WAP SUSTAINABILITY CONSULTING

Life Cycle Assessment of Construction Aggregates

Prepared for the National Stone, Sand, and Gravel Association

In support of the Product Category Rules for Construction Aggregates

October 20th, 2023

Updated for support of Theta Aggregate (v3)

March 20th, 2024

Updated for Errata (v4)

May 8th, 2025

Thrive ESG LLC
1312 17th St PMB 71416
Denver, CO 80202
(303) 304-1055

May 30, 2023

Michele Stanley
National Stone, Sand & Gravel Association
66 Canal Center Plaza Suite 300
Alexandria, VA 22314

Dear Michele,

I carried out an independent critical review of the National Stone, Sand & Gravel Association's (NSSGA) life cycle assessment (LCA) report for construction aggregates, developed by Trisight, now part of WAP Sustainability Consulting, and dated May 19, 2023. This was an independent external critical review per section 6.2 of ISO 14044:2006 and ISO 14071:2016, conducted after the study was developed. This letter serves as the critical review report and statement.

I reviewed the draft and final LCA report in reference to the requirements of ISO 14040:2006 and ISO 14044:2006. The NSSGA LCA report conforms to the requirements of these standards.

I reviewed the draft LCA report and identified minor technical and editorial gaps and opportunities for improvement. These comments were not material to the conformance to the requirements of the standards referenced above.

The author responded to my comments and updated the report accordingly. The list of comments and responses are appended to this letter.

I reviewed the updated and final LCA report in May 2023 and found the responses to the updates to be satisfactory. The LCA meet the requirements of the standards listed above.

As evidence of my independence, I declare the following:

- I am not an employee of NSSGA or WAP Sustainability Consulting
- I was not involved in defining the scope or carrying out any of the work to conduct the LCA
- I do not have a vested financial, political, or other interest in the outcome of this study

As evidence of my competence, I declare my proficiency in the aforementioned standards, LCA methodology and practice, critical review practice, scientific disciplines related to the study, the product system assessed, and the study language.

Sincerely,

James Mellentine
Principal, Thrive ESG

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Glossary of Abbreviations and Terms

ACLCA – American Center for Life Cycle Assessment
ANFO – Ammonium Nitrate Fuel Oil
BA – Balancing Authority
DOE – Department of Energy
EPD – Environmental Product Declaration
FERC – Federal Energy Regulatory Commission
FLCAC – Federal Life Cycle Assessment Commons (aka "The Commons")
ISO – International Standards Organization
LCA – Life Cycle Assessment
NETL – National Energy Technology Laboratory – A division of the Department of Energy
Shtn – Short ton
RCA – Recycled Concrete Aggregate
RAP – Reclaimed Asphalt Paving
TRACI – Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
USLCI – United States Life Cycle Inventory

Updates from v3

The values in the third column of Table 5 were updated to correct a copy/paste error. Similarly, the GWP values in the prose paragraph following Table 5 were updated. These updates were made in consultation with the Program Operator EPD NA, and are classified as "editorial".

Goal and Scope

The goal of this life cycle assessment (LCA) is to support the Product Category Rule (PCR) for Construction Aggregates for the environmental product declaration (EPD) program hosted by NSF®. The PCR addresses conventional construction aggregate, a processed granular material where the main form of processing is through a series of blasting, crushing, screening, washing, and/or other mechanical classifying equipment to properly size the finished product for use as a construction aggregate. Construction aggregates are generally used to produce concrete or asphalt mixtures but are also commonly used directly as aggregate base, stabilizing aggregates, fill, or other unbound functions.

Materials covered under the PCR include natural aggregates, slag aggregates, recycled concrete aggregates (RCA), and reclaimed asphalt pavements RAP). It does not include expanded shale, clay, and slate lightweight aggregates as these are covered in a separate PCR. Slag is addressed in a separate LCA study.

Relevant material standards include ASTM C33/C33M, C125, C144, C637, C1797, D8, D692/692M, D1073, D1139/1139M, D5106, D2940/2940M, D4992, D6711, and CSA A3.1. The PCR is expected to be compliant with International Organization for Standardization (ISO) core PCR ISO 21930.

The study was funded by the National Sand, Stone, and Gravel Association and conducted by Lianna Miller, LCACP and Ben Ciavola, PhD at Trisight, now a part of WAP Sustainability. The data collection commenced in August 2021 and was completed in December 2022. The intended audience of the PCR includes the following stakeholders:

1. Construction aggregate producers who want to quantify and declare the environmental impacts of the products they produce at their facilities;
2. Members of the architecture/engineering/contracting industries who are looking to purchase construction aggregates with an EPD to quantify the net life cycle impacts or embodied carbon of the projects;
3. Decision-makers and designers at local, state and federal transportation agencies who are seeking to quantify the environmental impacts of construction aggregates; and
4. Any downstream users of products that contain construction aggregates seeking to conduct an LCA for their products and services.

Representatives from all the above stakeholder categories were included in and involved with the PCR committee that supported the development of the PCR.

This LCA report achieved ISO14040/44 compliance in May 2023. The report was critically reviewed by Jim Mellentine, Thrive ESG. The purpose of the study is to support the PCR for construction aggregates, and it is not intended for public comparative assertions. The analysis is intended to represent construction aggregates sold through the period of validity of the updated PCR (2023-2028).

Declared Unit

While some downstream users of aggregate use a volume measure, within the aggregate industry, production and sales are tracked on a mass basis. Therefore, the declared unit for this assessment is one US Customary ton (2000lb or 0.907 metric tonne) of aggregate ready for shipment in accordance with the 2022 PCR for Construction Aggregates.

System Boundaries

This LCA and its governing PCR are cradle-to-gate and cover life cycle phases A1-A3 of the framework described in ISO 21930:2017. The system boundaries for this life cycle assessment are established in Figure 1. After production, aggregate sees a wide variety of uses, including roadbeds, landscaping, inclusion in asphalt pavements, and concrete for pavement or vertical construction. It is expected that this limited scope cradle-to-gate LCA (and associated EPDs) will provide a building block to compute the complete life cycle impacts of a pavement system or building, while at present supporting contractors in meeting procurement related reporting requirements.

Each solid-outline box in this figure corresponds to a life cycle process that may result in environmental impacts. Boxes with a dark fill are excluded from the assessment. Boxes with a dashed outline are groups of subprocesses that may have their impacts aggregated (e.g. fuel and electricity impacts for facility operations). Arrows indicate the flow of process outputs. Thin arrows indicate the flow of materials consumed in the production process, while thick arrows indicate the flow of feedstock, work in progress, and finished products.

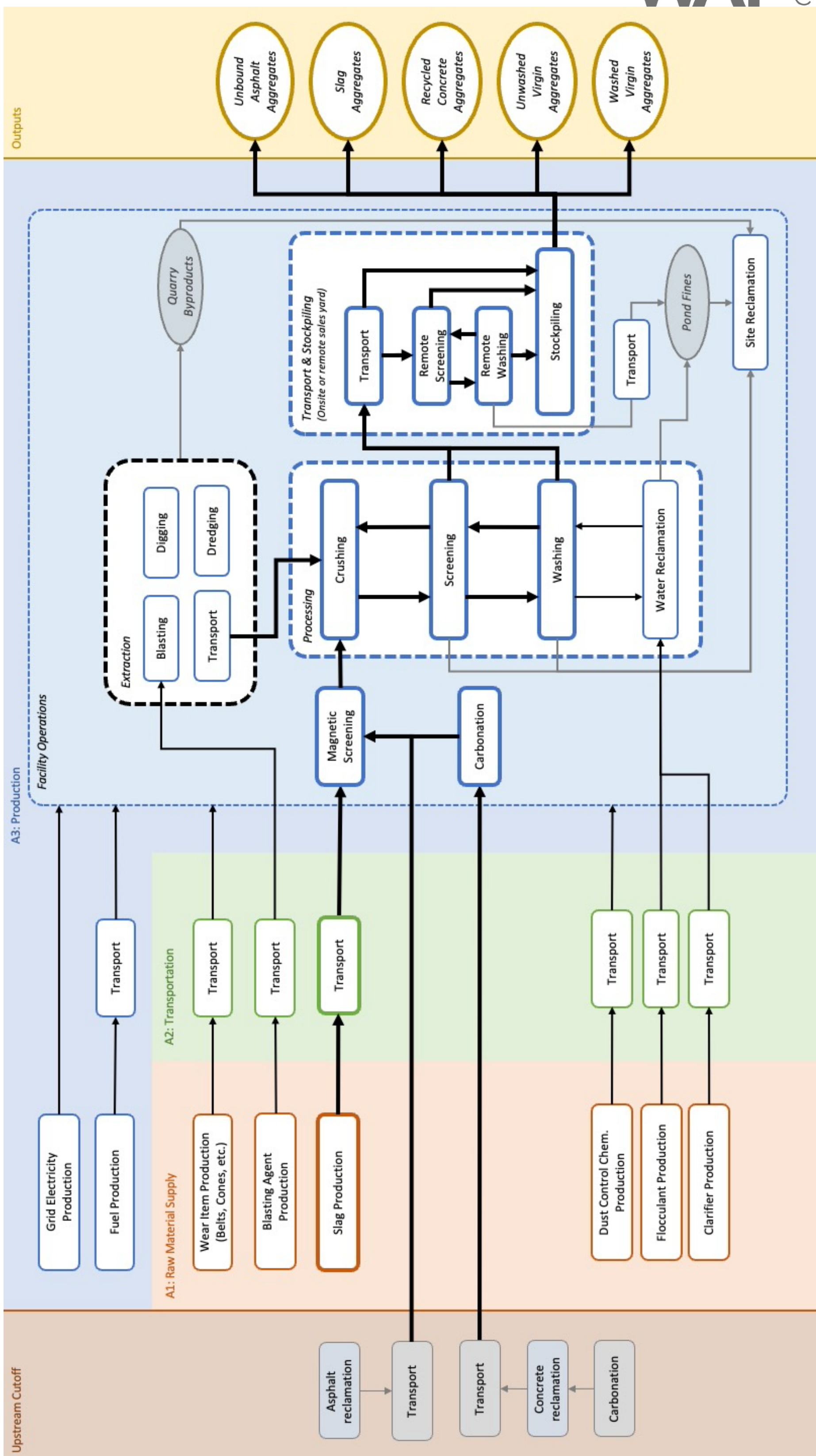

Figure 1: Aggregate Production Process

A1: Raw Material Supply

Life Cycle Phase A1 covers the supply of upstream materials used in the production process. For construction aggregates, these processing include the production of:

- Slag,
- Wear items including
  - Belts,
  - Crusher cones,
  - Tires,
- Blasting agent,
- Dust control chemicals,
- Flocculants and clarifiers.

The impacts of these upstream production processes are calculated using life cycle inventory data acquired from public and commercial datasets as described in the Life Cycle Assessment Inventory section later in this report.

The production of reclaimed asphalt and concrete is excluded from A1 calculations as an upstream cutoff. Environmental impacts associated with the reclamation and transport of these materials to an aggregate production facility are considered an end-of-life process and outside the scope of this assessment. Onsite transport and processing of these materials are covered under A3: Production.

A2: Transportation

The impacts of transporting material inputs to the production facility are assessed on a ton-mile basis. Transportation modes may include over-the-road trucking, train, inland barge, or open-ocean freight transportation. Each of these transport modes is assessed using mode-specific life cycle inventory data.

A3: Production

Construction aggregates are produced from four feedstock sources:

- Natural rock that excavated from the earth,
- Slag produced during the production of iron and steel,
- Reclamation of asphalt pavement, and
- Reclamation of concrete.

Each of the production processes is detailed below.

Extraction

Natural rock is excavated through processes including blasting, dredging, and digging. Blasting processes consume blasting agents and result in fragmented rock appropriately sized for transport and processing. Dredging and digging involve the operation of mechanical equipment powered by liquid-fueled internal combustion engines or electric motors. Raw material from these processes is transported by equipment to the facility's processing system.

Intake of Produced Materials

Reclaimed asphalt and concrete are secondary materials that are recycled and processed as construction aggregates.

Iron and steel slag (collectively "slag") are coproducts of the iron and steel production processes. It should be noted that slag aggregates and slag cement are different products from different processes. Slag aggregates are the subject of a sister study. Slag cement is not related to the construction aggregate industry.

Processing

The core processing component of construction aggregate production includes four primary processes and one secondary process. The primary processes include crushing, screening, transportation, and washing. The secondary process is water reclamation.

The primary processes may occur in any number of steps or stages and in any order. For example, one facility may have primary, secondary, and tertiary crushing and screening operations with recirculation, while another facility may have only a single crushing and screening stage with no recirculation.

The purpose of processing is to take feedstock material as an input and create sorted output products of consistent size and quality.

Transportation: Material is transported between processing stages using a system of belts. These belts are driven by one or more electric motors with nominal power usually in the 100+ HP range. Motors usually receive power from the electrical grid, but in some cases may be powered by onsite generation systems such as solar, wind, or diesel generators. Belts are between 18" and 56" in width and vary in length, with the longest belt systems traversing more than a mile from extraction to processing. Belts are a wear item that require regular replacement.

Crushing: Raw material – whether natural or produced – enters the processing system in the form of particles of various sizes from 12"+ down to sand, dust, and silt. The purpose of crushing is to take particles that are larger than desired and reduce them in size until they can pass through one or more filtering screens with apertures of known dimension. Crusher types include jaw- and cone-type. Jaws and cones are wear items that must be replaced, and are made of high-manganese steels optimized for anti-wear properties. Crushers are powered by electric motors driven by grid power or onsite generation.

Screening: Processed or partially processed materials are sorted using one or more screens in powered shaker systems. Material is transported into a screen tower by a belt system and is separated and distributed by size. Material that is too large to pass through one or another screen may be removed for processing (as finished material) or recirculated for additional crushing and screening. Screening towers are powered by electric motors driven by grid power or onsite generation.

Washing: Feedstock and partially processed material often contains high quantities of dust and silt that must be removed. Dust and silt are created naturally, during blasting, and during crushing operations, and is cleaned from in-process material using water. This water often comes from onsite wells, springs, or ponds. The washing process produces washed product and dirty water.

Water Reclamation: Dirty water from the washing process is reclaimed using clarifying systems. Sediment is allowed to settle from the water in reclamation pools, sometimes with the aid of flocculant or clarifier chemicals. The water is then separated from the settled material (known as pond fines) and reused in the washing process. Pond fines are stockpiled onsite or used for site reclamation.

Transport and Stockpiling

After primary processing material may be transported either within a facility or to a secondary facility for stockpiling or additional processing. Secondary processing facilities may perform some or all of the same steps as a primary processing facility. Material transportation between primary and secondary processing sites must be accounted for. This transportation may be performed by electrically driven belts or through one or more other modes such as truck, train, barge, or ocean freight transportation.

Outputs

Finished construction aggregate product categories include:

- Unwashed natural aggregate,
- Washed natural aggregate
- Slag aggregate
- Reclaimed concrete aggregate, and
- Unbound asphalt aggregate.

These types of finished products include many sub-categories that are differentiated based on particle size, shape, and other qualities. Different regions, customers, and specifying agencies have different categories and nomenclatures to distinguish specific product types.

Wear items such as tires, belts, screens and crusher jaws are landfilled or recycled depending on the material.

Electricity and fuel use

Per ISO 21930, the impacts from the production and transport of electricity and fuels used in the processes described above are included in the production phase. Grid electricity transportation is accounted for in the distribution model embedded in the electricity inventories developed by the United States Department of Energy (DOE) National Energy Technology Laboratory (NETL) dataset described in the Life Cycle Assessment Inventory section of this report.

Cutoff Criteria

All inputs and outputs to a unit process for which data are available have been included in the calculation. In case of insufficient input data or data gaps for a unit process, the cut-off criteria is limited to 1% of renewable and non-renewable energy usage and 1% of the total mass input of that unit process, unless a material has the potential of causing significant emissions into the air, water, or soil or is known to be resource-intensive. The total sum of neglected input flows is limited to 5% each of energy usage and mass.

Excluded from System Boundary

Upstream impacts of extraction, production, and manufacturing of any material not consumed in the production of construction aggregates is considered to be “part” of the site infrastructure and is excluded from the system boundary. These include:

- Onsite mobile equipment
- Production of machinery including all non-wear elements of belt, crusher, and shaker systems (belts, crusher cones, crusher jaws fall within system boundary)
- Onsite equipment for electricity generation
- Office and other administration materials
- Impacts of plant personnel, including commuting

Waste materials in an aggregate operation beyond wear items is very limited. A small amount of oil and lubricants is used in machine maintenance. Working with an early respondent revealed around 0.005 gallons of oil and lubricants per ton of aggregate production. This equates to about 1.9×10^{-5} tons of lubricants per ton of aggregate. This fell well below the cutoff criteria of 1% mass and given the high burden on respondents for data collection in this category, was eliminated from the study.

Overburden is the industry term for the layers of soil and rock that are removed from the immediate quarry vicinity in order to access high quality aggregate materials, and either stockpiled or transported to be used in construction or earthworks. Often this overburden is replaced at the end of the quarry life as a part of the site remediation. Quarries typically have long service lives, the reported expected service life in the study was 50+ years. On average within study participants, the initial stripping operations had occurred 30+ years ago – one had been in operation for an impressive 89 years, with an additional 25+ years of planned service. Given the lack of data, the long service life to amortize initial stripping activities, and the relatively small amount stripped at quarry startup compared to annual aggregate production, this was excluded from the system boundary. Following the same logic, end-of-life activities for the quarries are excluded as well.

Life Cycle Assessment Inventory

This section outlines the processes that contribute to the aggregate life cycle, classifying them as foreground and background/upstream data. Foreground data is defined as any data item whose sources have been directly observed and collected for the purpose of this study. Background/upstream data is defined as data inventories from other sources and that have not been directly observed for the sake of this study.

Foreground data

The following data were collected for each participating site. Each site provided data from a contiguous 12-month period in 2020-2021. This data was gathered for the LCA in January - June 2022. A total of 31 sites provided data. The full data collection instrument is included in Appendix 1.

- Total sales of construction aggregates [US short tons]
    - Crushed aggregate (non-RCA)
    - Non-crushed aggregate
    - Washed aggregate
    - Reclaimed Concrete Aggregate
    - Reclaimed Asphalt Pavement
- Total electricity used
    - Grid electricity purchased [kilowatt-hours]
    - Solar power generated onsite [kilowatt-hours]
    - Wind power generated onsite [kilowatt-hours]
- Onsite fuel consumption
    - Diesel fuel [gallons]
    - Natural gas [mcf]
    - Propane [gallons]
    - Gasoline [gallons]
    - Recycled Fuel Oil [gallons]
    - Residual Fuel Oil [gallons]
    - Renewable Natural Gas (RNG) [mcf]
    - Biodiesel [gallons], reported with biodiesel grade (e.g. B20, B80, etc.)
- Water use [gallons], including
    - Water use for dust control
    - Water use for washing
        - Recycling rate of washing water

- Water source, well water
- Water source, municipal water
- Water source, ponds (including settling ponds)

- Wear parts
    - Crusher liners, [pounds]
    - Screener screens
    - Belts [linear feet]
    - Tires [pounds]
- Chemicals
    - Blasting agents [pounds], including type
    - Flocculants [pounds], including type
    - Dust control additives [pounds], including type

The foreground data collected were based on utility bills, equipment fuel use logs, and purchase and sales records. In the case where exact water use was untracked, the estimating method used for each site was recorded along with the other data. Additional information was collected during this project, above and beyond those items listed above. This additional information was used to guide this study and may not be required for the development of EPDs.

There is no hazardous waste generated by this production process. All non-salable material is recycled or used for site reclamation and is not waste.

Recycled Concrete Aggregate (RCA)

When compared to other common aggregate sources, recycled concrete has a unique ability to absorb atmospheric carbon dioxide. In order to account for this carbonation phenomenon, extra attention was paid to gathering data about RCA.

Participating sites were asked to give details about any RCA processing and stockpiling at their locations. Stockpile size and shape, average particle size, total production, and number of times the stockpile was added to and/or turned over per year were all collected.

Allocation

Process inputs

Production facilities may acquire raw materials that are the result of other processes, including slag, reclaimed concrete aggregate (RCA), and reclaimed asphalt pavement (RAP). Slag is a special case for which a separate report is under development. The cut-off method is used for both RCA and RAP, as these are EOL products whose disposal process is their delivery to an aggregate production facility. This means that these products do not have upstream burdens (or credits) from their prior life cycle.

Process outputs

Aggregate facilities regularly produce multiple types of products differentiated by size, shape, mixture, feedstock material (e.g. natural rock vs. RCA), and whether or not the product has been washed. Some products may undergo multiple rounds of washing and crushing, and therefore may account for a larger proportion of total facility use of energy and consumables (e.g. crusher cones).

The nature of the available data make it impossible to calculate differences in per-product energy use without alteration to facility operations, and therefore all impact allocation has been performed on a uniform mass basis using total yearly production tonnage.

For example, say a facility produces 1m short tons of product and has a total A1-A3 GWP of 2.5m kg CO_2e. If the facility sells three products with the following distribution:

- 500k shtn: Type A - main product
- 250k shtn: Type B - extra crushing and recirculation
- 250k shtn: Type C - produced on separate, secondary production equipment

Then one short ton of each material will be allocated:

$$(2{,}500{,}000\ kg\ CO2e)/(1{,}000{,}000\ shtn)\ =\ 2.5\ kg\ CO2e/shtn$$

No extra impact will be allocated to any product and no reduction will be performed for any product, even though each undergoes a different type and degree of processing. This is further discussed in the Life Cycle Assessment Results section.

Background data

This effort benefits from the significant work performed by the ACLCA PCR committee to identify and prescribe recommended background datasets for all North American PCRs published after July 2022. The goal of the ACLCA effort has been to establish minimum data quality standards and drive cross-PCR harmonization of background datasets ("2022 ACLCA PCR Guidance"). The Construction Aggregates PCR committee adopted these standard datasets, and they are used in this report.

We defer to the ACLCA report *Guidance for Assessing Data Quality of Background Life Cycle Inventory (LCI) Datasets* for an in-depth discussion of the dataset selection criteria including the Enhanced Pedigree Matrix (EPM).

Some flows found in construction aggregate processing do not have prescribed datasets according to the ACLCA guidance. These include Canadian electricity inventories, chemicals such as flocculants and explosives, and wear items such as tires and manganese steel crusher components. The Construction Aggregates PCR Data subcommittee developed a selection hierarchy for various data types and sources used to fill these gaps.

Selection criteria

Background data was selected according to the following hierarchy, from most-preferred to least-preferred:

1. Valid facility-specific and product-specific EPDs with impact categories modeled according to TRACI 2.1 for the specific inputs associated with the EPD.
2. Either of the following:
    a. Valid industry average EPDs with impact categories modeled according to TRACI 2.1 as prescribed in Annex 1.
    b. Freely available public datasets as prescribed in Annex 1, including critically reviewed LCA studies that are compliant with ISO 14040/14044 that have been published to the USLCI.
3. Publicly available, critically reviewed LCA studies that are compliant with ISO 14040/14044 that have not been published to the USLCI
4. Either of the following:
    a. Commercial (proprietary) inventory data, when process or flow impacts are estimated to be >1% total, or
    b. Declared data gap, when process or flow impacts are estimated to be <1% total

The philosophy behind this selection hierarchy is to maximize data quality and transparency while minimizing data gaps. The goal of this selection process is to conform as closely as possible to the 2022 ACLCA PCR LCI data quality recommendations while providing flexibility for the use of high-quality, verified data sources for key high-impact process flows for which no public data exists.

Electricity - US Grid

The ACLCA recommended electricity dataset, developed by the National Energy Technology Laboratory, is relatively new and possesses many features not found in more familiar sources. In particular, it includes a complete distribution model that accounts for generation, transmission, exchange, and final distribution to end-users while legacy datasets such as eGRID only account for generation.

In the United States, grid electricity is provided to a facility by a local balancing authority. The NETL baseline electricity dataset - lists the set of balancing authorities (BAs) that service each US zip code. This dataset includes information for the 66 BAs in the United States but does not include information for Canadian or Mexican BAs. More information about the US BA system can be found at the US Energy Information Agency's website.

The procedure for identifying which balancing authorities are relevant for a particular facility involves using the NETL Grid Mix Explorer. This procedure includes applying the following algorithm described in the PCR for establishing estimated impacts due to electricity use:

1. Identify a facility's available balancing authorities using the facility zipcode and the NETL zipcode-to-BA mapping.

2. If multiple BAs are mapped to a zipcode, electricity impacts shall be estimated using the unweighted arithmetic mean of each TRACI 2.1 indicator for the set of BAs mapped to the given zipcode. For example, if balancing authorities BA1, BA2, and BA3 are mapped to zipcode C, then the GHG impacts for 1 MW of electricity for zipcode C will be calculated as: $GHG(C) = (GHG(BA1) + GHG(BA2) + GHG(BA3)) \div 3$

A strict arithmetic mean was chosen by the PCR committee to establish a procedure that:

A. is unambiguous, repeatable, and verifiable,
B. allows aggregate producers to receive "credit" for high-performing, low-impact BAs in their area, and
C. retains the zipcode-level granularity of the dataset, which provides significantly higher spatial data quality than using e.g. NERC or FERC regions.

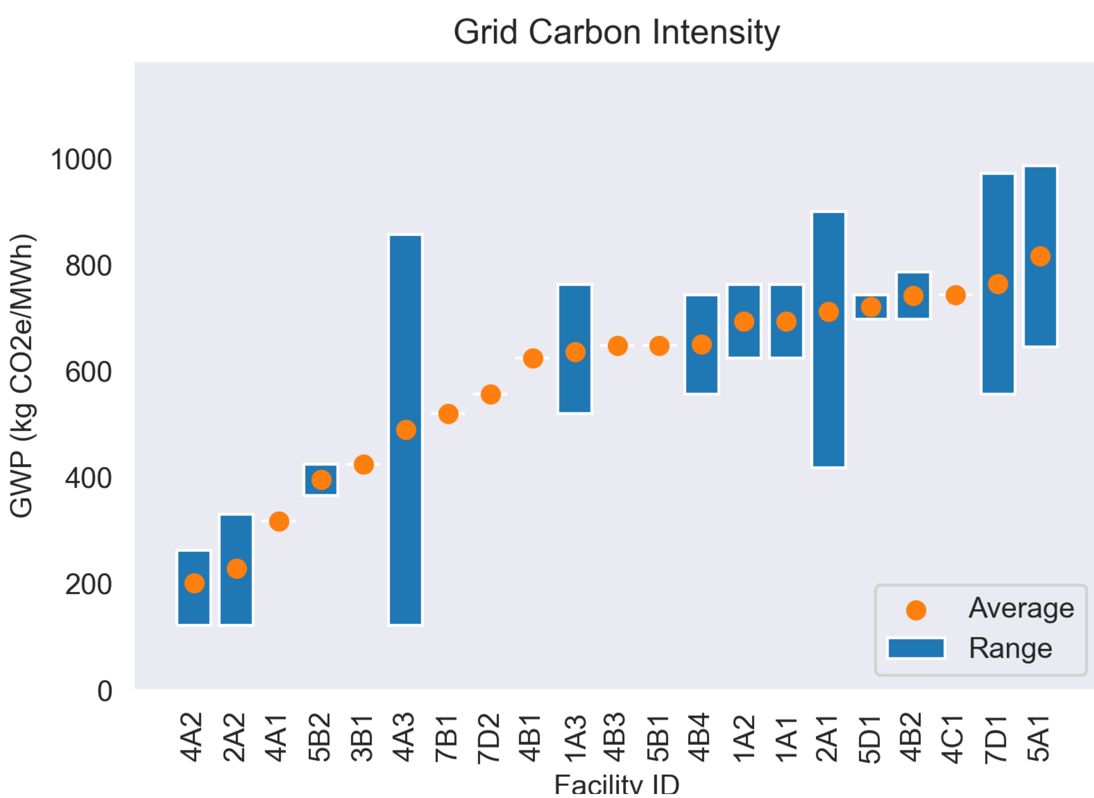

Figure 2: Effects of averaging balancing authority impacts per zip code

The results of applying this algorithm on the first 21 respondents to the data survey are shown in Figure 2. Most of the facilities in our sample set have more than one balancing authority indicated for their location. Table 1 shows the variability in GWP intensity from different balancing authorities within a given zip code. The difference between the lowest- and the highest-GWP intensity is as high as 735 kg CO_2e/MWh. In this case, the high-GWP balancing authority accounts for over 7x as much CO_2e emissions per unit of energy delivered than the low-GWP balancing authority.

	Min GWP BA	**Avg BA GWP**	**Max GWP BA**	**Range**
Mean of locations in study	513.25	571.73	625.14	111.89
Standard Deviation	218.20	192.57	214.41	194.81
min	0.10642	0.10642	0.10642	0
max	986.06	992.44	1517.04	1049.20

Table 1: Variability of balancing authority impacts per kWh at participating locations.

We applied this algorithm across the 32,562 US zip codes with valid balancing authority information to develop the following descriptive statistics (Table 1). Some zip codes have been found that do not have an associated BA, though these cases are rare (< 0.5% on a per-zip code basis). We find that the majority of zipcodes are served by one balancing authority, and of those that remain the majority are served by two. Examples with an extreme range of performance such as in the case of Facility 4A3 appear to be rare, as shown in Figure 3.

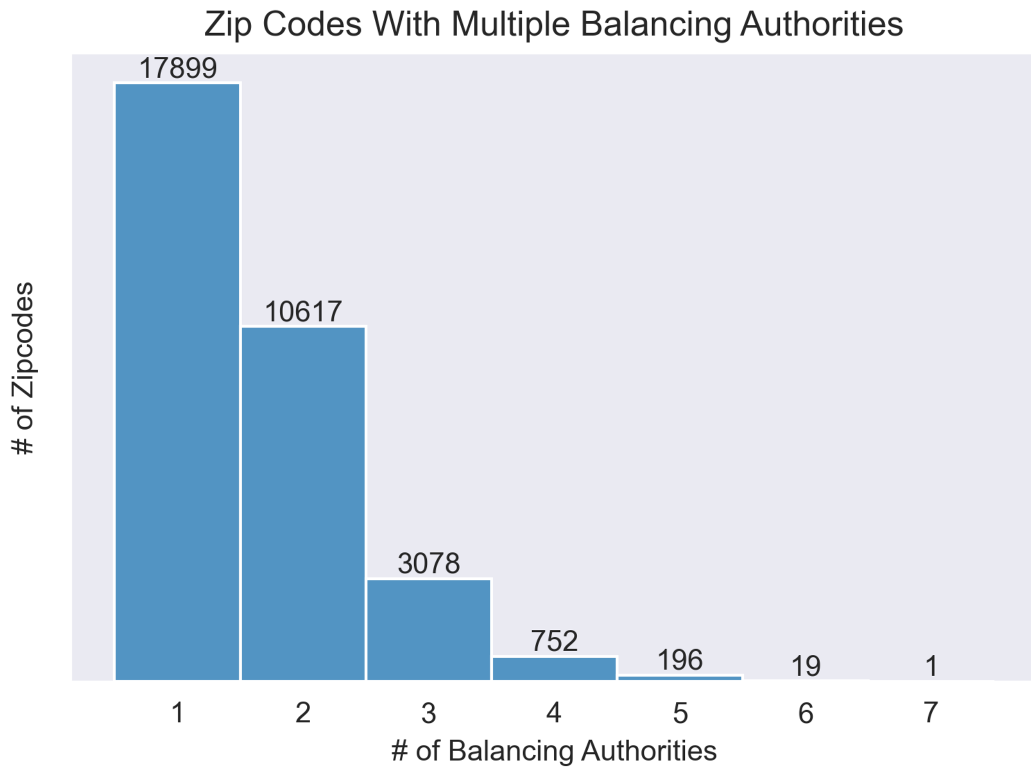

Figure 3: Number of balancing authorities per zip code

Manganese:

Source Data: Shahjadi Hisan Farjana, Nazmul Huda, M.A. Parvez Mahmud, Candace Lang, A global life cycle assessment of manganese mining processes based on EcoInvent database, Science of The Total Environment 688, 1102–1111 (2019).

Declared unit: 1 kg refined manganese

The indicators below are a global average of refined manganese, as given in the above study.

TRACI 2.1 Indicator	**Unit**	**Value**
Acidification	kg SO_2 eq	0.34
Eutrophication	kg N eq	0.088
Global Warming	kg CO_2 eq	4.53
Ozone depletion	kg CFC-11 eq	4.47E-8

Smog formation	kg O_3 eq	0.023

Figure 4: TRACI 2.1 Indicators for 1kg of manganese

Manganese Steel

Source Data: Manganese data cited above, and industry average "Environmental Product Declaration for Fabricated Steel Plate, American Institute of Steel Construction" performed by Sphera, 2021, https://www.aisc.org/globalassets/why-steel/epd-aisc-plate-2021.pdf

Declared unit: 1 kg of 15% Mn cast steel by weight

Model development:

Crushers are an integral part of aggregate operations. Their wear parts are typically made with a hardened manganese steel, with manganese contents varying from 14-17%. The indicators below are for a 15% manganese, 85% steel fabricated product. It uses the global manganese values given above, and values for steel from the industry average EPD for fabricated steel plate.

TRACI 2.1 Indicator	Unit	Value
Acidification	kg SO_2 eq	0.0546
Eutrophication	kg N eq	1.85E-3
Global Warming	kg CO_2 eq	2.34
Ozone depletion	kg CFC-11 eq	9.57E-9
Smog formation	kg O_3 eq	8.83E-3

Figure 5: TRACI 2.1 Indicators for 1kg of manganese steel

Explosives

Source Data: Dyno Nobel Asia Pacific Pty Limited. (2016, May). *ANFO (bagged) technical information - dyno nobel*. ANFO Technical Information. Retrieved August 4, 2022, from https://www.dynonobel.com/apac/~/media/Files/Dyno/ResourceHub/Technical%20Information/Asia%20Pacific/PackagedExplosives/ANFO%20Bagged.pdf

Declared unit: 1kg 95% Ammonium Nitrate / 5% Fuel Oil, detonated

Model development:

In hard rock and underground operations, explosives are used for initial aggregate extraction. Two types of explosives are commonly used: ANFO (ammonium nitrate / fuel oil) and emulsions. Chemically, they are very similar, and for this LCA are both modeled by the exothermic chemical reaction:

$$73NH_4NO_3 + 2C_{12}H_{23} \rightarrow 169H_2O + 73N_2 + 24CO_2 + O_2 + 3.68MJ$$

This may also be written on a weight basis. Below is the reaction per 1kg of ANFO (or 1kg emulsion):

$$945.83g(NH_4NO_3) + 54.17g(C_{12}H_{23}) \rightarrow 492.83g(H_2O) + 331.02g(N_2) + 170.97g(CO_2) + 5.18g(O_2) + 3.68MJ$$

These reactions were updated to a stoichiometric ideal or 5.4% fuel oil and includes 50 kg*miles of transit via diesel truck. Many thanks to Stuart Brashear of Austin Powder for expert knowledge on this material.

TRACI 2.1 Indicator	**Unit**	**Value**
Acidification	kg SO_2 eq	0.00354
Eutrophication	kg N eq	0.04990
Global Warming	kg CO_2 eq	1.84968
Ozone depletion	kg CFC-11 eq	1.9222e-9
Smog formation	kg O_3 eq	0.07469

Figure 6: TRACI 2.1 Indicators for 1kg of ANFO, exploded

Biodiesel:

The LCA supporting the PCR for Asphalt Mixtures has an excellent discussion on publicly available biodiesel datasets (Mukherjee 2021). This study used the methodology and impacts described for the supplementation of the soy biodiesel dataset.

Date Type	Background Inventory	Reference/ Comment
Electricity - US Grid[1]	US DOE National Energy Technology Laboratory Electricity Baseline	ACLCA Recommended

Electricity - Canadian Grid[2]	Ecoinvent 3.8 Province-level inventory	
Electricity - Onsite Solar		No such electricity use in study
Electricity - Onsite Wind		No such electricity use in study
Propane Fuel in Engines	USEPA-USLCI-GREET Operation of liquefied petroleum gas equipment, industry average >56 kW and <560 kW	ACLCA Recommended
Diesel Fuel in Engines	USEPA-USLCI-GREET Diesel, combusted in industrial equipment	ACLCA Recommended
Gasoline Fuel in Engines	USEPA-USLCI-GREET Gasoline, combusted in equipment	ACLCA Recommended
Renewable Diesel Fuel in Engines		Unknown, no such fuel used in study
Biodiesel Fuel in Engines	USEPA-USLCI-GREET Soy biodiesel, production, at plant	Complement with combustion factors from Mukherjee 2021
Compressed Natural Gas Fuel in Engines	USEPA-USLCI-GREET Operation of compressed natural gas equipment; industry average; > 56 kW and < 560 kW	ACLCA Recommended
Recycled Fuel Oil Fuel in Engines	Recycled Fuel Oil	Inventory developed for asphalt PCR, published publicly on FLCAC

Rail Transportation	NETL/USLCI Transport, train, diesel powered	ACLCA Recommended
Truck Transportation	NETL/USLCI Transportation, combination truck, diesel powered	ACLCA Recommended
Barge Transportation	NETL/USLCI Transport, barge, diesel powered	ACLCA Recommended
Ocean Transportation	NETL/USLCI Transport, ocean freighter, diesel powered	ACLCA Recommended
Tires		Data Gap
Crusher Wear Parts (Manganese)	LCA of manganese mining and refining	Factors reported above
Crusher Wear Parts (Steel)	AISC Industry Average EPD Fabricated Steel Plate	Industry Average EPD
Flocculant Chemicals		Data gap
ANFO Explosives		Factors reported above
Emulsion Explosives		Factors reported above

Figure 7: Upstream data selection matrix

Data Gaps

When a material is within the system boundary, but upstream data does not exist for that material, or the data does not meet the minimum data quality requirements, this leaves a data gap. Within the scope of this LCA, flocculants and tires are the identified data gaps.

Flocculant

There are many types of flocculant in commercial use, based on a variety of chemistries. A wide variety of chemical classes are used to accomplish the reduction of sedimentation in water, and information about flocculants used by a participant site beyond a trade name is very rare. Some examples of flocculant chemistries include cationic flocculants, polyamides, and biologically derived agents like alginates and chitosan.

Background data is not available for proprietary flocculant chemicals. A search of the Federal LCA Commons and EcoInvent databases revealed no upstream data for flocculants as a general class. A deeper search of published LCA did not reveal any data specific to flocculants. Even attempting to use proxy data is thwarted by the wide variety of chemical classes used as flocculants. This is a data gap in this analysis.

Based on the data collected for this study we found facilities use on average 0.041 lb (dry) or 0.053 gal (wet) flocculant per short ton of aggregate produced. More information about flocculant use in the aggregate industry as observed in this study is given in Foreground Data Analysis.

Tires

Tires for mobile equipment are a common wear item in aggregate operations. Remarkably, little upstream data exist for tires, especially for heavy equipment. The Federal LCA Commons and EcoInvent databases lack flows for tires. A survey of LCA literature did give some data for global warming potential, though for a function unit of one passenger vehicle tire, and no other impact categories than GWP. Assuming a passenger vehicle tire is 20-30lbs, the literature gave a range of 0.53 - 1.79 kg CO_2 eq per pound (Rangleov 2022, Shajadi 2019, Shanbag 2020, Sun 2016). While the impacts of manufacturing a passenger tire clearly vary from a heavy machinery tire, we can assume that the per pound value is sufficient for ballpark calculations. Participating sites in this study reported an average tire use of 0.0305 lbs per short ton of aggregate produced, or 1.53E-5 tons tire / tons aggregate. When multiplied by the GWP from the literature, this gives an approximate range of 0.016 - 0.055 kg CO_2 eq per short ton of aggregate produced. This hovers near 1% of GWP calculated in this study, and this makes tires a data gap.

Data Quality

Foreground data quality

Data was collected from 31 aggregate sites using the data collection instrument. Each site provided data from a 12 month continual period with beginnings varying from April 2020 to January 2021. The overwhelming majority of data was from the calendar year of 2021. The data gathering instrument is included in Appendix 1.

Multiple sites from each of the major quarry types participated: bank run (16 sites), dredge (2 sites), blast & crush (10 sites), and underground (3 sites), as well as a variety of geologies. Operation types can also be more broadly classified as using explosives (13 sites) and non-explosive (18 sites). Geographic representation across the US and Canada was generally good but lacking participant sites from Alaska, Hawaii, and the eastern provinces of Canada.

Operation size also varied with annual productions from <100,000 to 7,000,000+ short tons. Extra effort was also made to find 'unusual' operations, such as two sites that operated fully off-grid, and another that is no longer extracting aggregate, but crushing and sorting existing stockpiles.

Data were analyzed for outliers using z-tests with a cutoff of z=3. In several cases, data entry errors were identified and corrected, and two participant sites were eliminated from the study. In some cases, sites had outliers on one subset of data, such as diesel fuel use or wash water use, as a result of unusual operating conditions, like the sites operating off-grid, and were included in the study. These cases are highlighted and discussed in the results section.

Just four sites reported producing recycled concrete aggregates (RCA). Production volumes varied from 800 - 237,800 short tons of RCA. Average stockpiled particle size also varied widely from <1.5" to 3'. A further discussion of RCA, and the full data set, are given in the Life Cycle Assessment Results section.

Foreground Data Analysis

This section is an examination of the foreground data, collected at the participating sites, prior to going through environmental impact calculations. Environmental impacts, including both foreground and background impacts, are discussed in the Life Cycle Assessment Results section.

Electricity

Of the 31 participating sites, 29 used grid electricity. The average electricity use was 2.54 ± 1.52 kWh / short ton. The first 17 respondents to the data survey are plotted by operation type and size in Figure 8. No pattern was apparent, and the data did not show significant variation between operation types.

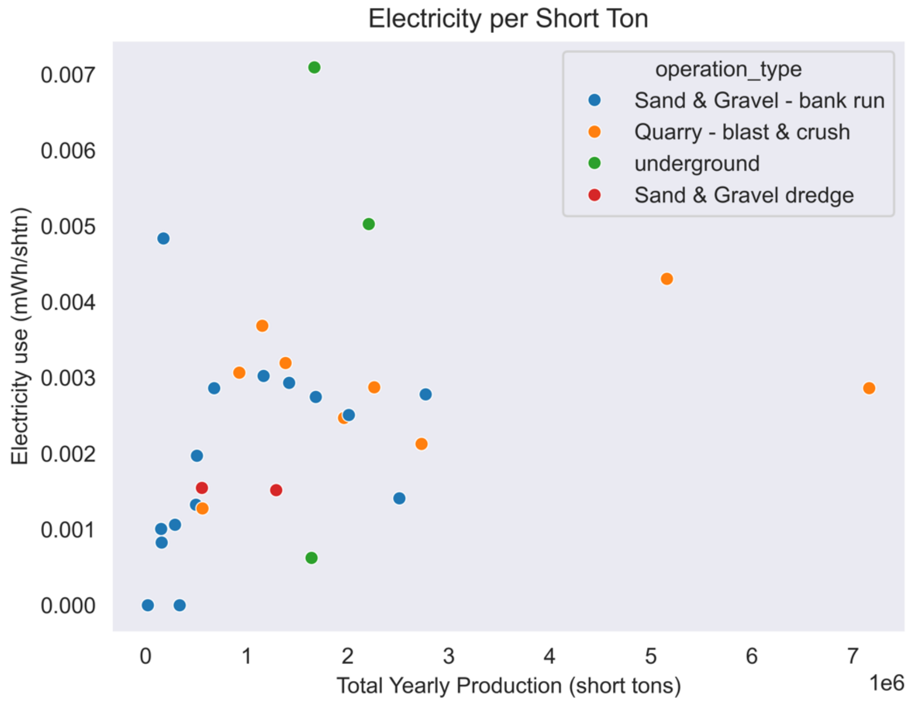

Figure 8: Electricity use per short ton of production for different operation types

Fuel

Every participating site provided fuel use numbers. By far the most common and highest use fuel was diesel, distantly trailed by gasoline.

Other fuel sources that were reported were natural gas, propane, biodiesel, and recycled fuel oil. Each of these fuels was still used in amounts that can be best described as supplementary to diesel fuel. It is also worth noting that while participating in PCR meetings, the following fuels were attested to being used in aggregate operations (though not in the sample set of this study): renewable diesel, renewable natural gas, & residual fuel oil.

Most fuels were used in mobile equipment, though two participating sites also created all onsite electricity using diesel generators. The first was a very small operation, <30,000 short tons of annual production. The second site, a bank run operation with about 400,000 short tons of annual production, shared specific data about their fuel use in electricity generation. Designated 4A1, this site unsurprisingly had the highest rate of diesel use, at 0.539 gallons / short ton. The average throughout the study was 0.153 ± 0.094 gals / short ton. It also had the highest total energy use per short ton of any facility, so high as to render it an outlier. 4A1 also provides a highlighted case in the sensitivity analysis section below.

Explosives

Thirteen of the participating sites fell into the general operation types of blast & crush or underground and therefore used explosives as a regular part of their extraction process.

Since ANFO and emulsions are chemically very similar, they were summed into a total explosive category. Explosive use had a lower variance than most other major inputs, with average rates of 0.697 ± 0.196 lbs / short ton.

Total Energy Use

Individual energy inputs did not reveal any patterns, but once summed into total energy use, began to show statistical differences. In order to calculate total energy use, each source was multiplied by the energy density or lower heating value given in Table 2 ("Fuel Gases - Heating Values.").

Energy Type	**Value**	**Unit**
Electricity	3.60	MJ / kWh
Natural gas	1.036×10^3	MJ / Mcf
Propane	87.5	MJ / gal
Diesel	136	MJ / gal
Gasoline	121	MJ / gal
Biodiesel	126	MJ / gal
Recycled fuel oil	148	MJ / gal
Explosives	8.16	MJ / lb

Table 2: Energy density factors

Explosives are included in the total energy use because of their integral role in extraction. Notably, in non-explosive operations, much of the extraction process is performed by diesel powered mobile equipment.

Comparing the total energy use of explosive operations (underground and blast & crush) against non-explosive operations (bank run & dredge) reveals that the explosive operations, on average, require more energy per short ton of aggregate produced. Figure 9 shows the spread of data collected.

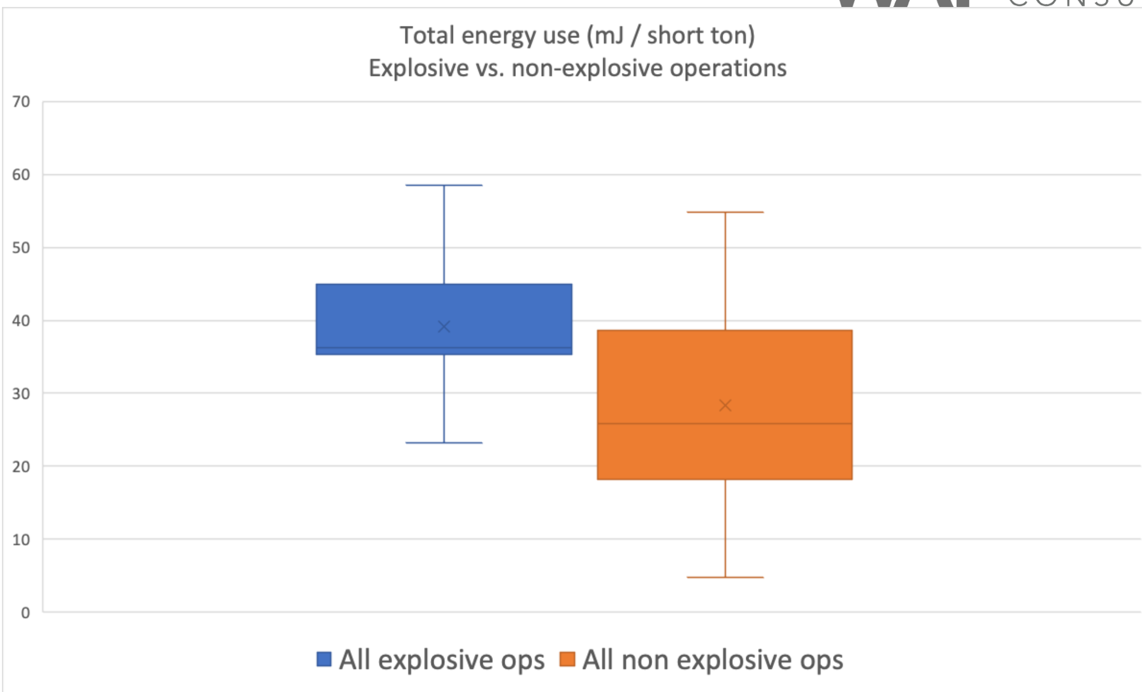

Figure 9: Energy use per short ton of production between explosive and non-explosive operations

It is notable that the increased energy per short ton does not come from the addition of the explosives alone. It is accompanied by statistically significant increases in electricity and diesel use. Presumably this is from the increased crushing and processing needed at a hard rock operation vs. non-explosive operations to get a similar set of products.

Water

Water is a commonly used resource in aggregate operations. It serves two main purposes: Dust control and washing aggregates. Not all operations produce washed products, but all locations are running dust control.

Sources for water included water pumped out of quarries to keep operations from flooding, holding ponds (fed either by rainwater, springs, or water pumped from quarries), wells, and rarely, municipal water. Most operations had a combination of sources. The highest usages, by far, were from holding ponds and water pumped out from quarries.

Of all the data gathered in this study, water usage had by far the greatest variability, as well as the fewest direct observations. Of the study participants, only a few had metered all of their water use. The rest reported their water consumption using reasonable assumptions. For instance, many facilities were able to estimate their water use for dust control by multiplying the number of trips taken by their water truck(s), something typically tracked at a facility, by the capacity of the truck. Estimates for wash water tended to be less concrete. All facilities that provided estimates rather than metered data were required to also report their confidence in the estimate. Some participants did not report on water use at all and were excluded from this section of the analysis.

Water used for dust control is assumed to leave the facility via evaporation, as it is dispensed as a spray throughout the facility, especially on roads, tracks, and on conveyor belts. This water was allocated universally across all products, with an average of 4.2 ± 6.3 gals / short ton.

A percent of water used for washing leaves the facility in the product. Moisture content of washed products varies on climate and storage, but typical numbers are 2-7% by weight. The rest of the water is recycled, using either settling ponds or clarifiers with flocculants. The water which was not recycled was allocated to washed products, with a higher use per short ton than dust control at 33 ± 47 gals / short ton washed aggregate.

Figure 10 shows the water used per short ton of washed product. Note the wide spread of data. These data were confirmed with the producers.

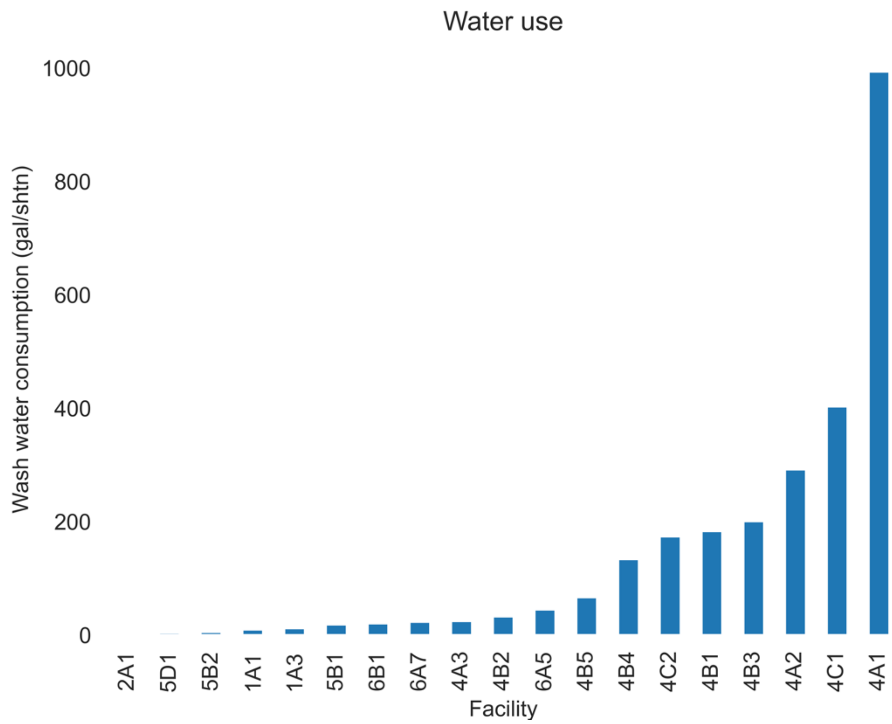

Figure 10: Water use per short ton production differences across facilities

Flocculant

Reported flocculant use varied widely amongst sites. Some were able to provide only trade names for products, while others gave chemical types. This was most commonly true in the cationic flocculant class (e.g. zirconium). Some of the flocculants were reported in gallons, suggesting polyacrylamides. Overall, the use of flocculant varied from ~0.01 to 0.15 pounds per short ton of aggregate production. When restricted to only washed products, the number increases to 0.01 to 0.24 pounds per short ton of washed product, or on the high end, 7.5×10^{-5} tons flocculant per ton washed aggregate. Given the low relative mass, and lack of clarity and upstream data (as discussed in Data Gaps), flocculants were not included in the impact assessment.

Transportation

Transportation of aggregates within facilities is accomplished through a combination of mobile equipment and fixed or semi-mobile conveyor belts, typically moving from the extraction process to crushing to stockpiling. The associated fuel and electricity consumption are rolled up in the total production process.

Over the course of the data gathering process, we learned of several non-typical transport uses. Some facilities have multiple stockpiles that are services from the same quarry, or are transported significant distances from quarry to stockpile or sales yard, by rail, truck, or barge, in some cases 100 miles or more. While this study did not have any participants with such dramatic intra-operation transport, it is worth mentioning for future efforts. Assuming the scope of cradle to gate is still to the point of sale, these long distance transports are still internally attributable to any products that are transported.

Conversely, since the study was cradle to gate, no transport data after the point of sale was collected. This is out of the hands of the producers, and changes for each customer and project. In some cases, the impacts from transport can be significant, and it is recommended to anyone making procurement decisions to include these impacts when selecting products or producers.

Transport of major consumables like manganese crusher jaws and tires to the quarries was assumed to be equal across all locations. These items have complex, global supply chains, and aggregate producers are typically only privy to the final transport leg of these items to their locations.

Electricity transport losses were included in the NETL data set used by zip code.

As the cutoff boundaries for unbound asphalt and recycled concrete aggregates were both as delivered to stockpile, no transport to the quarry is included.

Life Cycle Assessment Results

This study was undertaken to support the PCR for Construction Aggregates. The PCR is intended to govern the creation of EPDs in North America. The TRACI 2.1 indicators have emerged as a preferred set in the American horizontal infrastructure market, and so this study focuses on these indicators: Acidification, Eutrophication, Global Warming Potential, Ozone Depletion, and Photochemical Ozone Formation (Bare 2012). All TRACI 2.1 impact calculations were performed using the EPAs version of TRACI that is compliant with the [Federal Elementary Flow List] accessible from the Federal LCA Commons. The model was built in OpenLCA.

Energy resource use indicators were calculated using the cumulative energy demand reporting (Frischknecht 2005) Since the goal is to inform the creation of EPDs, the following indicators are reported in accordance with ISO 21930. Comments specific to construction aggregate are provided.

- Nonrenewable primary energy resources for energy, in MJ: This includes nuclear fuels as well as fossil fuels.
- Nonrenewable energy resources as a material, in MJ: A small percentage of asphalt binder is present in RAP, representing a potential energy source that is instead used as a material. But since this has crossed the system boundary from its first use (as asphalt pavement), it is not included here.
- Renewable primary resources for energy, in MJ
- Renewable primary resources with energy content used for material, in MJ: the production of aggregate does not include the use of bio-based products as a material.
- Secondary Materials: RAP and RCA are the major contributors in this system to this indicator.
- Renewable secondary fuels, in MJ: No participating sites reported any fuel use that fell into this category.
- Non-renewable secondary fuels, in MJ: No participating sites reported any fuel use that fell into this category.
- Recovered energy, in MJ: No participating sites reported any fuel use that fell into this category.

The other resource use indicators are reported:

- CO_2 uptake from calcination and carbonation, in kg eq CO_2
- Freshwater consumption, in m3

GWP from land use change is not included as the startup and end-of-life of the quarry is outside of the scope of this study. Waste streams from aggregate facilities were also found to be extremely nominal, less than 0.0001 tons waste / ton production.

A note on the following discussion: As global warming potential is currently the indicator subject to the most scrutiny, the next section focuses on the GWP indicator. Other indicators are given in tabular form and are not given in depth discussion when they follow similar trends to the GWP. When an indicator followed a different trend, it is discussed.

Overview

Figure 11 shows the global warming potential for each of the participating sites, and major contributors.

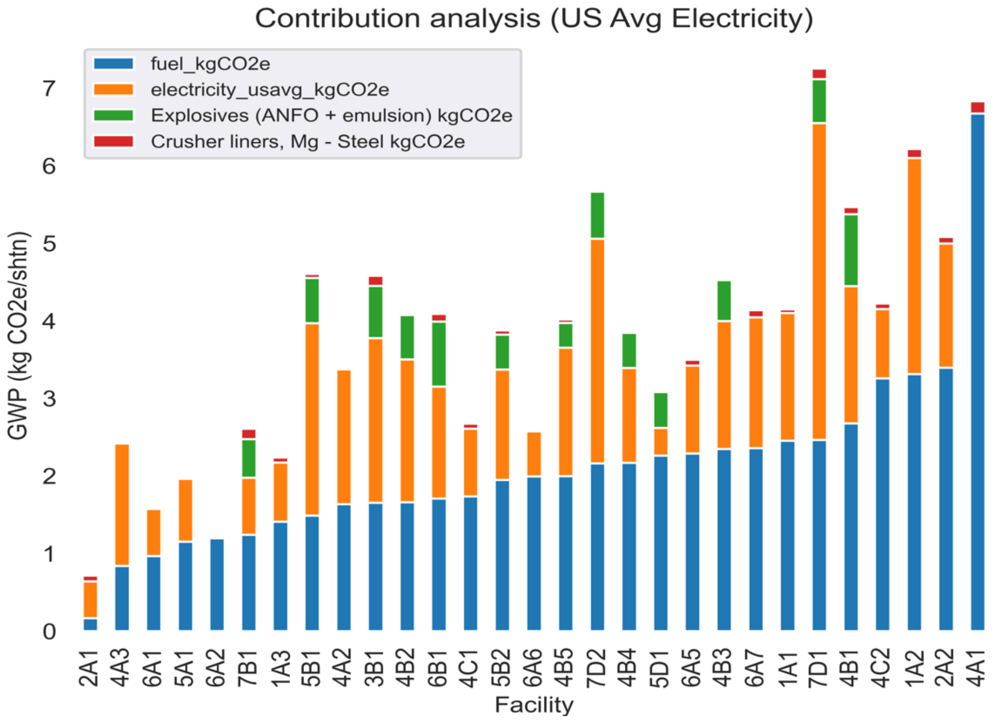

Figure 11: Major contributors to GWP per short ton of production across facilities

An attempt was made to find discernible trends within the data. Figure 12 shows the GWP impact for all participating sites broken out by operation type and size. Figure 13 gives the same data but split out by geography. T-tests were performed to see if any subgroup varied statistically from another. No trend was identified.

ISO 21930 requires that the impacts from generation of electricity and extraction and production of fuels used in the manufacturing phase be included in A3, leaving only the production and transport of explosives, flocculants, and tires to significantly contribute to phases A1 & A2. As flocculants and tires are data gaps in this study, all impacts are reported as sums of A1-A3 to simplify the interpretation of the results.

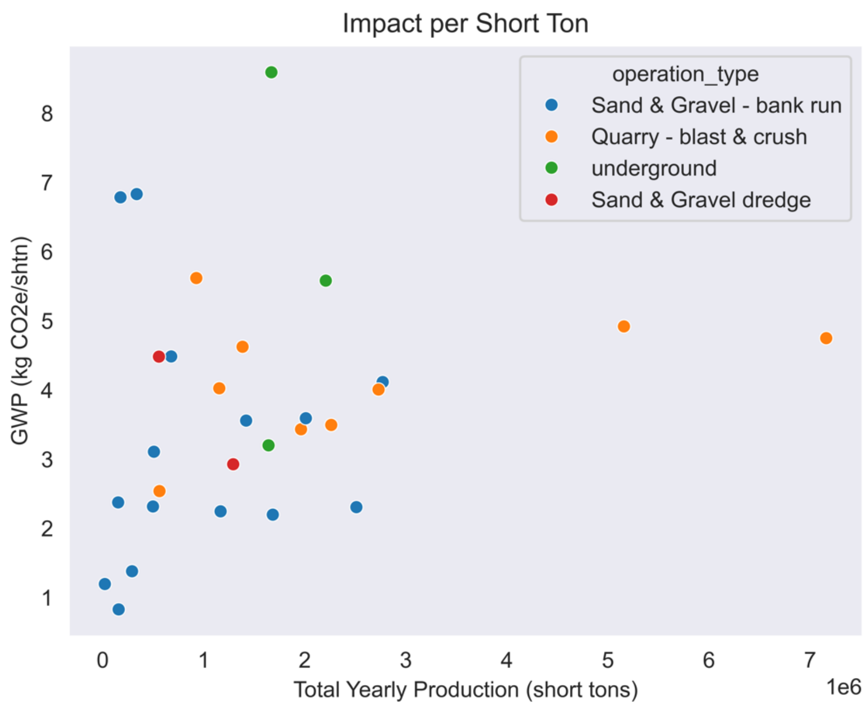

Figure 12: GWP impacts separated by operation type

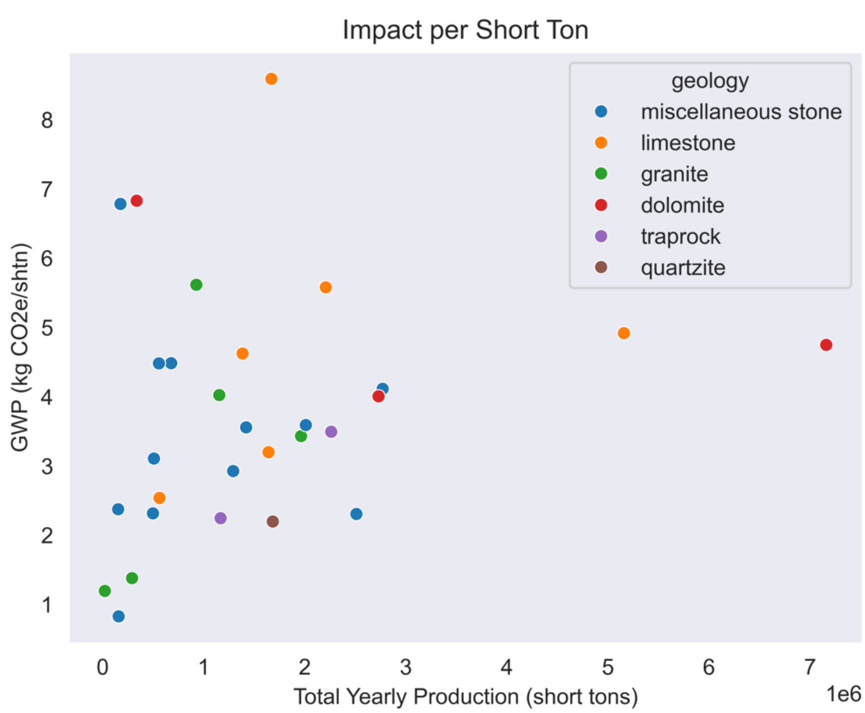

Figure 13: GWP impacts separated by geology

This lack of trend was similar in other impact categories.

It isn't until production is grouped into explosive and non-explosive operation that a distinct separation is revealed. A similar trend as discussed in the Foreground Data Analysis subsection. Total Energy Use was seen in the impacts of explosive and non-explosive operations. In order to look deeper at impact categories and their driving factors, "typical" operations for both explosive and non-explosive operations were created.

Creating & modeling "typical" operations

Major variations in impacts and energy use per ton were observed when facilities were grouped into explosive and non-explosive operations. A model of a typical operation of each type was developed by averaging data from each type of site.

Table 3 gives the variables used to characterize these models. The US average was used for electricity generation.

Flow	**Typ. Explosive Op.**	**Typ. Non-explosive Op.**	**Unit**
Total annual production (all products)	*1,710,000*	*1,710,000*	Sh tn
Annual production (washed only)	*1,044,000*	*1,044,000*	Sh tn
Water, dust control	*3.8550*	*3.8550*	Gal / sh tn
Water, washing only	*33.25*	*33.25*	Gal / sh tn
Grid electricity	*3.1634*	*2.1326*	kWh / sh tn
Diesel	*0.1604*	*0.1375*	Gal / sh tn
Gasoline	*0.0117*	*0.0117*	Gal / sh tn
Explosives	*0.6868*	*0*	lb / sh tn
Manganese steel	*0.0594*	*0.0594*	lb / sh tn

Table 3: Characterization factors of typical explosive and non-explosive operations

Three unique scenarios were run: washed aggregates from the typical explosive operation and the typical non-explosive operation, as well as unwashed aggregates from the typical explosive operation. Table 4 gives the resulting impacts (using the TRACI 2.1 Indicators) for both the explosive and non-explosive scenarios, while Table 5 shows impacts from washed and unwashed products.

TRACI 2.1 Indicator	**Unit**	**Typ. Explosive Op., washed product**	**Typ. Non-explosive Op., washed product**
Acidification	kg SO_2 eq	0.03253	0.02660
Eutrophication	kg N eq	0.01740	0.00157
Global Warming	kg CO_2 eq	4.53222	3.08301
Ozone depletion	kg CFC-11 eq	4.1595E-8	3.02999E-8
Smog formation	kg O_3 eq	0.99482	0.82329

Table 4: TRACI 2.1 Impact indicators for washed products from typical explosive and non-explosive operations

TRACI 2.1 Indicator	**Unit**	**Typ. Explosive Op., washed product**	**Typ. Explosive Op., unwashed product**
Acidification	kg SO_2 eq	0.03253	0.03253
Eutrophication	kg N eq	0.01740	0.01740
Global warming	kg CO_2 eq	4.53222	4.53222
Ozone depletion	kg CFC-11 eq	4.1595E-8	4.1595E-8
Smog formation	kg O_3 eq	0.99482	0.99482

Table 5: TRACI 2.1 Impact indicators for washed and unwashed products from typical explosive operation

Unsurprisingly the products from explosive operations have higher impacts across the board. For instance, the global warming potential of a washed product from a typical non-explosive operation is 3.08301kg CO_2 eq, versus 4.5322 from the typical explosive operation, a 47% difference in impact. It is important to note that this analysis ends at the aggregate producer gate, and we must remind those in geological areas that necessitate explosive extraction methods searching for lower embodied carbon to consider post-gate transport impacts before seeking a far flung non-explosive operation.

Eutrophication differences were the starkest, an increase of 900%, due to the use of ammonium nitrate in the production of the explosives. The other TRACI indicators followed the same trend as global warming potential.

This difference in eutrophication is seen in all responding sites when grouped into explosive and non-explosive groups as shown in Figure 14.

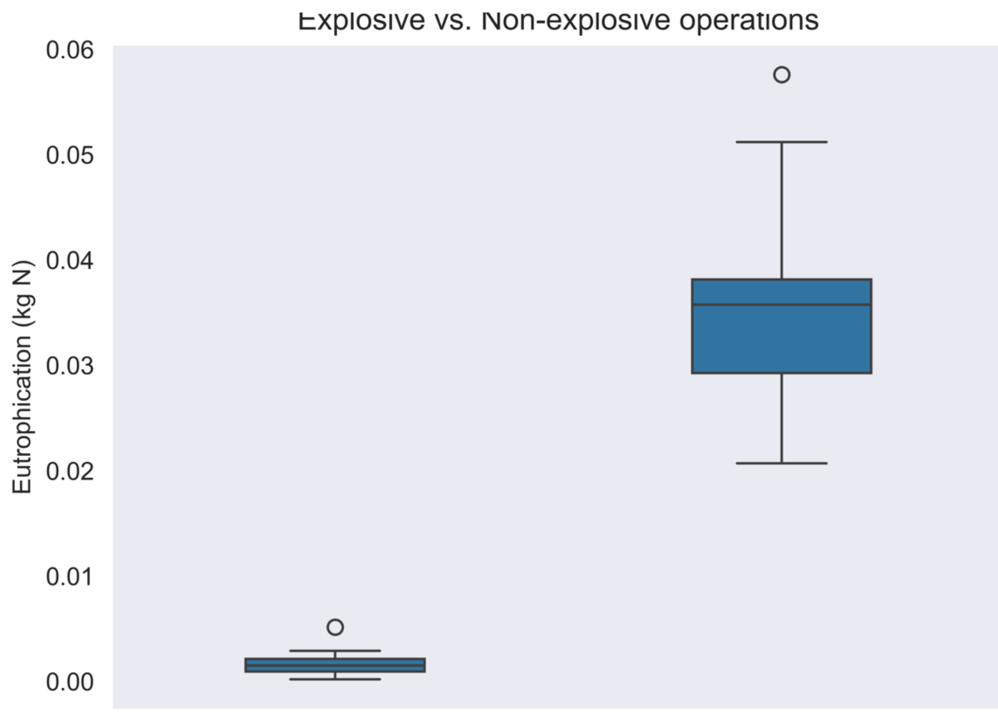

Figure 14: Eutrophication impacts from explosive and non-explosive operations

Washed and unwashed products, on the other hand, had no variance in the TRACI 2.1 indicators. The difference shows up in resource use, shown in Table 6. In the typical aggregate operation, water leaves the drainage system by two methods: evaporation and by being transported away with washed products. Accordingly, water used for dust control and evaporation from storage ponds is distributed across all products, while water used for washing is allocated to washed products only. Water used for washing was defined as total gallons of water entering the washing system times the recycling rate of the washing system. Not all participating sites closely tracked water use, but several in the arid west had precise washing numbers. The typical recycling efficiency of their systems, about 65%, was then applied across all sites with washed products. The addition of upstream water use reduces the differences in water use between products, but total fresh water use per short ton is about 16% higher in washed products.

Indicator	Unit (per shtn)	Typ. Explosive Op., washed product	Typ. Explosive Op., unwashed product	Typ. Non-explosive Op., washed product
Non-renewable energy: fossil fuels and nuclear	MJ	67.79	67.79	42.16
Renewable energy: hydro, wind, solar and thermal	MJ	7.75E-3	7.75E-3	6.12E-3
Secondary material use	kg	0	9.42E-3	0
Fresh water	m^3	0.921	0.795	0.921
Waste – hazardous & nuclear	kg	0	0	0
Waste – nonhazardous	kg	1.78E-6	1.78E-6	1.203E-6

Table 6: Other indicators for washed and unwashed products from the typical explosive and non-explosive operations

In aggregate operations, both recycled concrete aggregates (RCA) and unbound asphalt aggregates enter the system after the end of a prior life cycle. About 50% of the participating sites reported producing one or both of these materials, though no site reported washing these products, resulting in the difference in secondary materials use.

Crusher Impacts, or why isn't aggregate size a factor?

It would seem logical that the smaller an aggregate is, the more processing it has required, and therefore, the higher the associated impacts should be. So why is there no discussion of the relative impacts of crushing?

The answer is twofold; fundamental differences in local geologies and markets, and a lack of specific data.

First, localized mismatches in markets and geologies. Imagine you are in an area where, millions of years ago, a large alluvial plain existed. The local aggregate operations are therefore bank run. Very little crushing is needed to provide an abundance of 1.5" aggregate – they are just screened out from the mix. On the other hand, there is very little angulated sand. The local operation may have to crush up some of the overabundance of 1.5" to create a product known as manufactured sand to meet the market need. Now imagine the local geology is granite. Aggregate is produced from a blast and crush quarry. Almost all 1.5" aggregate must be created by crushing (after larger pieces are extracted by blasting). But angulated sand is created as a co-product at the same time. So in one operation, sand requires additional crushing (and assumedly has higher associated impacts), while at another it does not.

This is where the second issue comes into play: a lack of specific data. No operations had separate metering of different crusher lines. And while a model of a crushing and screening line could be constructed using motor sizes and efficiencies, these models would have to be recreated for each individual operation, quickly becoming unreasonable for a whole-industry survey. Additionally an operation may have several crushing lines that are mostly permanent, complemented by one or more ephemeral cells, that may be reconfigured regularly to accomplish different tasks (like switching from RCA processing to creating manufactured sand). Finally, there is a lack of data about how many times a particular rock may be looped through a crushing process before finally being screened out at the desired size. Consider how the following would complicate the allocation of impacts; if a particular rock comes into the crushing line once and is crushed to x pieces of exactly 1.5" versus that same rock being crushed into y/x pieces of 1.5" and the rest having to be put through the crusher again, perhaps multiple times, in order to reach the desired size.

This study did not have enough available data to characterize these factors. It is hoped that by the time the PCR goes for its next review, sufficient data will have been gathered to give better modeling of this aspect.

Carbonation

Carbonation is the process where atmospheric carbon dioxide reacts with calcium oxide or calcium hydroxide to form calcium carbonate. This is of especial interest in concrete. The absorption of atmospheric carbon dioxide by concrete is fairly well studied and modeled, especially during the use phase. It is a function of the initial formulation of the concrete, the surface area exposure to air, and time. It can also be significantly slowed by moisture, so a concrete placed in Seattle will have a very different uptake of carbon from an identical concrete placed at the same time in Phoenix. Studies of the End-of-Life phase were much slimmer. A literature review revealed no studies measuring the carbonation of stockpiled RCA. All methods of estimating carbonation at EOL (prior to becoming RCA) were based on models that did not account for carbonation during the use phase.

In harmony with the concrete PCR, this study considers the end of the life cycle of concrete to be after transport of the concrete to either its direct placement in a new product, landfilling, or in the case of RCA, when it is first stockpiled. It is at that point unburdened, though all consequential crushing, screening, internal transport and washing are allocated by mass in the same way as virgin or natural aggregates.

Only four sites in this study reported processing RCA. The complete RCA data set is given in Appendix 2. Production volumes varied from 800 - 237,800 short tons of RCA and average stockpiled particle size also varied widely from <1.5” to 3’, the average size being 8”. Interestingly, some of the respondents were already taking steps to encourage carbonation by spreading out stockpiles to increase surface area. On average, RCA was being added to the stockpile every 3 days.

Several methods of estimating carbonation were examined, notably the IPCC Fourth Assessment Report referenced in section 7.2.8 Carbonation of ISO21930, the MIT Whole Life Cycle Carbon Uptake Tool, and the GCCA Industry EPD Tool for Cement and Concrete (Pachauri 2007, “Concrete EPD Tool.”, “Whole Life Cycle Carbon Uptake Tool”). Carbonation of RCA was also a topic of vigorous discussion in the committee for the PCR update, which occurred concurrently with this LCA creation. A copy of the carbonation annex to the PCR is included here in Appendix 3. It is notable that the PCR update is not formally released yet but has gone through the expert panel review and is now out for public comment.

The MIT tool, while very good for estimating total life cycle carbon uptake, has an stockpile particle size upper limit of 64 mm. Only one of the four sites in the study could be evaluated using it.

The IPCC report recommends using a value of 5 kg CO_2/m3 (about 2.1 kg CO_2 / short ton) of concrete. The study is targeted at providing national level estimates of carbon intensities, and it is problematic to apply such large scale estimates at the short ton level. It also does not have a time factor, instead it is implied that the length of atmospheric exposure is a year or more, differing greatly from the average 3 day exposure found in this study. Indeed, the lead author of the IPCC report advised the Construction Aggregate PCR update committee that the model was not appropriate for EOL stockpile models of concrete during a roundtable discussion.

Finally, the GCCA EPD tool. This is paywalled, but a temporary access for the purpose of this LCA and the PCR update was arranged. Based on the same underlying studies as the IPCC report and the MIT tool, this tool was also estimated the total life cycle carbon uptake, taking into account the cement content and environmental exposure parameters in the use phase. Again it did not have sufficient range in particle size to calculate the carbonation during EOL stockpiling.

The PCR update committee attempted to synthesize the available EOL stockpile carbonation models into a conservative estimate, assuming one week of stockpiling and an 3000psi mix, resulting in a value of 0.3468 kg CO_2 eq per short ton of RCA. Applying that to the four sites with RCA production results in an average carbonation uptake value of 0.0101 kg CO_2eq per short ton of total annual production, as seen in Appendix 2.

This is an interesting first look at carbonation in RCA, but four sites is not enough to fully characterize a large industry and is a limitation of this LCA.

Sensitivity Analysis

The two largest contributors to GWP revealed in this study are diesel and electricity. The selection of electricity data set can have major changes in impacts depending on whether national average, FERC regions, or Balancing Authority (BA) level data are used. For this study, zip-code level BA data was selected, as detailed in the Life Cycle Assessment Inventory section. The electricity use for each site was run using the US average and zip-code specific data, shown in Figures 15 and 16 respectively.

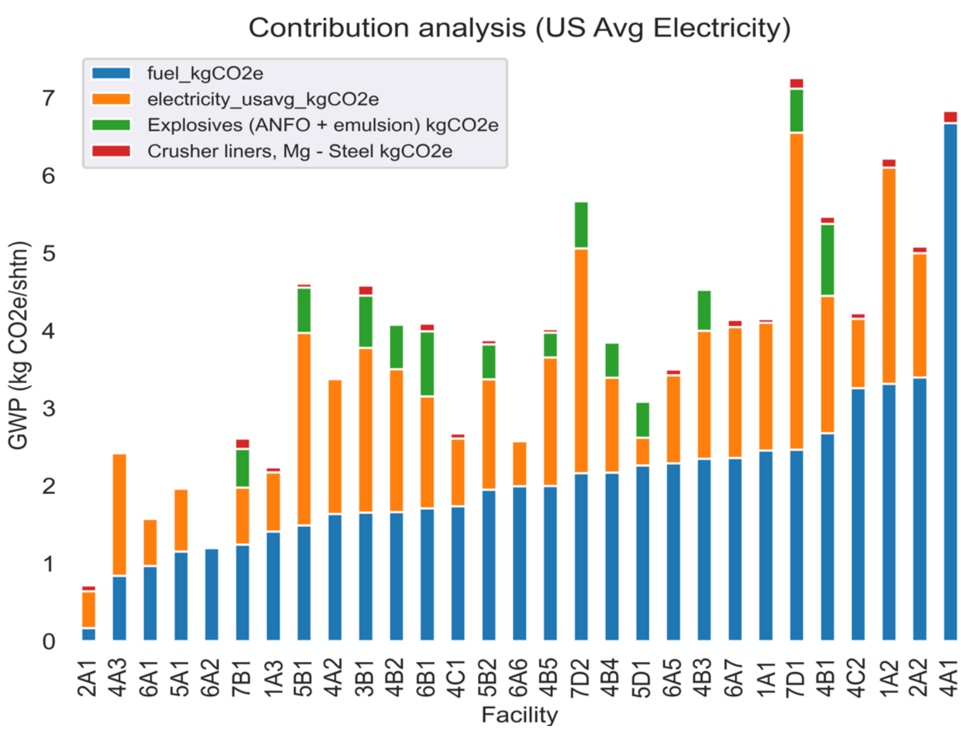

Figure 15: Major contributors to GWP per short ton of production across facilities using US average electricity data

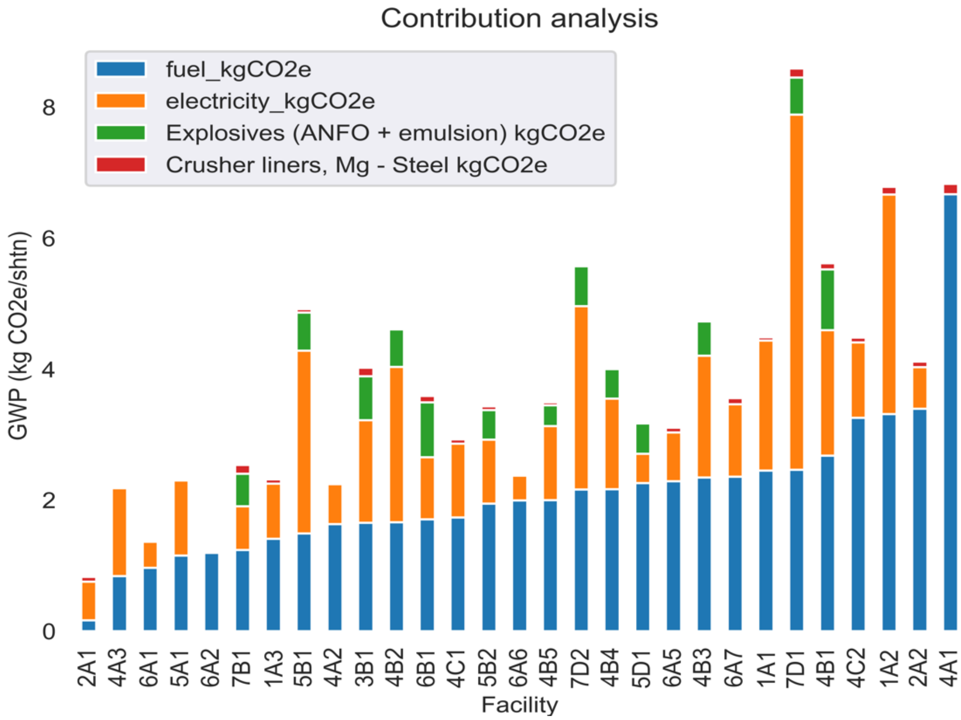

Figure 16: Major contributors to GWP per short ton of production across facilities using BA electricity data

Unsurprisingly, the GWP from electricity use (the orange bar in the above figures), rises at some facilities and decreases at others. An easy example to contemplate is site 4A2; it is located in a relatively clean grid, and the GWP impact more than doubles when using the US average electricity data.

Aggregate is fundamentally supplied at a regional level. Using zip code specific data is crucial to allow for comparisons at the local supplier level.

Case Study of 4A1

The quarry designated 4A1 presents an interesting study. It is a small to middle sized (300k - 400k short ton annual production) bank run operation in the northeast region. 4A1 had no grid connection and all electricity used on site was provided by a diesel generator. After data collection, the diesel generator broke down and the operators performed a multi-objective analysis to decide whether to replace the diesel generator or switch to grid electric. Switching to grid electric had reasonable capital investment numbers, was favorable from a maintenance perspective, and allowed for increased production capacity. In a sign of the times, the quarry operator also wanted to include sustainability in the evaluation, specifically global warming potential.

4A1 had tracked the wattage produced by their generator, as well as accurate diesel consumption of the generator alone (separate from the mobile equipment), allowing for accurate comparative analysis. First, it should be noted that the diesel generator was unrealistically efficient based on the data provided, generating 28 kWh per gallon of diesel, or almost 100% efficiency. The theoretical maximum efficiency of a diesel generator is 70% (U.S. Energy Information Administration). Thus far, extremely efficient generators operate at about 50%. This gives a reasonable ceiling of 19 kWh / gal of useful electricity produced. Using this assumption, and that the facility would continue to have similar electrical needs, the carbon impacts of remaining on diesel or switching to grid electric were calculated.

Table 6 shows the resulting global warming potentials for the electrical production portion of the operation.

Impact measurements	Unit	Diesel Generation	Local Grid
Annual GWP	kg CO_2 eq	1.61E6	4.95E5
GWP per kWh	kg CO_2 eq / kWh	0.772	0.238

Table 7: Change to GWP impacts if site 4A1 switches from a diesel generator to grid electricity

Switching to the local grid would reduce the global warming potential from electrical use by 69%. It's notable that in order to join the grid, a substation would need to be installed, and these numbers do not include this carbon-capital outlay.

The quarry operators were advised of these outcomes, and when balanced with the other factors, chose to switch to the local grid for their electricity.

Conclusions

This study was conducted to give the aggregate industry a clear picture of its environmental impacts and support the update of the PCR for construction aggregates. It was a cradle-to-gate analysis of virgin and recycled aggregates, including recycled concrete aggregates.

The study revealed a clear delineation between natural aggregates extracted via non-explosive methods (like bank run and dredging operations) and explosive operations (underground and blast-and-crush quarries). Explosive operations showed 30-40% higher impacts in all TRACI indicator categories, except eutrophication, which was about 900% higher.

Additionally, the selection of upstream electricity data sets can significantly affect the calculation of environmental impacts. The PCR committee or those creating EPDs should consider the most location specific data set possible.

A reminder for those looking to reduce impacts; This study is only valid to the gate of the operation. The transport and use of these products should be considered when evaluating their impacts and should be done on a project-by-project basis, as transport distances and methods can vary wildly, and quickly overshadow differences in aggregate extraction methods. But for those looking to create baselines or limits, it is essential to evaluate aggregates based on their extraction method group, rather than a single average.

Some indicators required for ISO 21930 compliant EPDs, like abiotic depletion of fuels, were not included in this study. It is recommended these be included in PCR committee discussion.

Areas for further study include better characterization of carbonation in stockpiled RCA, and greater granularity of electricity and fuel data to allow for modelling crushing as a step separate from extraction, and to better allocate impacts to different sizes or types of aggregate products.

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Appendix 1: Data gathering instrument

See associated file Aggregate LCA Data Gathering 9dec21.xlsx

Appendix 2: RCA data set

Location Indentifier	6A1	6A5	5A1	4A2	AVERAGE
Do you produce any recycled concrete aggregate (RCA)?	*Yes*	*NO*	*Yes*	*Yes*	n/a
What is your total annual production?	*290,464*	*507,147*	*2,510,606*	*1,166,697*	1,118,729
How many tons of RCA did you produce during the data gathering period?	*3,500*	*0*	*237,318*	*12,200*	63,255
How many tons of RCA did you receive during the period?	*4,200*	*800*	*156,000*	*12000*	43,250
How many times did you receive RCA during the period?	*N/A*	*N/A*	*240*	*almost daily. Estimate 195 days*	109
How tall are your RCA stockpile(s)? If it changes often, give your best estimate for average height, in ft	*20*	*10*	*35*	*20*	21
On average, how old is your RCA stockpile?	*1-5 years*	*5 YEARS*	*2 years*	*1 year*	2.75
Do you have a maximum target size for your RCA stockpile(s)?	*NO*	*NO*	*350,000 cubic yards (600,000 tons)*	*20,000*	n/a
Is your stockpile a typical cone shape, or do you manipulate it to another shape (e.g. spread out until X feet tall)	*spread out at 20ft tall*	*SPREAD OUT AT 10 FT*	*spread out until 35 feet tall*	*Typical cone shape and spread out to facilitate volume*	n/a
About what size is the RCA in your stockpiles?	*1" - 12"*	*1"-12"*	*6" to 3'*	*1.5" - 0*	7.75
Do you know what the concrete was used for previously (road surface, road bed, building?)	*NO*	*1166697*	*material from truck washout and rejected loads*	*Road Bed*	n/a
Carbonation value calculated using PCR committee value of 0.3468 kg CO2 eq per short ton RCA	1214	0	82302	4231	21937
Carbonation value per ton of total production	0.0042	0.0000	0.0328	0.0036	0.0101

Appendix 3: PCR Carbonation Annex

Concrete, at end of life, is commonly reprocessed through crushing for reuse as a secondary product known as recycled concrete aggregate (RCA). The process of crushing concrete demolition waste exposes additional surface area to atmospheric carbon dioxide, which can accelerate carbonation reactions on the surface of the RCA. Carbonation is a well-known, well-documented, inherent quality of concrete and RCA. Carbonation represents sequestration of carbon dioxide from the atmosphere via mineralization through reactions with calcium oxide, calcium hydroxide or calcium-silicate hydrates. ISO 21930:2017 Section 7.2.8 requires that environmental impacts considered during the production, use and end-of-life stages shall include carbonation.

Per ISO 21930 Section 7.2.8 Carbonation, carbonation is an inherent property of concrete, for details see ISO 21930.

This PCR recognizes that while the quantification of carbonation is complex and influenced by several variables, approximate and empirical models can form the basis of calculation. There is a growing body of literature surrounding carbonation during end-of-life processing of concrete; this PCR update attempts to advance the state of the PCR by providing a conservative approach to account for carbonation while recognizing that future updates will provide opportunities for iterative refinements to this methodology as the science evolves.

This PCR update proposes three approaches of increasing complexity to account for carbonation in RCA.

The application of these methods in accounting for carbonation in RCA is limited to RCA exposed to atmospheric CO_2. Per allocation rules in Section 7.5, only elemental flows associated with reprocessing, handling, sorting, and transportation from the generating industrial process to their use in the production process need to be considered. While a growing number of innovations in this space either currently exist or are under development, technologies that involve inputs beyond RCA and atmospheric carbon dioxide are beyond the scope of this PCR and thus it is recommended that LCA be conducted to more accurately account for environmental benefits and impacts including carbonation for these materials.

The primary variables impacting carbon uptake of stockpiled RCA include RCA aggregate size, stockpile geometry, and how long the RCA is held in a stockpile (AzariJafari, 2021[1]). E J

The following three methods for quantification of carbonation associated with RCA may be used:

Method 1. Apply a singular, conservative carbonation coefficient of -0.35 kgCO2e / short ton of recycled concrete aggregate (RCA), regardless of site conditions.

The carbonation coefficient of -0.35 kgCO2e/short ton (note factor converted from concrete yardage reference Table 1 which follows) was derived from evaluating numerous scenarios through the Global Cement and Concrete Association Industry EPD tool for Cement and Concrete v3.1 (LCA Model, North American Version) (Dauriat, A. et. al.[2]). The default carbonation coefficient proposed for use is the most conservative carbonation coefficient provided through the scenarios evaluated. The scenarios evaluated impact of two variables on the rate of projected carbonation: concrete strength and duration RCA is held in stockpile

Concrete mix designs were based on Benchmark Ready-Mix Designs as detailed in the July 2022 study commissioned by the National Ready-Mix Concrete Association (NRMCA) “A Cradle to Gate Life Cycle Assessment of Ready Mixed Concrete Manufactured by NRMCA Members – Version 3.2”. The concrete strength classes evaluated included 2500, 3000, 4000 and 5000 psi. A recycling rate of 100% was assumed in the GCCA model. It was also assumed that the stockpile was exposed to precipitation.

The carbonation coefficients derived from the GCCA EPD Tool (v3.1) as influenced by mix design, concrete strength and RCA stockpile duration are illustrated in Table X. This PCR proposes the use of the most conservative carbonation coefficient derived from the iterative runs of the GCCA model and is highlighted in Table A1 below.

[1] Hessam AzariJafari, Fengdi Guo, Jeremy Gregory, Randolph Kirchain, Carbon uptake of concrete in the US pavement network, Resources, Conservation and Recycling, Volume 167, 2021

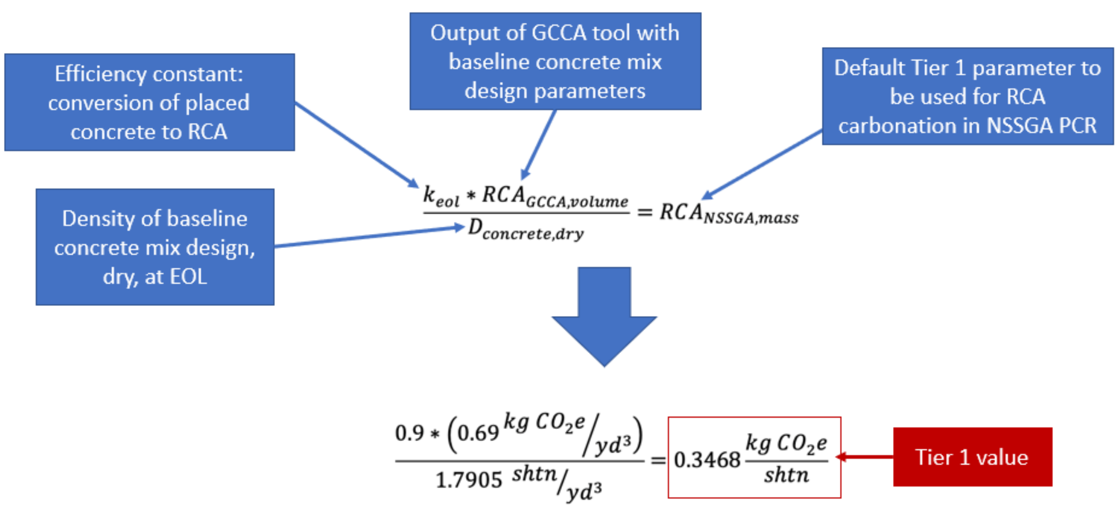
[2] Dauriat, A., A. Coulon, J. Bitar, X. Liao and C. Delerce-Maurice. (2021) GCCA Industry EPD Tool for Cement and Concrete (v3.1) LCA Model, International Version. Retrieved from https://www.concrete-epd-tool.org/

Table A1. Impact of mix design, concrete strength and RCA stockpile duration on carbonation coefficient from the GCCA Industry EPD Tool for Cement and Concrete v3.1.

GCCA Tool End of Life Ready Mix C3 waste processing
Table B1- NRMCA U.S. National Benchmark Mix Designs (per cubic yard)

		Resulting recarbonation (CO2 eq./ yd³ of ready-mix concrete)											
		100% Portland Cement Mixes								100% Portland Limestone Mixes			
		Table (page 67 of NRMCA Study)				Table (pages 48 & 49 of NRMCA Study)							
Compressive Strength	**psi**	**2500**	**3000**	**4000**	**5000**	**2500**	**3000**	**4000**	**5000**	**2500**	**3000**	**4000**	**5000**
RCA Stockpile Duration	**months**												
	0.25	1.05	**0.69**	0.84	1.01	1.26	0.85	1.07	1.34	1.14	0.77	0.97	1.21
	1	2.09	1.38	1.67	2.02	2.5	1.69	2.14	2.67	2.26	1.53	1.93	2.41
	3	3.58	2.38	2.87	3.48	4.3	2.91	3.69	4.59	3.89	2.63	3.33	4.16
	6	5.03	3.35	4.04	4.9	6.03	4.09	5.19	6.47	5.45	3.7	4.69	5.85
	12	7.03	4.71	5.68	6.89	8.43	5.75	7.29	9.09	7.63	5.2	6.59	8.22
	24	9.79	6.6	7.96	9.65	11.74	8.06	10.21	12.73	10.62	7.29	9.23	11.51

The conversion of the carbonation coefficient per unit mass (short tons) was derived from the following calculation:



$$\frac{k_{eol} * RCA_{GCCA,volume}}{D_{concrete,dry}} = RCA_{NSSGA,mass}$$

$$\frac{0.9 * \left(0.69 \, {}^{kg\ CO_2e}/_{yd^3}\right)}{1.7905 \, {}^{shtn}/_{yd^3}} = \boxed{0.3468 \frac{kg\ CO_2e}{shtn}}$$

Method 2. Calculate carbonation coefficient based on a limited set of unique conditions present at the RCA producer facility using the current version of the free, open source, MIT Whole Lifecycle Carbon Uptake Tool.

Only the portion of the Tool related to End-of-Life shall be used to estimate end-of-life carbon uptake**.** Site specific input parameters are: stockpile geometry (diameter at top of stockpile, diameter at bottom of stockpile and stockpile height, slope and whether is it sheltered from the rain), RCA aggregate size, stockpile duration and mass of RCA. Tool and documentation can be accessed at: [https://cshub.mit.edu/whole-life-cycle-carbon-uptake-tool.](https://cshub.mit.edu/whole-life-cycle-carbon-uptake-tool)

Requirements

- Document input variables used to populate the tool: stockpile top diameter, stockpile bottom diameter, stockpile height, RCA aggregate size, stockpile duration and mass of RCA.
    - If a producer has a stockpile that does not conform to the basic stockpile requirements of the MIT method, this method cannot be used.
- Provide documentation to justify input variables used
- Use the most current version of the MIT Tool at the time of calculation and document the version of the MIT Tool used in the EPD.
- Use the NRMCA benchmark mix of 3000 psi. SeeNational Ready-Mix Concrete Association (NRMCA) "A Cradle to Gate Life Cycle Assessment of Ready Mixed Concrete Manufactured by NRMCA Members – Version 3.2".

Method 3. Quantify average carbonation rate in RCA stockpile through field sampling and lab tests for carbonation.

Sampling Methodology. This PCR recognizes that RCA stockpiles will be heterogeneous and dynamic in nature as additions to the stockpile will be made over time, and that the source of recycled/demolished concrete will vary. As such, a consistent approach to sampling methodology is critical.

The practitioner shall establish the baseline carbon content present in RCA at time of receipt of RCA at the receiving facility.

Stockpile sampling shall be representative, and the practitioner *shall describe the methods utilized.* An example method is provided below:

- **Sampling to quantify carbon sequestered** in RCA after receipt at producer facility.
    - **Stockpile heterogeneity**. Ensure sampling methodology accounts for heterogeneity of carbon uptake based on spatial location within the stockpile (according to ASTM D75).
    - **Sample preservation.** Describe the sample preservation method employed to ensure that samples shall be immediately preserved after collection in a manner that will stop additional carbonation reactions from taking place after sample collection.
    - **Minimum sample size.** A minimum sample size of 30 grab samples per sample event stockpile
    - **Document dates of stockpile additions.** Document quantity and date of all stockpile additions
    - **Document dates of sample collection**

- **Lab Methodology**. The methodology developed by D'Avela et al (2016)[3] or Thermogravimetric Analysis in accordance with ASTM E1131 and ISO 11358 to quantify total carbon mineralized shall be followed.
- **Calculation**: coefficient for carbon sequestered through the exposure of RCA to atmospheric carbon dioxide shall be based on

$$\boldsymbol{Carbonation = \bar{X}\_(Baseline\ Carbon\ in\ RCA)/\gamma - \bar{X}\_(Mineralized\ Carbon\ Samples)/\gamma}$$

Baseline Carbon in RCA: mineralized carbon content in concrete waste at the point of receipt at the concrete processing facility, prior to any processing occurring. This is quantified through the methodology developed by D'Avela et al (2016) or Thermogravimetric Analysis as detailed above and calculated as the average of the samples taken during a single sampling event.

Carbonation Samples: mineralized carbon content in the RCA after processing and stockpiling. This is quantified through the methodology developed by D'Avela et al (2016) or Thermogravimetric Analysis as detailed above and calculated as the average of the RCA samples taken during a single sampling event.

[3] Bao, Jiangyin & D'Avela, Canan & Croxen III, Fred & Downs, Robert & Fickett, Steve & Rodrigues, Hugh & Rothstein, David & Thompson, Jason. (2016). Preliminary Method to Determine CO2 Sequestration in Cementitious Units. TMS eJournal. 34. 19.