New York State
Pollution Prevention Institute

New York State
Pollution Prevention Institute

RIT | Golisano Institute for Sustainability

Final Report for:

Green Sulfcrete Corp.

Longbeach, NY

Greenhouse Gas Evaluation of Green Sulfcrete Corp.'s Sulfur Polymer Technology

February 9, 2023

Prepared for:

William Biamonte
Co-Founder
Green Sulfcrete Corp.
342 West Penn Street
Long Beach, New York 11561
Phone: (516) 967-3062
Email: Biamonte@Greensulfcrete.com

Prepared by:

New York State Pollution Prevention Institute (NYSP2I)
Rochester Institute of Technology
111 Lomb Memorial Drive
Building 78, Room 2000
Rochester, New York 14623-0426
Phone: (585) 475-2872
E-mail: nysp2i@rit.edu
Website: http://www.nysp2i.rit.edu

New York State Pollution Prevention Institute

Funding Acknowledgment and Disclaimer

This technical report is prepared consistent with the terms and purposes of the Research Agreement between Green Sulfcrete Corp (the “Company”) and Rochester Institute of Technology (RIT) on behalf of the New York State Pollution Prevention Institute (NYSP2I) that was effective August 1, 2022. This report is the product of work conducted by RIT for a project entitled, “Greenhouse Gas Evaluation of Green Sulfcrete Corp.’s Sulfur Polymer Technology,” which was funded [in part] by a grant to RIT from by the Environmental Protection Fund as administered by the NYS Department of Environmental Conservation. All conclusions herein are subject to the research warranty and liability limitations, and other provisions, described in the Research Agreement executed by RIT and Green Sulfcrete Corp.

RIT and NYSP2I cannot endorse any particular product or service. This report is the result of the tests, meetings, and/or studies conducted and described; it is not to be interpreted as any type of specific endorsement of any product or service. Further, any opinions, findings, conclusions or recommendations expressed are those of the author(s) and do not necessarily reflect the views of New York State.

This report is intended for Green Sulfcrete Corp’s internal use only. Green Sulfcrete Corp may use the report externally if used in its entirety. Any other use of less than a complete version of this report is allowed only if Green Sulfcrete Corp first obtains the written permission of RIT.

Table of Contents

Funding Acknowledgment and Disclaimer 2

Table of Contents 3

A. Executive Summary 4

B. Introduction 4

C. Project Objective 4

D. Work Performed and Results 5

E. Conclusions and Next Steps 14

F. Appendix 14

A. Executive Summary

The New York State Pollution Prevention Institute (NYSP2I) at Rochester Institute of Technology (RIT) conducted a project entitled, "Greenhouse Gas Evaluation of Green Sulfcrete Corp.'s Sulfur Polymer Technology" for Green Sulfcrete Corp. (GSC) to perform a greenhouse gas (GHG) impact assessment of their product.

The objective of this project was to estimate the GHG emissions reduction potential (ERP) associated with GSC's projected product use in New York State as compared to a conventional product. To this end, NYSP2I worked with GSC to select Portland cement and a blended hydraulic cement as baselines for comparison. The GHG impact of one ton of each baseline material was first estimated, focusing just on the raw material extraction and manufacturing life cycle phases. GSC then supplied information related to the energy use, transportation, and material inputs to their Sulfcrete cement pellets, and NYSP2I estimated the GHG impact associated with both life cycle phases. The estimated impacts of the baselines and new product were then compared to determine the potential reduction in GHGs on a per ton basis, as well as on an annual basis using projected market volumes for New York State.

The analysis resulted in a GHG ERP of 564 – 744 kg CO2e/ tonne pellets, and an annual estimated GHG ERP between 20,466 tonne - 26,998 tonne CO2e/ year. The analysis also revealed that the use of their proprietary modifier as well as transportation distances were the main contributors to the GHG impact of the Sulfcrete products. GSC is working on developing new partnerships and scalable processes for utilizing waste oils in their product manufacturing, which would decrease the GHG ERP further. GSC may pursue another GHG ERP assessment at a future time if any product component significantly changes.

B. Introduction

Green Sulfcrete Corp. (GSC) was formed for the purpose of licensing, developing, and commercializing sulfur polymer concrete technology invented, developed, and patented by Brookhaven National Laboratory (BNL) and a team of BNL scientists. (Corp., Green Sulfcrete, 2017) Sulfur polymer concrete (SPC) technology was originally developed in the 1970s, but was never mass commercialized as it required expensive modifiers to produce. The BNL process provided a way to replace the expensive modifier, enabling production of sulfur polymer concrete at costs comparable to those of traditional concrete. GSC intends to commercialize this technology as Sulfcrete™ sulfur polymer cement that can be sold to concrete manufacturers, thereby reducing demand for the more energy-intensive Portland cement. It should be noted that while GSC technology replaces cement in precast concrete, alternative processes, mainly re-melting of Sulfcrete cement pellets, are required to produce the precast concrete using GSC technology as compared to cement. Furthermore, due to the polymer material, Sulfcrete cement pellets are currently intended for use in concrete with non-structural applications, to eliminate the potential for fire exposure. These process distinctions are apparent in the process flow diagrams developed by NYSP2I representing both conventional precast concrete manufacturing (Appendix A) as well as precast concrete manufacturing using GSC technology (Appendix B).

C. Project Objective

The objective of this project was to estimate the GHG emissions reduction potential (ERP) associated with GSC's projected product use in New York State as compared to a conventional product or "baseline". To meet this objective, the following tasks were performed.

D. Work Performed and Results

Task 1. Identify the baseline and gather information on GSC/s technology, Sulfcrete

NYSP2I worked with GSC to establish a baseline product for comparison as well as a functional unit to normalize the analysis considering raw material extraction and manufacturing life cycle phases only. GSC indicated that their end market is precast concrete. While precast concrete would make an appropriate baseline, cement was instead chosen as GSC indicated that they did not have access to precast manufacturing data using their technology, which is required to complete an analysis. In addition, GSC noted that the concrete mixes used are variable and therefore it would be difficult to choose one concrete mix that would represent an average product. Considering these factors, cement was chosen as an alternative baseline. In fact, two baselines were considered: Portland cement as well as blended hydraulic cement to account for cement produced using supplementary cementitious materials (SCMs)[1]. The functional unit was identified as one ton of cement, which encompasses Portland cement and blended hydraulic cement, as well as sulfur polymer cement/ Sulfcrete cement pellets.

[1] Supplementary cementitious materials are natural materials or industrial byproducts that exhibit cementitious behaviors when combined with either water or water and other compounds. (NPCA, 2017)

Data sources for the baseline technologies included Environmental Product Declarations. An Environmental Product Declaration (EPD) is defined by the International Organization for Standardization (ISO) 14025 as a Type III declaration that "quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function", (ISO, 2022). EPDs are based on ISO 14040/44 compliant life cycle assessment (LCA) methodologies and are often published for products in the construction industry. For this analysis, industrywide average EPDs were used, considering data from across the United States and representing the average formulation and weighted values for inputs, such as energy source or clinker production technologies, where there might be many different factors impacting GHG emissions. This approach provides results that are representative of a large variety of manufacturers, proving advantageous as a baseline.

NYSP2I also worked with GSC to obtain pertinent information regarding the production of Sulfcrete cement pellets. To calculate GHG impact, NYSP2I needed information related to energy use throughout the raw material and production lifecycle phases of Sulfcrete cement pellets. To that end, GSC provided energy used in the production process, the amount of cement pellets produced for the given energy consumption, typical mix proportions and materials, shipping distances and methods for sourcing raw materials, and whether or not a material was a waste product. NYSP2I and GSC had several conversations regarding the variability in transportation distances, mix proportions, materials used, and market projections for sales in NYS. In cases where there was inherent variability, a conservative value was selected. The specific information provided by Sulfcrete, as well as assumptions made are explained in detail in Task 3.

Task 2. Quantify the GHG impact for baseline technology

For the Portland cement baseline, an industrywide average EPD was chosen as a conservative estimate of the impact of cement containing no SCMs (PCA, EPD, Portland Cement, 2022a). This industry-wide average represents cement with 91.4% clinker by weight and has a GHG impact of 922 kg CO2e/metric ton of cement. For the blended hydraulic cement baseline, an industry-wide average EPD was also used and provided information on a blended cement composed of 70.7% clinker by weight (PCA, EPD, Blended Hydraulic Cement, 2022b). This EPD also includes slag (10.7%), fly ash (6.0%) and other SCMs (<1.0% each) including anhydrites and pozzolans that are less commonly used and has a GHG impact of 742 kg CO2e/metric ton of cement. The analysis for the baseline included impacts associated with raw material extraction, transportation, and manufacturing, as shown in Figure 1.

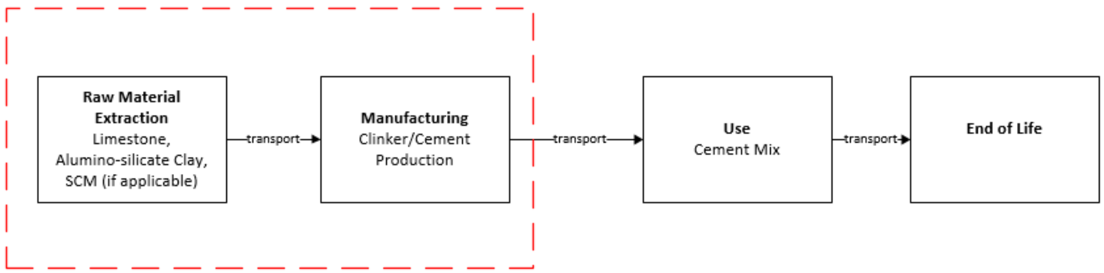


Figure 1: Analysis Boundary for *GHG ERP of* Baseline *Technology (Portland cement and blended hydraulic cement)*

Task 3: Quantify the GHG impact for GSC's technology Sulfcrete

GSC provided information regarding energy use, transportation, and materials needed to calculate the GHG impact of the raw material and manufacturing phases of their product, Sulfcrete cement pellets. Figure 2 shows the analysis boundary, and Table 1 summarizes the key pieces of information provided by GSC used to inform the assumptions in the analysis. Impacts were calculated for the raw material phase and the manufacturing phase separately, and then added for a total GHG impact.

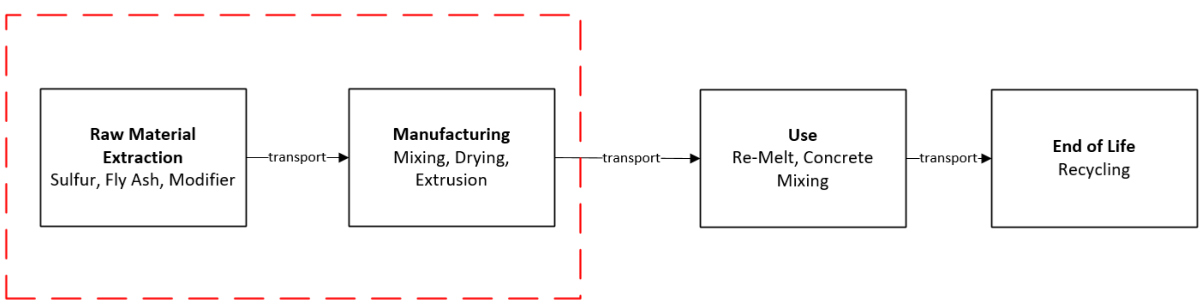


Figure 2: Analysis boundary for GHG ERP of Sulfcrete cement pellets

Table 1: Information provided by GSC for GHG ERP analysis

Component	Description	Value Provided by GSC
sulfur	waste product	20-40% by mass
coal ash	waste product	50-70% by mass
modifier	Similar to canola oil, refined, produced in Canada or US, does not need to be food grade. Also possible to use waste oil.	5% by mass
transportation of sulfur	insulated rail car	1,089 miles/1,753 km (Tampa, FL to Pennsylvania)
transport of ash	18 wheel tractor trailer	maximum 50 miles/ 81 km
transport of modifier	18 wheel tractor trailer	maximum 50 miles/ 81 km
production phase energy use	includes all processes (drying, extrusion, mixing) to produce 3-4 tons of Sulfcrete cement pellets	10 kWh

Raw Material Extraction Phase

Impacts associated with the raw material extraction phase for Sulfcrete cement pellets were calculated using information provided by GSC, publicly available emissions factors, and emissions factors from the ecoinvent Version 3 Database[2].

The use of sulfur and GSC's proprietary modifier is consistent in the production of Sulfcrete cement pellets. However, the nano-aggregates used (e.g., coal ash, slag), vary depending on the desired specifications and materials available. For purposes of this analysis, coal ash was selected as the nano-aggregate because it is one of the more commonly used nano-aggregates and is readily available to GSC. Based on the mix proportions provided by GSC, shown in Table 1, the mass of each of the three material components was defined for the production of one ton of Sulfcrete cement pellets as follows: 50 kg modifier (5% by mass), 550 kg coal ash (55% by mass), 400 kg sulfur (40% by mass).

Both sulfur and coal ash are sourced as waste products, therefore no environmental burdens were associated with the extraction of the materials. Because GSC's modifier is proprietary, GSC and NYSP2I agreed upon the best proxy material to use for the analysis. GSC noted that the oil modifier they use is very similar to a refined canola oil. NYSP2I identified rape seed oil in

[2] The ecoinvent Database is an internationally recognized, commonly used database containing many thousands of life cycle inventory (LCI) datasets. It is used by life cycle assessment professionals (LCACP) all over the world to access environmental impact data.

ecoinvent as a proxy, as it is made from the same plant as canola oil. The specific material selected was “Rape oil, crude {RoW}| market for | Cut-off, U”, a vegetable oil extracted from rape by means of cold-press extraction in an oil mill producing rape meal and crude oil. The process starts at the gate of the activities that produce crude rape oil, and ends with the supply of the oil to the consumers of the crude oil product. This process is representative of a global average, as indicated by {RoW}, and transportation impacts are not included. Simapro 9.2.0.2 software (PRé Sustainability, 2022) was used to calculate the global warming impacts of 50 kg of rape oil as 84.9 kg CO2e. Since GSC uses a refined oil as their modifier, and a refined rape oil process was not available in ecoinvent, the calculated value for crude rape oil was adjusted to account for the added impacts of refining processes. To do this, NYSP2I calculated the increase in impact between crude and refined oil for three oils that were available in ecoinvent: soybean, palm and cottonseed oil as 11%, 52%, and 56%, respectively. To be conservative, the highest increase of 56% was then applied to the calculated GHG impact of crude rape oil, to determine the total estimated GHG impact of the GSC modifier as 132.4 kg CO2e/ tonne Sulfcrete cement pellets and shown in Equation 1. GSC claims their product can also be manufactured using waste oils, and there are future plans to use this material. Should GSC replace virgin oil with waste oil in the future, the environmental burden associated with the modifier oil would be eliminated.

Equation 1: Calculation of GHG impact associated with modifier oil for Sulfcrete cement pellets

$$\frac{84.9\ kgCO2e}{50\ kg\ modifier} \times \frac{50\ kg\ modifier}{tonne\ pellets} \times 156\% = \frac{132.4\ kg\ CO2e}{tonne\ pellets}$$

<u>Transportation</u>

Because raw materials have to be transported to the manufacturing site, the impacts of transportation were also considered. Impacts associated with transportation for Sulfcrete cement pellets were calculated using information provided by GSC, and emissions factors from the ecoinvent Version 3 Database[3].

Using input from GSC, the transportation methods and distances of each material were defined and summarized in Table 1. Both the coal ash and modifier are sourced within 50 miles, or 81 km of the GSC manufacturing plant, and are transported by truck. The waste sulfur is sourced from

[3] The ecoinvent Database is an internationally recognized, commonly used database containing many thousands of life cycle inventory (LCI) datasets. It is used by life cycle assessment professionals (LCACP) all over the world to access environmental impact data.

Tampa, FL and is transported by insulated rail car to Pennsylvania, an approximate distance of 1,089 miles, or 1,753 km. Using this information, impact factors for transport were selected from ecoinvent.. For the goods transported by tractor trailer, the transport process selected from ecoinvent was “Transport, freight, lorry >32 metric ton, euro3 {RER}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U”, which resulted in an emissions factor of 0.092 kg CO2e/tkm. This process considers only the transport of the goods. The vehicle is assumed to operate on diesel fuel with an emission standard of EURO3. To account for the sulfur transported by railcar, a separate process was selected in ecoinvent: “Transport, freight train {US}| market for | Cut-off, U”, which resulted in an emissions factor of 0.057 kg CO2e/tkm. This process considers only the transportation of the goods, and assumes the vehicle operates with diesel, electricity or coal.

These emissions factors, along with the mass of each component, and distance traveled, were then used to calculate the total impact associated with transportation of the three materials as 44.5 kg CO2e/ tonne Sulfcrete cement pellets. These components and calculated impacts are summarized in Table 2.

Table 2: Summary of transportation components and calculated GHG impact for each

Material	Transport Method	Impact Factor (kg CO2e/tkm)	Mass (kg)	Distance (km)	Calculated GHG Impact (kg CO2e/ tonne pellets)
sulfur	insulated rail car	0.057	400	1,753	40.0
coal ash	tractor trailer	0.091	550	81	4.1
modifier	tractor trailer	0.091	50	81	0.4
					44.5

Manufacturing Phase

The GHG impact of the manufacturing phase was calculated based off the energy used to manufacture Sulfcrete cement pellets. GSC provided an energy use value of 10 kWh for 3-4 tons of pellets produced. This includes all manufacturing processes of mixing, drying, and extrusion, which are all powered by grid electricity. For a conservative approach, NYSP2I assumed three (3) tons of pellets were produced using 10 kWh. The impact factor of 697.5 lb CO2e/MWh was selected for this analysis, representing grid electricity impacts in Pennsylvania, where GSC’s pilot manufacturing plant is located. Using the impact factor, energy use, and material throughput, the impact of the manufacturing phase for Sulfcrete cement pellets was calculated to be 1.17 kg CO2e/ tonne pellets, as shown in Equation 2.

Equation 2: Calculation of GHG impact of manufacturing phase of Sulfcrete cement pellets

$$\frac{10\ kWh}{3\ tons\ pellets} \times \frac{697.5\ lb\ CO2e}{MWh} \times \frac{MWh}{1000\ kWh} \times \frac{kg}{2.2\ lb} \times \frac{1\ ton}{0.907\ tonne} = \frac{1.17\ kg\ CO2e}{ton\ pellets}$$

Total GHG impact for raw material and manufacturing phase of Sulfcrete cement pellets

The final step to calculating the impacts for Sulfcrete cement pellets was to sum the impacts calculated for the raw material and manufacturing phases. This resulted in a total GHG impact of 178 kg CO2e/ tonne pellets, as shown in Equation 3.

Equation 3: Calculation of total GHG impact of raw material extraction and manufacturing phases for Sulfcrete cement pellets

$$\frac{132.4\ kg\ CO2e}{tonne\ pellets} + \frac{44.5\ kg\ CO2e}{tonne\ pellets} + \frac{1.17\ kg\ CO2e}{tonne\ pellets} = \frac{178\ kg\ CO2e}{tonne\ pellets}$$

Task 4: Calculate the GHG emissions reduction potential (ERP) for GSC's Sulfcrete

The GHG ERP of Sulfcrete cement pellets was calculated by subtracting the GHG impact of Sulfcrete cement pellets from the GHG impact of the baseline. Since two baselines were considered – Portland cement, and a blended hydraulic cement, GHG ERP was calculated in comparison to both, and presented as a range: 564 – 744 kg CO2e/ tonne pellets. These calculations are shown in Equation 4 and Equation 5 below.

Equation 4: GHG ERP of Sulfcrete cement pellets compared to Portland cement

$$\frac{922\ kg\ CO2e}{tonne\ portland\ cement} - \frac{178\ kg\ CO2e}{tonne\ pellets} = \frac{744\ kg\ CO2e}{tonne\ pellets}$$

Equation 5: GHG ERP of Sulfcrete cement pellets compared to blended hydraulic cement

$$\frac{742\ kg\ CO2e}{tonne\ blended\ hydraulic\ cement} - \frac{178\ kg\ CO2e}{tonne\ pellets} = \frac{564\ kg\ CO2e}{tonne\ pellets}$$

Next, the total annual GHG ERP was estimated, using the projected market volume for NYS. GSC expects to be able to work with at least two of the 28 precast companies in NYS in year one, and that these businesses will use Sulfcrete cement pellets to replace 20% of the 100,000 tons of cement used annually. Based on these numbers, GSC expects that approximately 40,000 tons (36,287 tonnes) of their Sulfcrete cement pellets will be used in NYS annually, displacing an equivalent amount of cement as shown in Equation 6 below. Using the per unit GHG ERP calculated above, this sales volume translates to a total annual GHG ERP of between 20,466 tonne - 26,998 tonne CO2e as shown in Equation 7 and Equation 8 below.

Equation 6: Calculation of projected annual sales volume of Sulfcrete cement pellets in NYS

$$\frac{100{,}000\ tons\ cement}{precaster \cdot yr} \times 20\% \times \frac{2\ precasters}{New\ York\ State} = 40{,}000\frac{ton}{yr} = 36{,}287\frac{tonne}{yr}$$

Equation 7: Calculation of annual GHG ERP of Sulfcrete cement pellets compared to blended hydraulic cement

$$\frac{564\ kg\ CO2e}{tonne\ pellets} \times \frac{36{,}287\ tonne}{yr} = 20{,}466\ tonne\ CO2e/yr$$

Equation 8: Calculation of annual GHG ERP of Sulfcrete cement pellets compared to Portland cement

$$\frac{744\ kg\ CO2e}{tonne\ pellets} \times \frac{36{,}287\ tonne}{yr} = 26{,}998\ tonne\ CO2e/yr$$

<u>Additional potential benefits of Sulfcrete</u>

GSC provided information to NYSP2I about the claimed benefits of their product, which NYSP2I reviewed. Then, NYSP2I looked into publicly available literature to corroborate these benefits and to note additional potential benefits of sulfur polymer concrete as compared to conventional concrete. The benefits listed here are not exhaustive, but rather a selected list of some of the main potential benefits. The examined literature discussed characteristics of sulfur polymer concrete in general. Characteristics of various sulfur polymer concretes vary based on composition of the concrete, the material(s) used as the modifier, and other factors. Therefore, except where noted, the potential benefits listed here pertain to sulfur polymer concrete in general, rather than GSC's product specifically.

Potential benefits of sulfur polymer concrete, as compared to conventional concrete, include:

- **Improved structural properties:** Sulfur-based concrete has been found to have a higher compressive, flexural, and tensile strength than ordinary Portland Cement-based concrete (Fediuk, et al., 2020) (Gulzar, Rahim, Ali, & Khan, 2021) (Moon, Kalb, Milian, & Northrup, 2016) (Mohamed & Gamal, 2007). In addition, sulfur-based concrete has several properties that indicate better durability, including higher fatigue resistance, lower compression creep, and low shrinkage (Fediuk, et al., 2020).[4]

- **Increased resistance to water, frost, acids, and salts:** Sulfur-based concrete is more impermeable to water than regular concrete. This, along with other factors, contributes to a greater resistance to frost, acids, and salts (Fediuk, et al., 2020) (Gulzar, Rahim, Ali, & Khan, 2021).

- **Reduced water consumption:** Conventional precast concrete requires over 2,000 liters of water to produce one ton of concrete. Most of this water is used when the cement, aggregates, water, and other materials are blended together to produce the concrete (Athena Sustainable Materials Institute, 2019). In contrast, Sulfcrete's cement pellets can be melted and blended directly with the heated aggregates, without any water.

- **Faster cure time**: Sulfur-based concrete achieves most of its mechanical strength in less than one (1) day, with no specific temperature and moisture requirements (Mohamed & Gamal, 2007) (Fediuk, et al., 2020). In contrast, conventional concrete needs 28 days to attain most of its mechanical strength, and requires hydration for those 28 days (Fediuk, et al., 2020).

- Lower resistance to alkaline environments, microbial corrosion, and fire (Fediuk, et al., 2020) (Gulzar, Rahim, Ali, & Khan, 2021).

---

[4] The exact strength values of sulfur-based concrete depend on the composition, including the concentration of aggregate (Fediuk, et al., 2020). Furthermore, low-temperature creep of sulfur-based concrete can be higher or lower than regular concrete, depending on the formulations and conditions (Fediuk, et al., 2020).

E. Conclusions and Next Steps

The objective of this project was to estimate the GHG emissions reduction potential (ERP) associated with GSC's projected product use in New York State as compared to a conventional product.

The analysis resulted in a greenhouse gas emissions reduction potential (GHG ERP) of 564 – 744 kg CO2e/ tonne pellets, and an annual estimated GHG ERP between 20,466 tonne - 26,998 tonne CO2e/ year. The analysis also revealed that the use of GSC's proprietary modifier as well as transportation distances were the main contributors to the GHG impact of the Sulfcrete products. GSC is working on developing new partnerships and scalable processes for using waste oils in their product manufacturing, which would decrease the GHG ERP further. GSC may pursue another GHG ERP assessment at a future time if any product component significantly changes.

The estimated GHG emissions impacts calculated by NYSP2I at RIT are based on information and claims provided to NYSP2I by GSC relative to their product and the baseline technology. It should be noted that this analysis considered the raw material extraction and production phases only and did not consider use, distribution, or end-of-life life cycle phases. It should also be noted that the results are an order of magnitude estimate of the GHG ERP of the GSC Sulfcrete cement pellets. GSC may consider updating the GHG ERP analysis if any components, including modifier source, or transportation distances for material components, change significantly.

F. Appendix

Appendices A and B are included, showing the high level steps of how the baseline cements and the Sulfcrete cement pellets are used to produce concrete.

- Appendix A – Concrete Production Using Portland Cement
- Appendix B – Concrete Production Using Sulfcrete Cement Pellets

References

Athena Sustainable Materials Institute. (2019). *An Industry Average Cradle-to-Gate Life Cycle Assessment of Precast Concrete Products for the US and Canadian Markets.* West Conshohocken, PA: ASTM International.

Corp., Green Sulfcrete. (2017, April 20). *Sulfcrete Business and Commercialization Plan.*

Fediuk, R., Amran, M. Y., Mosaberpanah, M. A., Danish, A., El-Zeadani, M., Klyuev, S. V., & Vatin, N. (2020). A Critical Review on the Properties and Applications of Sulfur-Based Concrete. *Materials*, 1-23. doi:10.3390/ma13214712

Gulzar, M. A., Rahim, A., Ali, B., & Khan, A. H. (2021). An investigation on recycling potential of sulfur concrete. *Journal of Building Engineering*, 1-9. Retrieved from https://doi.org/10.1016/j.jobe.2021.102175

ISO, I. S. (2022, December 15). *ISO 14025:2006(en) Environmental labels and declarations — Type III environmental declarations — Principles and procedures*. Retrieved from ISO Online Browsing Platform: https://www.iso.org/obp/ui/#iso:std:iso:14025:ed-1:v1:en

Mohamed, A.-M. O., & Gamal, M. E. (2007). Sulfur based hazardous waste solidification. *Environmental Geology*, 159-175. doi:10.1007/s00254-006-0631-4

Moon, J., Kalb, P. D., Milian, L., & Northrup, P. A. (2016). Characterization of a sustainable sulfur polymer concrete using activated fillers. *Elsevier*, 20-29. Retrieved from http://dx.doi.org/10.1016/j.cemconcomp.2015.12.002

NPCA. (2017, March 13). *SCMs in Concrete*. Retrieved from National Precast Concrete Association, NPCA: https://precast.org/2017/03/scms-in-concrete/

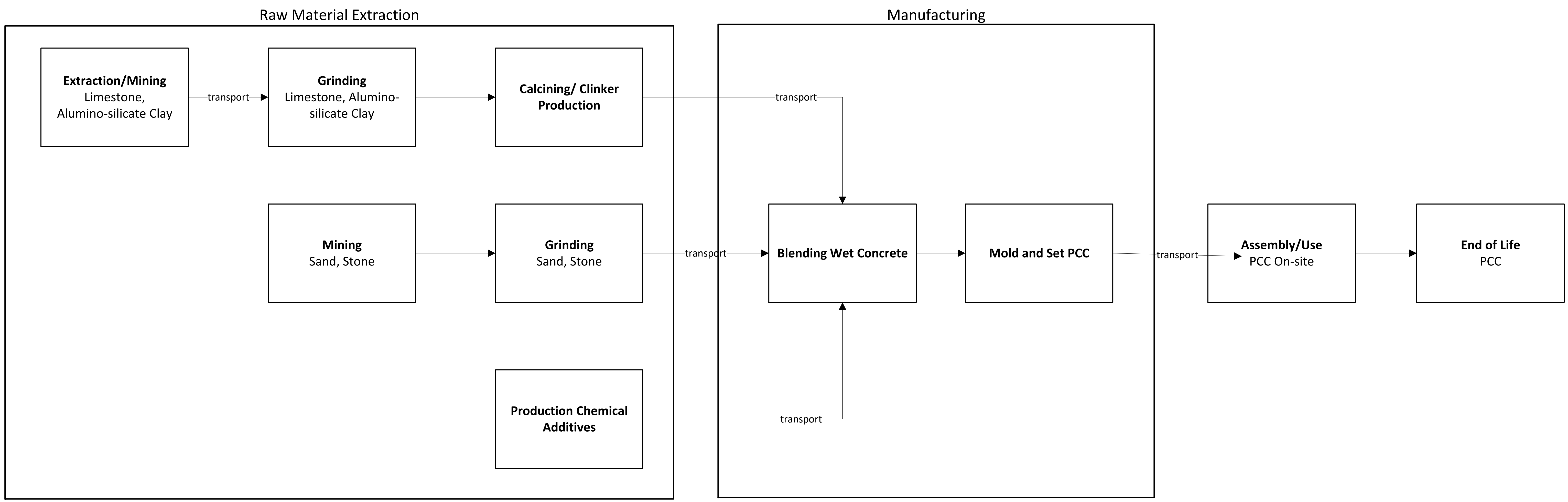
PCA, P. C. (2022a, December 15). *EPD, Portland Cement.* Retrieved from PCA, America's Cement Manufacturer's: https://www.cement.org/docs/default-source/epds/pca_epd_portland_athena_final_revised_04082021.pdf?sfvrsn=3e4affbf_2

PCA, P. C. (2022b, December 15). *EPD, Blended Hydraulic Cement.* Retrieved from PCA, America's Cement Manufacturer's: https://www.cement.org/docs/default-source/epds/pca_epd_blendedhydraulic_athena_final_revised_01312022.pdf?sfvrsn=4a4affbf_2

PRé Sustainability. (2022). SimaPro 9.2.0.2. the Netherlands.

Appendix A - Concrete Production using Portland Cement

February 3, 2023



Appendix B – Concrete Production Using Sulfcrete Cement Pellets

February 3, 2023