Life cycle assessment of crushed glass abrasive manufacturing from recycled glass

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Abstract. Sustainable Development Goals (SDGs) are the key motivation factors to determine the characteristics of green abrasives, contributing to carbon emissions reduction, reduce waste generation and build up a recycling-based sustainable blasting industry. Such aim can be evaluated through life cycle assessment as a structured basis for evaluating the performance of environmental impacts and benefits of green abrasives application in blasting industry. Crushed glass is one of zero free silica content abrasives from recycled glass, and it is widely used due to inert and safe characteristics. Database of life cycle inventory (LCI) are obtained through literature review. Production of 1 ton/year of crushed glass abrasives has been modelled at gate-to-gate boundary where the human health appears as the major impact potentials (0.71 DALY, disability-adjusted life year) at the production stage. The selection of 100% recycled glass as the raw materials in the supply chain has led to insignificant impact potentials of resources scarcity and ecosystem damages per unit production of 1 ton of crushed glass at USD 4.79 and 0.06 species, year, respectively.

Keywords: Life cycle assessment; crushed glass abrasive; glass cullet; intermediate glass processing; gate-to-gate

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1. Introduction

The first Life Cycle Assessment (LCA) has gained global attention, progressively as the awareness on the environmental protection rises. Businesses and scientists use LCA as a qualitative and comprehensive tool to analyze the environmental impacts of a product along its supply chain [1]. A life cycle assessment generally comprises four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation [2]. While it depends on the system boundary, impacts of a product can be assessed from the phase of raw material acquisition,
through product manufacturing process, logistic distribution until the recycling or end-of-life disposal [3]. This systematic approach on products and services can provide a big picture on sustainability for businesses and industries to consider the health and environmental impact caused by their business activities [4,5]. LCA is useful to allow strategic planning for further environmental performance improvement contributing to effective marketing, policymaking and product development [2].

Glass is a material that can be found anywhere and is widely used in our everyday life. Glass can be easily sourced as it is made from silicon, the second most common element on earth [6]. It exists in the form of containers, such as bottles, food container jars, cosmetics and other products; or to be used in the industries for construction or manufacturing of electronics, automation, etc. Mass production will generate enormous amount of waste. In 2018, the United States has generated 12.3 million tons of glass waste, contributing to 4.2% of total municipal solid waste generation [7]. Therefore, recycling of glass is highly encouraged to avoid waste disposal to landfills [8].

After the realization of the glass recycling opportunity, companies such as Strategic Materials, Inc. and N.T. Ruddock Co., Inc. began to create business using recycled glass as the key product [9,10]. The recycled glass is processed into crushed glass for various uses depending on its coarseness. One of the usable end products is crushed glass abrasive. It has been recommended as alternative abrasive media due to it environmentally friendly features, generates less dust while performing higher cleaning rate [11]. However, less studies on the environmental performance of crushed glass abrasives is documented, hence, this work will serve as a precursor for evaluating the performance of environmental impacts of crushed glass abrasives application in blasting industry.

The objective of this study is to quantify the potential environmental impact associated with the production of crushed glass abrasive manufactured from recycled glass production through gate-to-gate life cycle assessment.

2. Methodology

2.1. Data Collection

Secondary data from literature or other published documents are the main source of data for Life Cycle Inventory (LCI) using the relevant keywords like “glass cullet”, “glass recycling” “glass abrasive” and “life cycle assessment”. Articles, books, journals, thesis from various web-based resource including ResearchGate, Elsevier, Google Scholar, Science Direct are reviewed. Other private company consulting report or government agency report which are relevant to glass abrasive production are studied too. Note, as well, the energy consumption and water quality impact of glass container recycling information is retrieved from Ching-Ling Tsai et al., 2010 [13]. Life cycle impact assessment (LCIA) was carried out using SimaPro software. The impact potentials are quantified using ReCiPe

Figure 1. Phases of LCA and Applications. Source: ISO (2006a)
2016 Endpoint (E) V1.04 method, followed by simplification of the impact categories into three main areas namely, human health, ecosystem damages and natural resources depletion.

2.2. **Functional Unit**
The product system to be evaluated in this study is the production of 1 ton/yr of crushed glass abrasives based on the United States database.

2.3. **Goal and Scope**
The goal of this LCA study is to conceptualize the environmental performance of the crushed glass abrasive process for decision support at micro level of which will not cause any structural changes in the system. The result will serve as supporting knowledge towards better sustainable crushed glass production management [12].

The boundary system LCA study focuses on the gate-to-gate life cycle. The assessment comprises overall intermediate cullet processing at cullet manufacturing stage encompasses processes such as crushing, screening, contaminant removal and packaging. Note, the transportation to primary or secondary consumer is beyond the scope of this LCA study. Presumably, the location of cullet processing factory is in United States based on the available inventory input data.

3. **Assumption and Life Cycle Inventory**
Assumption is made to scope and specify the inventory analysis. Quantity of input and output are determined based on literature database. Although in the real case scenario, the material input can be various type of glass including color sorted container glass, windshield, windows, mix container glass, borosilicate, automotive glass, etc. either from curbside or collected from suppliers, but in this study, it was narrowed down by assuming to be sorted glass cullet from general waste glass.

Figure 2 shows the conceptual of product system of 1000 kg of 3-mix-processed crushed glass abrasive comprises the material (crushed glass, kraft paper) energy (natural gas) and elementary flow (water etc) along with the product (crushed glass abrasive) as well as the impact potentials results from the Life Cycle Impact Analysis (LCIA). The unit processes are important for LCA to model the impact of crushed glass abrasive production at gate-to-gate life cycle stage.

![Figure 2. Product system of 1000 kg of 3-mix-processed crushed glass abrasive.](image-url)
The operating process is simplified into four major processes i.e., crushing, screening, contaminant removal and packaging (Figure 3). These are the main process in intermediate cullet processing. The energy consumed for glass cullet processing is in the form of electricity considering no combustion or melting processes involved. Presumably, the type of energy for electricity generation is from natural gas considering that it is the largest energy source (38%) in United States. Note, in this study, consideration on fuel consumption is given only for skid-steer loader to transport cullet within the plant. As well, the paper used for packaging is supposed at 300g paper per standard size of 22.68 kg glass abrasive. Hence, it is estimated that about 13.2 kg of paper is used per 1000 kg of glass abrasive packaging. Furthermore, it is estimated that 26.75% of glass input will be discarded in the form of glass particles and rejected glass cullet. Another 3% of the waste is identified as non-glass waste such as paper, organics, metal contaminant and ferrous contaminants[14]. Table 1 shows the inventory input and output selected based on literature study for SimaPro life cycle impact assessment.

![Figure 3. Life Cycle Inventory (LCI) flowchart.](image-url)
Table 1. Inventory Input and Output selected in SimaPro.

| Products                                      | Amount       |
|-----------------------------------------------|--------------|
| 3-mixed crushed glass abrasive                | 1000 kg      |
| Input                                         |              |
| Glass cullet, sorted {RoW}                    | 1344.3 kg    |
| Kraft paper, bleached                         | 13.2 kg      |
| Electricity sourced from natural gas          | 35.56 kWh    |
| Excavation, skid-steer loader                 | 1 m³         |
| Output                                        |              |
| Particulates < 10 um                          | 267.5 kg     |
| Carbon dioxide                                | 0.062 kg     |
| Metal waste                                   | 15 kg        |
| Packaging waste, paper and board              | 2 kg         |
| Waste, inorganic                              | 15 kg        |

4. Limitation

All data sources are literature-based data. Note, the data may not be as accurate compared to primary data which measured directly from the processes without much spatial or time differences. In addition, the database in Simapro is generic, but still useful in conceptualizing the impact potentials of the product system.

5. Results and Discussion

5.1. Life Cycle Impact Assessment (LCIA)

The impact categories are selected based on total impact value of $1 \times 10^{-4}$ or higher followed by normalized impact into the three indicators: human health (disability-adjusted life year (DALY)), ecosystem damage (species. year) and resources scarcity (USD 2013). In general, one DALY represents the loss of equivalent of one year of full health. DALY is used to measure impact towards human health categories. The ecosystem damage is described as the number of species disappear in a year (Species. year). While the USD 2013 expressed as the surplus costs of future resource production (assuming constant annual production), considering a 3% discount rate in USD unit.

The characterization of LCIA for production of 1000 kg crushed glass abrasive was observed at the mid-point level where climate change, toxicity, particulate, fossil resources and mineral resources appear as the major contributor to the product’s environmental footprints (Table 2). Moreover, the selection of 100% recycled glass as the raw materials for the supply chain of crushed glass abrasives has led to impact potentials of resources scarcity per unit production of 1 ton of crushed glass, estimated at USD 4.79. In addition, surplus cost potentials of fossil resources at USD 29.30 may suggest the opportunity for the industry to switch to renewable energy-based operations, thus, potentially, the USD 29.30 may be reduced.
Table 2. Characterization of LCIA for production of 1000kg crushed glass.

| Impact Category                        | Unit            | Total     | 3-mixed crushed glass abrasive | Glass cullet input | Kraft paper | Natural gas | Excavation, skid-steer loader |
|---------------------------------------|-----------------|-----------|--------------------------------|--------------------|-------------|-------------|-------------------------------|
| Global warming, human health,         | DALY            | 7.17E-3   | 7.75E-7                        | 6.85E-3            | 2.23E-4     | 9.80E-5     | 6.28E-6                       |
| Fine particulate matter formation     | DALY            | 8.00E-4   | -                              | 7.65E-4            | 3.38E-5     | 1.46E-6     | 9.07E-7                       |
| Human carcinogenic toxicity           | DALY            | 1.67E-2   | -                              | 1.65E-2            | 1.99E-4     | 5.27E-6     | 2.56E-6                       |
| Human non-carcinogenic toxicity       | DALY            | 3.87E-2   | -                              | 3.79E-2            | 7.53E-4     | 1.74E-5     | 3.93E-6                       |
| Mineral resource                      | USD2013         | 4.79      | -                              | 4.78               | 0.0128      | 4.24E-4     | 2.23E-4                       |
| Fossil resources                      | USD2013         | 29.3      | -                              | 26.4               | 1.69        | 1.15         | 7.14 E-2                      |

Though, when it was normalized to the end-point results (Table 3), it showed that the health is the most pronounced impact (0.71 DALY). Given the fact that the raw material is 100% recycled glass, hence it shows almost no impact for ecosystem damage (0.06 species.year) and resource scarcity (0.00). It is depicted that the glass cullet is the main contributor to potential impact of human health, ecosystem damage and resources followed by paper (orange color) for packaging (Figure 4). Note, the packaging is considered as an ideal packing material due to its recyclable feature too. Based on the input-output determined at inventory phase, the production of crushed glass abrasive using 100% recycled glass is safe and environmentally friendly. Study has showed that at manufacturing stage, energy and emissions are reduced significantly when the recycled glass become the option as material for production [15]. Note, however, in this study, the results limit to gate-to-grave boundary.

Table 3. Normalization data of LCIA to produce 1000 kg 3-mixed crushed glass abrasive.

| Damage Category   | Total    | 3-mixed crushed glass abrasive | Glass cullet input | Kraft paper | Natural gas | Excavation, skid-steer loader |
|--------------------|----------|--------------------------------|--------------------|-------------|-------------|-------------------------------|
| Human Health       | 0.710    | 8.68E-6                        | 0.695              | 0.0136      | 1.37E-3     | 1.53E-4                       |
| Ecosystem          | 6.05E-2  | 1.84E-6                        | 5.89E-2            | 1.32E-3     | 2.46E-4     | 1.94E-5                       |
| Resources          | 1.21E-3  | 1.11E-3                        | 6.08E-5            | 4.10E-5     | 2.56E-6     | 2.56E-6                       |
In addition, for every 10% of glass cullet used for crushed glass production, potentially, carbon emissions and energy consumption are reduced by 5% and 3% respectively. The used of glass cullet as raw materials will avoid the melting process, hence, reduces carbon emission [16]. In fact, if compare with the common copper slag abrasive, the crushed glass abrasive performs equally, produce a cleaner result than black colored copper slag with less risk of heavy metal and toxic pollutants. As well, NIOSH has categorized the glass dust as only "nuisance" dust because it contains less than 0.1% free silica [16]. The life cycle CO₂ emission assessed in previous study shows glass abrasive have emission of 19 kg CO₂/tonne lower than the emission for copper slag [17]. The emission of recycled glass varies depending on its application. In the case of shot blast abrasive application, the emission is relatively low compared to remanufacturing of glass containers and filtration [13].

As reported in the Circularity Gap Report 2021, in 2020, human activities have triggered global warming of 1.1 °C. The rise is expected to hit 3.2 °C this century under current trajectory. The world needs to increase the circular economy from 8.6% to 17% to halt global warming [18]. One of the main aspects of circular economy is using waste as secondary resource through reuse and recycling. That way it will maximize the uptake of circular materials in consumables that close loops and boost value in secondary markets. Crushed glass abrasive application in blasting industry can be one of the circular economy initiatives. The use of recycled-based abrasive is in line with the Sustainable Development Goals 12, responsible consumption and production. -reducing waste generation through prevention, reduction, recycling and reuse, thus, increase circulatiry of the recycled glass in value chain (circular economy).

6. Conclusion

Production of 1 ton/year of crushed glass abrasives has been modelled at gate-to-gate boundary where the human health appears as the major impact potentials (0.71 DALY) at the production stage. The selection of 100% recycled glass as the raw materials in the supply chain has led to insignificant impact potentials of resources scarcity and ecosystem damages per unit production of 1 ton of crushed glass at USD 4.79 and 0.06 species. year, respectively. This work provides first order impact potentials assessment on crushed glass abrasive manufacturing.

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