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Economic and life cycle assessment of recycling municipal glass as a pozzolan in portland cement concrete production

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ABSTRACT

The environmental and economic qualities associated with processing recycled glass cullet recovered from a municipal solid waste (MSW) materials recovery facility (MRF) into glass powder (GP) to be used as a pozzolanic material in the production of portland cement concrete were assessed. Through an evaluation of life cycle impacts and system costs, the feasibility of a potential pozzolan market was evaluated in comparison to the two most common management strategies for recycled glass cullet: (1) traditional recycling into new glass containers, and (2) disposal to a landfill (including potential use as landfill depression fill material). The investment of a MRF in a GP processing system became feasible if at least 50,000 metric tonnes (tonnes) of cullet were processed annually (based on a 10-year lifespan and 4500 h per year plant operating time). At this annual throughput capacity, a MRF could achieve a processing cost capable of producing GP at a cost competitive with the current retail value of Class F coal fly ash, another known pozzolan. GP processing costs decreased as annual cullet throughput increased. The feasibility of such a GP pozzolan market was further analyzed through an applied case study of MRF cullet availability in North Central Florida, USA.

1. Introduction

In the municipal waste recycling industry, recovered glass containers from residential and commercial recycling operations have provided a consistently low market value relative to other recovered materials (Dhir and Lymbachiya, 2001). Some municipalities have elected to no longer include glass in their residential recycling programs, while others pay for its disposal (Ng, 2015). The most common recycling market for glass recovered from a municipal materials recovery facility (MRF) is to provide cullet (recycled crushed glass) to a facility that utilizes it as a virgin material replacement in the manufacturing of new glass containers. Some other less common applications for processed cullet include use as raw materials in fiberglass manufacturing, paint fillers, sandblasting media, and aggregate material (Chen et al., 2002). Recycled cullet not recovered for glass container manufacturing (due to unsuitable sizing, contamination, or market conditions) is often disposed of in a landfill as residue (Dhir and Lymbachiya, 2001).

In recent years, several investigators have examined the potential to use size-reduced glass as a pozzolanic material to partially replace portland cement in concrete manufacturing, with the belief that such an application could provide economic and environmental benefits (Shayan and Xu, 2006). Glass which is processed to a fine powder to an average particle size below 20 μm is reactive when combined with portland cement (Ferraro et al., 2017). Shi et al. (2005) found that the partial replacement of portland cement (PC) with glass powder (GP) reduced alkali-aggregate reaction (AAR) induced expansion in concrete. Ferraro et al. (2017) discovered that 20% replacement of portland cement with GP resulted in higher resistivity values, which contributed to improved durability characteristics. Shayan and Xu (2006) similarly concluded that GP could replace between 20% to 30% of cement in 40 MPa concrete without causing detrimental effects. Furthermore, it was determined that partially replacing portland cement with 20% GP could develop higher compressive strength in concrete at 28 days in comparison to no replacement (Shi et al., 2005; Ferraro et al., 2017). The ability of glass, a low market-valued commodity, to achieve conventional concrete durability and strength requirements when utilized as a pozzolan leads to the inquiry of whether this application could be economically feasible on a larger scale.

In addition to meeting conventional concrete strength requirements, Jiang et al. (2014) found through a life cycle assessment (LCA) that environmental impacts (e.g., carbon emissions and energy usage) from conventional concrete production were reduced when GP was included as a pozzolanic material. The use of GP as a partial replacement of

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portland cement in concrete results in mixture designs that require lower cement content, and use less energy as the energy consumption associated with grinding recycled glass to a powder form offsets the energy saved from less fuel combustion occurring in cement manufacturing kilns, thus making GP usage in concrete production more environmentally favorable.

The overall purpose of this research was to assess the feasibility of processing and subsequently marketing recycled glass for use as a pozzolan in the portland cement concrete industry in comparison to the two most common systems of current cullet management: (1) traditional recycling into new containers and (2) disposal to a landfill. This feasibility was further examined in the context of a case study for glass recycling in North Central Florida, USA.

2. Feasibility analysis

Both environmental and economic factors were considered as part of the feasibility analysis of further processing recycled municipal solid waste (MSW) MRF cullet into glass powder for use as a pozzolan to partially replace portland cement in concrete manufacturing. The results of a previously conducted LCA study (Jiang et al., 2014) for GP concrete were further analyzed to depict the application's positive environmental impacts through carbon emission and energy use reductions in concrete manufacturing. Similarly, the Jiang et al. (2014) study was used to compare GP concrete's environmental impact values to those associated with traditional cullet recycling into new glass containers and landfill disposal. An economic comparison of each system was conducted through evaluation of known costs associated with the current management strategies (traditional recycling and landfilling) and application of a cost analysis estimation of potential GP pozzolan processing costs based on annual cullet throughputs in USD per metric tonne (tonne).

2.1. Systems definition

Household recyclables in the USA are typically collected by recycling trucks through either a single-stream or dual-stream recycling system. In a single-stream system, all recyclable materials (e.g., paper, plastic, glass, metal) are commingled in a single container. In a dual-stream system, fiber materials such as newspaper and cardboard are separated from recycled containers including plastic, glass and metal products to create two separate material streams. These two material streams are transported to MRFs for further materials separation and preparation for end-user product manufacturers. Currently, most cullet recovered from MRFs is recycled in the production of new glass containers (GPI, 2016a). Otherwise, MRF cullet not traditionally recycled into new containers is most often disposed of in landfills (Dhir and Lymbachiya, 2001). The aforementioned two most common management systems for recovered MRF cullet were compared to a third potential system where cullet is size-reduced on-site at a MRF to a powder form for reuse as a pozzolanic material in concrete production. For purposes related to this study, all three systems were evaluated starting from the point where recycled glass is recovered from a MRF processing line (see Fig. 1).

2.1.1. National glass statistics

Of the 230 million tonnes of MSW generated in the United States in 2013, 80 million tonnes were recovered through either recycling (75% of recovered waste) or composting (25% of recovered waste) (USEPA, 2014). Glass accounted for approximately 3.6%, or approximately 3 million tonnes, of the waste recovered (for this exercise, glass was assumed to be recovered solely through recycling and not composting), implying that 3.0 million tonnes of glass were sent to MRFs nationwide in 2013. In 2012, approximately 736 MSW MRFs were reported to be operating in the USA, with roughly 52% operating as dual-stream and 33% as single-stream (Gershman and Bratton, 2015; Kessler Consulting, 2009). The landfilling rates for single-stream and dual-stream recycled glass were 40% and 10%, respectively (CRI, 2009). Higher glass breakage and cross-contamination rates occur during single-stream processing, generating larger quantities of unmarketable lower-quality cullet which accounts for its significantly higher landfilling rate (GPI, 2014). Applying 2012 figures, it is estimated that approximately 160,000 t of dual-stream and 400,000 t of single-stream recycled glass, or at least 560,000 total tonnes of recycled glass, were landfilled in the United States in 2013, accounting for roughly 20% of the total recycled glass recovered from the MSW stream.

This landfilling rate implies that approximately 2.5 million tonnes of recycled glass containers were actually recovered for recycling into new glass containers. According to the Glass Packaging Institute, 80% of all recycled glass containers recovered by MRFs are used in the manufacturing of new glass containers (GPI, 2016b). Therefore, 2.0 million tonnes of recycled glass containers were estimated as used in manufacturing new marketable glass containers nationally in 2013.

2.1.2. System #1: traditional container recycling

Traditional glass recycling involves recovered MRF cullet being sent to a glass processing facility for further contamination removal (e.g., paper by air jets, metals by magnets or eddy current separators), crushing for size uniformity (maximum 19 mm), and color sorting (e.g., clear, green, and amber) by means of optical sorters (GPI, 2016b). Processed cullet is then sent to a glass container manufacturing facility where it is first combined with other raw materials such as sand, soda ash and limestone, then melted in a furnace and eventually molded into new glass containers ready for market distribution. Recycled glass can substitute up to 95% of raw materials used in the manufacturing of glass containers (GPI, 2016a).

Recovered MRF cullet is typically contaminated and not color-sorted making it of low quality, and therefore, of low value. Mixed color cullet consisting of commingled flint (clear), green and amber (brown) glass is referred to as '3-mix.' Low-grade 3-mix cullet currently has a negative market value of approximately $-20/tonne and considered unprofitable (Recycling Markets Limited, 2016). Contrastingly, the reported current average commodity values for processed and separated flint, amber and green cullet are $33/tonne, $30/tonne and $14/tonne, respectively. Glass processing companies are typically unwilling to pay for 3-mix due to its negative market value, and as a result, MRFs are losing money on this commodity. For example, twenty years ago, Strategic Materials Inc. (SMI) – the largest private glass processor in North America – paid MRFs for their recovered recycled glass as incoming truckloads contained 98% glass with only 2% contamination (Ng, 2015). However, due to increasing contamination rates over the years as a result of many MRFs shifting from dual-stream to single-stream recycling, SMI's incoming material contamination rate is currently closer to 50% (Ng, 2015). This higher contamination rate has caused SMI to invest in more expensive sorting equipment to separate out non-glass materials, and in turn, has increased its residue disposal cost. To offset the costs of new equipment and increased disposal rates, SMI now charges MRFs $11 to $44 per tonne for their contaminated cullet (Ng, 2015).

2.1.3. System #2: landfill disposal

A MRF may dispose of its recovered glass as residue in a landfill if it is economically more favorable than participating in a traditional glass container recycling market. When a MRF landfills its cullet as residue, there is an associated transportation cost, additional labor and administration costs, and a possible landfill tipping fee in addition to the MRF's standard materials processing and equipment costs. In 2013, the average national MSW landfill tipping fee in the USA was approximately $55 per tonne of material disposed (USEPA, 2014). A MRF typically incurs both a transportation cost and a landfilling fee when under different ownership than the landfill receiving its residue.

Some MRFs send their low-quality cullet to operating landfills for

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