meal	N/A	Dry process raw storing, non-preblending						
Raw Materials Grinding; Ground Meal	N/A	Dry raw grinding, ball mill						
Raw Meal Blending/Homogenization; Blended Meal	N/A	Raw meal homogenization, blending, and storage						
Pyroprocessing; Clinker	N/A	US Average kiln						
Clinker Cooling; Cooled Clinker	N/A	Reciprocating Grate Cooler (modern)						
Finish Milling/Grinding/Blending with PC; Blended/Traditional Portland Cement	N/A	Ball mill						
Fuel Options for Pyroprocessing, Specify Fuel Inputs to Preheater Kiln								
Bituminous Coal	%	64						
Lignite Coal	%	0						
Distillate (Diesel or Light) fuel oil	%	0.8						
Petroleum Coke	%	21.2						
Residual Fuel (Heavy) oil	%	0.2						
Natural Gas	%	3.7						
Waste Oil	%	0.3						
Waste Solvent	%	4						
Waste Tire (whole)	%	1.8						
Waste TIre (shredded)	%	1.8						
Waste (Other) (non-hazardous)	%	2.3						
Waste Paper, cardboard	%	0						
Waste Plastics	%	0						
Waste Sewage Sludge (dry)	%	0						
Waste (Other) (hazardous)	%	0						
Clinker Cooling PM Control Technology Options								
Technology Option	N/A	Electrostatic Precipitators						
Conveying Technology Options								
Raw Meal Conveyance Distance	m	20	20	20	20	20	20	20	20
Raw Meal Conveyance Mode		Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump

Avg Raw Meal Conveyed	kg	589	295	589	412	589	577	560	655
Ground Meal Conveyance Distance	m	20	20	20	20	20	20	20	20
Ground Meal Conveyance Mode		Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump
Avg Ground Meal Conveyed	kg	589	295	589	412	589	577	560	655
Blended Meal Conveyance Distance	m	20	20	20	20	20	20	20	20
Blended Meal Conveyance Mode		Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump
Avg Blended Meal Conveyed	kg	589	295	589	412	589	577	560	655
Clinker Conveyance Distance	m	20	20	20	20	20	20	20	20
Clinker Conveyance Mode		Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump
Avg Clinker Conveyed	kg	347	174	347	243	347	340	330	386
Clinker Cooled Conveyance Distance	m	20	20	20	20	20	20	20	20
Clinker Cooled Conveyance Mode		Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump
Avg Clinker Cooled Conveyed	kg	347	174	347	243	347	340	330	386
Blended/Traditional Portland Cement Distance	m	20	20	20	20	20	20	20	20
Blended/Traditional Portland Cement Mode		Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump	Screw Pump
Avg Cement Conveyed	kg	365	183	365	256	365	358	347	406
Batching Plant PM Control Technology									
Technology (including material transfer, loading, and unloading processes)	N/A	Controlled with Fabric Filter							
Batching Plant Loading/Mixing Options									
Technology for Loading into Mixer Trucks	N/A	Mixer Loading (Central Mix)							

Notes: This table represents the inputs into the University of California, Berkeley's Green Concrete LCA Web Tool. Mix design assumptions are for 1 m^3 of ready mix concrete. LCA results for biochar, RCA, portland-limestone cement, LC3, and curing were manually adjusted due to the tool's limited scope. [a]The LCA calculations for LC3 were identical to the baseline except all cement-specific CO_2e emissions were reduced 40%. Cement-specific CO_2e emissions include quarrying; raw materials prehomogenization; raw materials grinding; raw meal blending and homogenization; preprocessing; clinker cooling; milling, grinding, and blending; and in-cement plant conveyance. [b]The LCA calculations for portland-limestone cement were identical to the baseline except all cement-specific CO_2e emissions were reduced 10%. [c]2.2 mt of CO_2 is sequestered in a mt of biochar which equates to about 16 kg CO_2 sequestered in a m^3 of concrete; this amount was subtracted from the CO_2e value determined by the tool. [d]The total CO_2 emissions added from liquid CO_2 use is 9.36 kg CO_2 per m^3 of concrete. Emissions from production contributes 0.053 kg CO_2 per m^3 concrete, emissions from transportation over 200 miles accounts for 0.007 kg CO_2 per m^3 concrete, and emissions from the production, transportation, and operation of the equipment contributes 9.3 kg CO_2 per m^3 concrete. Curing has a 60% CO_2 absorption efficiency and therefore sequesters 0.312 kg CO_2 out of the 0.521 kg CO_2 pumped into a m^3 of concrete. [e]The tool did not account for the substitution of RCA for traditional coarse and fine aggregates. The aggregate-specific CO_2e emissions were therefore multiplied by a factor of 2.05.

APPENDIX E. Comparisons to the NRMCA

The NRMCA published a LCA titled "A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members - Version 3" in November 2019. This was updated February 20, 2020. Comparisons between the NRMCA's and this report's mix designs and CO_2e for the baseline, fly ash, and GGBS scenarios can be made. This provides a check for this paper's accuracy.

The NRMCA report was not solely used to determine mix designs and CO_2e footprints because their mix designs were limited to only three of this report's eight scenarios.

Table 12: Comparisons Between This Report's and the NRMCA's Mix Designs

Mix Design	Compressive Strength (psi)	Water Cement Ratio	Fly Ash Content (%)	Slag Content (%)	Air Entrained (Y/N)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Slag (kg/m^3)	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)
NRMCA's 4000-00 FA/SL	4000	0.42	0	0	Yes	365	0	0	155	995	744
Baseline[a]	4000	0.5	0	0	No	365	0	0	169	1054	807
NRMCA's 4000-30-FA	4000	0.42	30	0	Yes	276	119	0	155	995	650
Fly Ash[a]	4000	0.48	30	0	No	256	110	0	170	1054	787
NRMCA's 400-50-SL	4000	0.42	0	50	Yes	183	0	183	155	995	731
GGBS[a]	4000	0.5	0	50	No	183	0	183	169	1054	793

Note: Mix design assumptions are for 1 m^3 of ready mix concrete. [a]Indicates the mix design is specific to this study.

Table 13: Comparisons Between This Report's and the NRMCA's CO_2e Reportings

Mix Design	CO2e (kg/m³)	CO_2e Difference (kg/m³) (NRMCA - This Study's Mix Design)
NRMCA's 4000-00 FA/SL	427.75	
Baseline[a]	407.16	20.59
NRMCA's 4000-30-FA	333.33	
Fly Ash[a]	295.26	38.08
NRMCA's 400-50-SL	262.82	
GGBS[a]	231.62	31.20

Note: Mix design assumptions are for 1 m³ of ready mix concrete. [a]Indicates the mix design is specific to this study.

APPENDIX F. Other Key Sources

Table 13: Key Sources for Cost-Benefit Analysis

Other Key Sources	
Dataset	**Source**
Batching Plant Size	Bureau of Indian Standards[26]
Total Cost of Transportation From Plant to Concrete Contractor	Cecile Vaudevire Roman, Holcim
Material Transportation Cost	Calcima[54]
Carbon Curing Operation Cost	Robert Niven, CarbonCure
Operating Cost per Batching Plant	Cecile Vaudevire Roman, Holcim
Cement Price	Construction Economics[40]
Portland-Limestone Cement Price	Cecile Vaudevire Roman, Holcim
LC3 Cement Price	Scrivener et al.[64]
Cement Transportation Mileage	NRMCA[52]
Coarse Aggregate Price	Construction Economics[40]
Coarse Aggregate Transportation Mileage	NRMCA[52]
Fine Aggregate Price	Construction Economics[40]
Fine Aggregate Transportation Mileage	NRMCA[52]
Recycled Coarse and Fine Aggregate Price	USGS[55]
Recycled Coarse and Fine Aggregate Transportation Mileage	An estimate based on the many RCA articles
GGBS Price and Transportation Mileage	USGS[60]
GGBS Transportation Mileage	NRMCA[52]
Fly Ash Price	Concrete Construction[59]

Fly Ash Transportation Mileage	NRMCA[52]
Biochar Price	SEP's Biochar Topic Report[108]
Biochar Mileage	SEP's Biochar Topic Report- Note, this was calculated using a ratio of cement to biochar production plants[108]
CO2 Transportation Cost and Mileage	National Energy Technology Laboratory (NETL)[63]
Final Product Sale Price	Construction Economics[40]
Cost of Diverting Waste	KPMG[61]
Cost of CO2 Gas	IEA[62]
Social Cost of Carbon	United States Government[23]
Carbon Credit Revenue	Bloomberg[104]
Carbon Tax Credit Revenue (45Q)	KPMG[28]

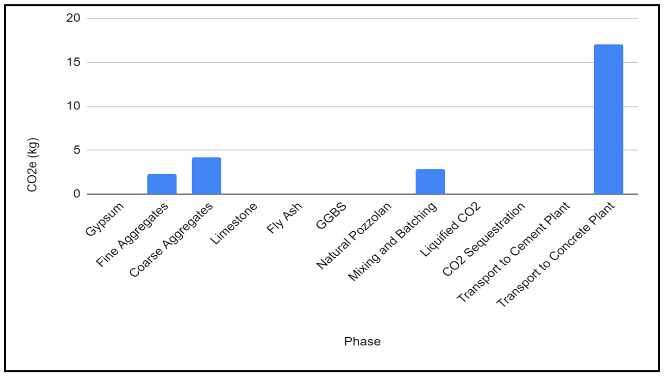
APPENDIX G. Emissions by Phase

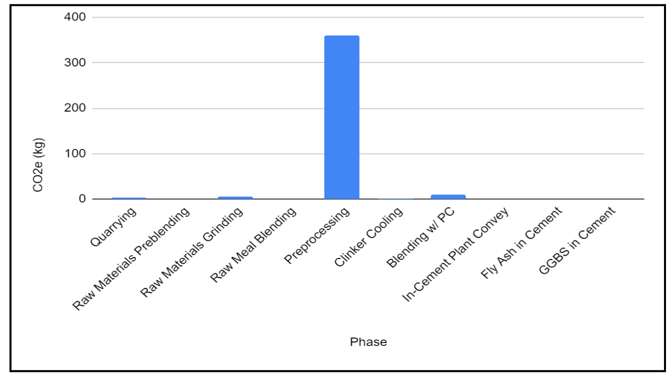
Figures 18 - 33: CO_2e Breakdown by Concrete Production Phase

All values are for 1 m^3 of ready mix concrete.

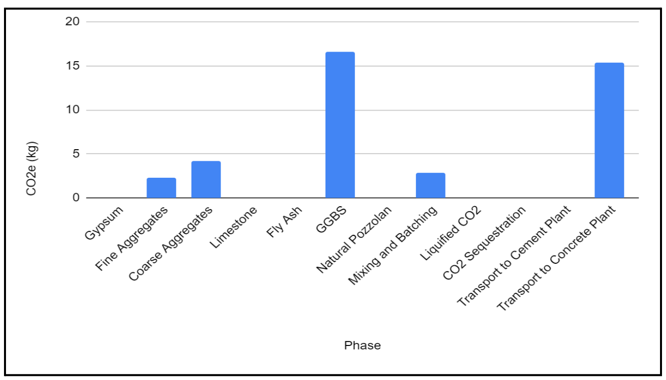
Mix Design | **CO_2e for Concrete Production** | **CO_2e for Cement Production**

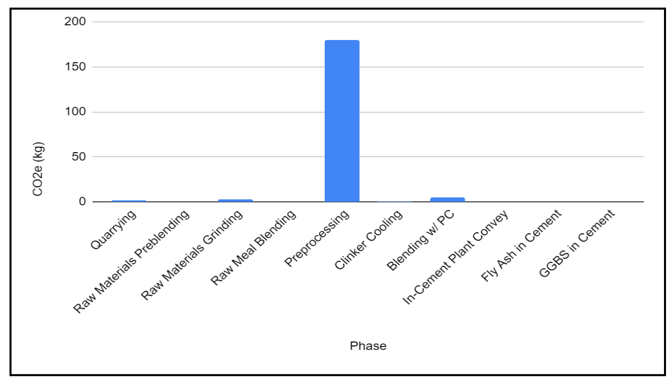
Baseline

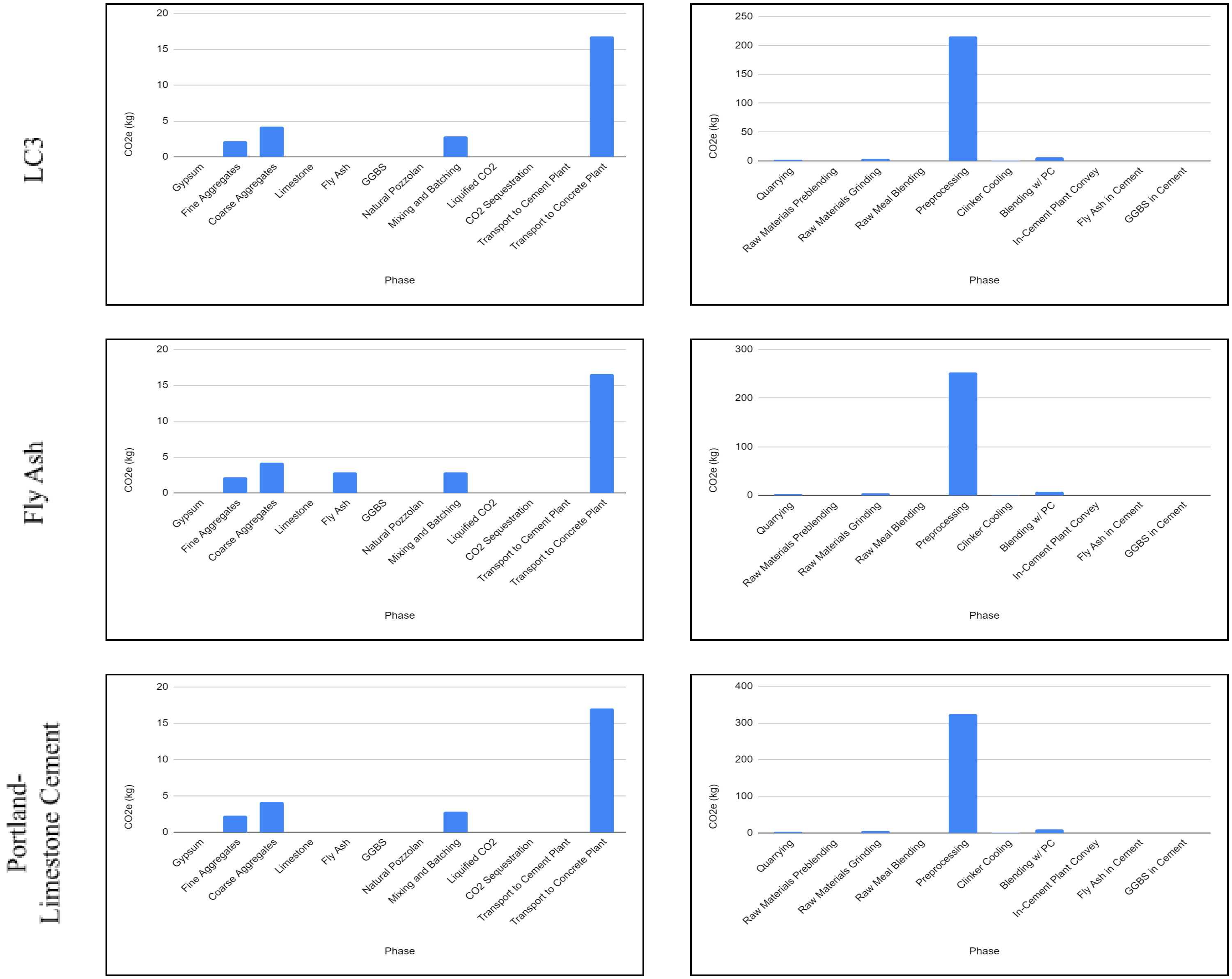




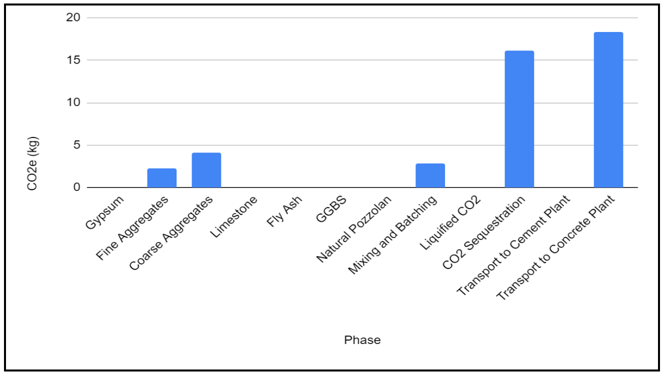
GGBS

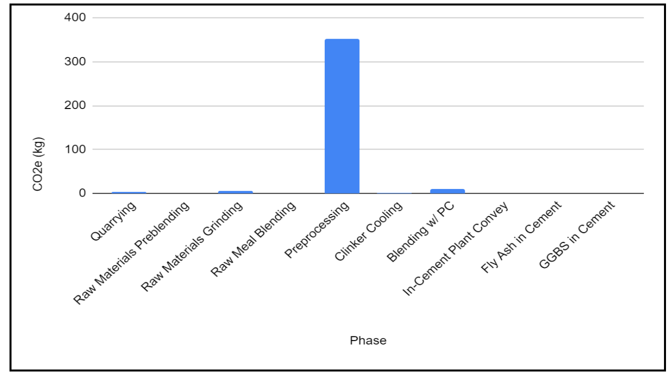




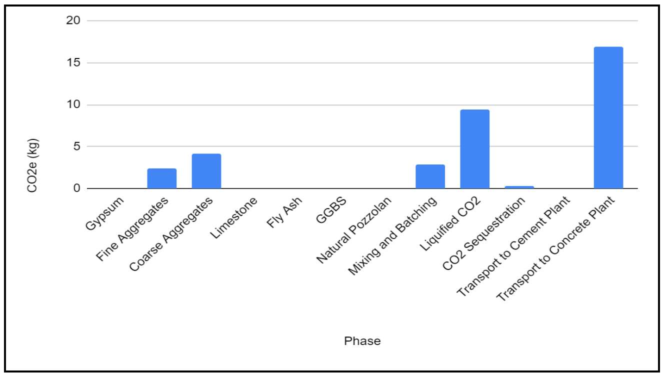

LC3
Fly Ash
Portland-
Limestone Cement
CO2e (kg)
Phase
Gypsum
Fine Aggregates
Coarse Aggregates
Limestone
Fly Ash
GGBS
Natural Pozzolan
Mixing and Batching
Liquified CO2
CO2 Sequestration
Transport to Cement Plant
Transport to Concrete Plant
Quarrying
Raw Materials Preblending
Raw Materials Grinding
Raw Meal Blending
Preprocessing
Clinker Cooling
Blending w/ PC
In-Cement Plant Convey
Fly Ash in Cement
GGBS in Cement

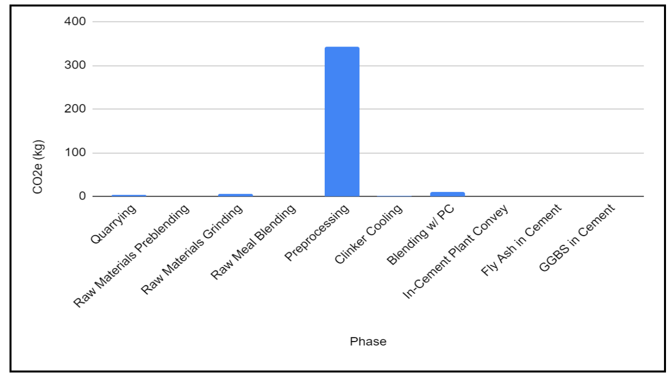
Biochar



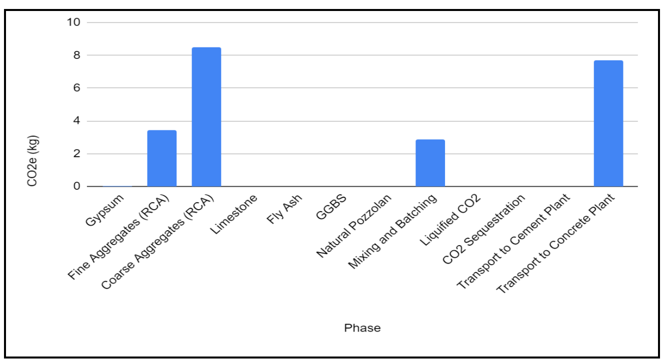


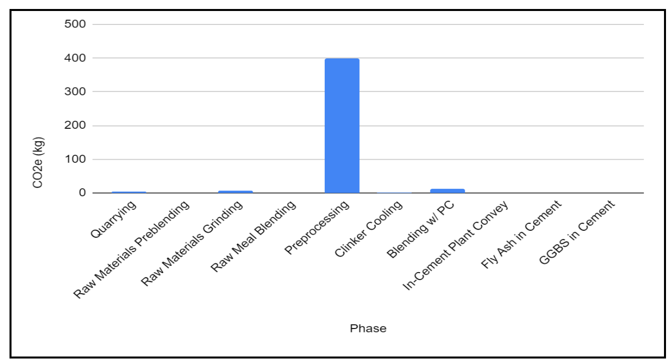
Curing





RCA





APPENDIX H. Regional Sensitivity Analysis

The following table is a regional sensitivity analysis of the costs for the coarse aggregates, fine aggregates, and cement contents in the baseline ready mix design. Ingredient cost differences by region were provided by Holcim.

Table 14: Regional Sensitivity Analysis of Concrete Ingredients

Regional Sensitivity Analysis: Traditional Ready Mix Ingredients (Coarse/Fine Aggregate, Cement)							
	Baltimore, DC	**Boston**	**Dallas, Houston**	**New Orleans**	**Denver, Colorado Springs**	**Buffalo**	**National Average**
Total Cost of Ingredients	$9,340,854	$8,789,928	$10,080,144	$7,887,028	$11,892,082	$9,924,532	$9,652,428
Dollar Change from National Average	-$311,574	-$862,500	$427,716	-$1,765,400	$2,239,654	$272,104	$0

Note: Mix design assumptions are for a ready mix batching plant that produces 100,000 m^3 of concrete per year. Each geography may offer a different mix of materials. For example, GGBS is not available in Dallas/Houston and Denver.