The functional and environmental performance of mixed cathode ray tubes and recycled glass as partial replacement for cement in concrete

Brian Hilton⁎, Kimberly Bawdenb, Kathryn Winnebeckb, Chathurani Chandrasiric, Erandi Ariyachandrac, Sulapha Peethamparancc

a Golisano Institute of Sustainability at Rochester Institute of Technology, Rochester, NY, USA
b NYSPollution Prevention Institute at Rochester Institute of Technology, Rochester, NY, USA
c Clarkson University, Potsdam, NY, USA

ARTICLE INFO

Keywords:
Pozzolan
Concrete
Life cycle assessment (LCA)
Cathode ray tube (CRT)
Recycle
Glass

ABSTRACT

Concrete is one of the most abundantly produced and commonly used construction materials in the world. The production of cement—the main binder in concrete—is energy-intensive, using roughly ten times the national average ratio for energy to gross output of goods and services. Given the high demand for concrete globally and the amount of energy used to produce cement, it is worthwhile to find lower embodied-energy materials to partially replace cement to improve the environmental impacts of concrete without decreasing the concrete performance. One such potential cement replacement is the panel glass found in discarded cathode-ray tubes (CRTs). It is against this backdrop that this study aimed to investigate the technical feasibility and the environmental impacts of using a novel blend of recycled glass and CRT panel glass as Pozzolanic material for replacing a portion of ordinary portland cement (OPC) in concrete. Additionally, this study simultaneously looked at the concrete functional performance and environmental impact, and the study was performed at an industrial scale using existing production infrastructure, production volumes, standardized testing, and a life-cycle assessment (LCA) to support the functional testing and environmental impact quantification. Results show that the novel blend of glass met the required performance standards, and when it was blended with cement, the mixture produced concrete with similar or improved functional performance and significantly reduced environmental impacts across all examined impact categories. Future work is needed to examine the additional benefits of diverting CRTs from their current end-of-life pathways and de-risking CRT storage.

1. Introduction

According to the United States Geological Survey (USGS), the U.S. cement industry produced 85.9 million metric tons of cement in 2017, representing only 2.1% of the 4.1 billion metric tons produced in the world (Zinke and Werkheiser, 2018). Moreover, global production is expected to increase by 12–23% from current levels by 2050 (OECD/International Energy Agency, 2018). Cement production is also the third-largest consumer of industrial energy; the required energy production represents about 7% of global carbon dioxide (CO2) emissions. Identifying lower embodied-energy material as substitutes for a portion of high-energy-intensive cement is an important strategy for combating the environmental impacts of cement production (OECD/International Energy Agency, 2018; van Oss, 2017; Lothenbach et al., 2011; UN Climate Change Newsroom, 2017).

To this end, the International Energy Agency (IEA) partnered with the World Business Council for Sustainable Development (WBCSD) as part of the Cement Sustainability Initiative (CSI) to develop a technology roadmap to reduce the CO2 intensity of cement production (OECD/International Energy Agency, 2009). This roadmap identified four main levers for CO2 reductions: 1) improving thermal and electric efficiency; 2) using less carbon-intensive fuels in the cement production process; 3) substituting lower carbon material with cementitious properties for the higher energy clinker; and 4) capturing CO2 before it is released and storing it securely. However, according to Chatham House’s Flex Preston, “Of the four well-known levers … there is untapped potential for clinker substitution in particular which is already resulting in a global saving of approximately 500 million tons of CO2 per annum.” (UN Climate Change Newsroom, 2017).

Pozzolans have a lower embodied energy than cement and can be...
used as a substitute. Pozzolans are a broad class of siliceous and aluminosilicate materials that, when added to cement as a finely ground powder and in the presence of water, react with a byproduct (calcium hydroxide) of cement hydration to form secondary calcium silicate hydroxide (C-S-H). Industrial byproducts such as fly ash from coal-fired power plants (most common) and silica fume from elemental silicon or ferro-silicon alloy production are examples of artificial pozzolans (Portland Cement Association, 2018). Life-cycle assessment (LCA) results have shown reduced environmental impacts associated with ready-mix concrete that uses ordinary Portland cement (OPC) composed of 15–40% fly ash (NSF International, 2017). However, global energy production is trending away from the use of coal, causing the fly-ash supply to decrease. The reduced supply is presenting a challenge for concrete manufacturers (National Precast Concrete Association, 2017), thereby opening up market opportunities for other pozzolans.

Pozzolans developed from recycled glass are readily available commercial products (Urban Mining Northeast, 2018). They have been shown to be promising cement replacements that also result in reduced environmental impacts (Carsana et al., 2014; Du and Tan, 2017; Schwarz et al., 2008; Islam et al., 2017; Alalbado et al., 2016; Jani and Hogland, 2014; Hossain et al., 2017). Finely ground glass particles (25 μm or less) exhibit considerable pozzolanic behavior, which is critical for viable cement replacement (Mizrahi and Riding, 2015). In fact, Du and Tan (2017) examined fine glass powder as a cement replacement at rates of 0%, 15%, 30%, 45%, and 60%. They identified the replacement rates of 15% and 30% as exhibiting the highest compressive strength. When the rate went beyond 30%, Du and Tan found that calcium hydroxide became insufficient for the pozzolanic reaction of the glass powder.

The success of using commonly recycled glass as a pozzolan in cement is an inspiration to look at other less recycled glass as potential cement replacements. Cathode Ray Tube (CRT) glass is a potential recycled glass that currently has limited beneficial end-of-life pathways (Iniaghe and Adie, 2015). While old CRTs can be recycled into new CRTs, demand for new CRTs has collapsed in favor of flat panel technologies. The U.S. currently has a maximum recycling capacity of 128,000 tons per year; however, it is projected that at least 206,000 tons of CRT glass will be recovered in the U.S. annually, leaving a gap of about 78,000 tons with no responsible end-of-life option (Kuusakoski Recycling, 2016). Moreover, nearly 80 percent of the CRT recycling capacity is located in India and Mexico, increasing environmental impacts associated with transport and reducing the overall benefits of recycling. Further increasing recycling challenges, CRTs contain lead and are regulated as hazardous waste under the U.S.’s Resource Conservation and Recovery Act (U.S. Environmental Protection Agency, 2017).

Rising recycling costs, lack of recycling options, and shifts in CRT-glass markets have caused some processors and recyclers to store CRTs indefinitely rather than recycle them, increasing mismanagement and/ or abandonment risks of retired CRTs (U.S. Environmental Protection Agency, 2014). In fact, an estimated 270,000 tons of CRTs and CRT glass are known to be stockpiled in fourteen states in the U.S., with over 150,000 tons found abandoned in warehouses by recyclers themselves (Association of State and Territorial Solid Waste Management Officials, 2017; Powell, 2013; Koebler, 2017a, 2017b). At least one fire has occurred at a recycler, involving over 750 tons of CRTs and CRT glass stored outside on the ground (U.S. Environmental Protection Agency, 2018). The volume of CRTs needing an environmentally friendly end-of-life pathway represents only about 0.2% of the cement made in the US annually, an amount that could easily be incorporated into current cement production. Given the challenges associated with recycling CRTs and the estimated increase in global production of cement, recycling CRT glass in cementitious systems could be viewed as an economical, technically feasible, and environmentally friendly management strategy for this waste stream (Iniaghe and Adie, 2015).

A particular challenge associated with using CRT glass in cement and concrete is the potential leaching of lead. CRTs contain panel and funnel glass—lead is located in the latter. Exposure to lead leaching from the CRT funnel glass can result in irreversible damage to the human central nervous system (Zhao and Poon, 2017). To avoid lead leaching in uses such as cement, CRT panel glass can be separated from the leaded funnel glass and recycled separately. It is estimated that two thirds of a CRT’s mass is panel glass, allowing for a significant portion of the CRT mass to be recycled through non-hazardous systems (Méar et al., 2006). Potential treatment methods and uses for leaded funnel glass are also described in literature (Liu et al., 2018a; Yao et al., 2018; Zhao and Poon, 2017).

A number of studies have focused on CRT glass as a fine aggregate or sand replacement in mortar and concrete (Iniaghe and Adie, 2015; Ling and Poon, 2011; Romero et al., 2013; Liu et al., 2018a, 2018b; Yao et al., 2018; Zhao and Poon, 2017). However, consistent with previous work on glass as a fine aggregate, findings indicate that CRT glass increases the alkali-silica reaction (ASR) which can be detrimental to the durability of concrete (Iniaghe and Adie, 2015; Ling and Poon, 2011; Romero et al., 2013; Rashad, 2014; Federico et al., 2011). In contrast, very little research has focused on CRT panel glass as a pozzolan for cement replacement where particles are below 100 μm and ASR may not be a potential problem (Federico et al., 2011). While CRT panel glass alone does not meet the chemical composition requirements for ASTM C618 pozzolans, mixing it with higher reactivity glass can overcome this limitation (Méar et al., 2006; ASTM International, 2017a; Grasso Jr., 2018). This study examines the functional feasibility of mixing finely ground CRT panel glass with higher reactivity glass pozzolans as cement replacement.

As a second component of this study, we use an LCA to examine the environmental impacts associated with mixing CRT panel glass with higher reactivity glass pozzolans as cement replacement. LCA is a common tool for evaluating the environmental impacts of industrial systems, including building materials. It is an approach that assesses the environmental impacts of a product or process throughout its life cycle. It provides a picture of the environmental trade-offs often made in product or process selection and it can help avoid shifting burdens from one life-cycle phase and environmental impact to another (Scientific Applications International Corporation, 2006).

Finally, we had unique access during this study to process data for glass and CRT recycling at a production scale within the existing industrial infrastructure. The opportunity to analyze the functional and environmental implications of CRT and glass recycling in a circular-system model at an industrial scale, revealed a number of benefits and limitations to consider in future system design scenarios (Ellen MacArthur Foundation, 2015).

2. Materials and methods

We analyzed the performance and environmental impacts of cement and concrete with a portion of the cement replaced by a recycled-glass pozzolan incorporating CRT panel glass. To achieve the desired pozzolanic traits, the CRT panel glass was processed and mixed with recycled-mixed-container-glass waste. Our analysis is specific to this project and the collected primary data and does not represent all CRT and glass processing.

The process for preparing CRT panel glass for use as a pozzolan was documented during a site visit to the Electronic Recyclers International (ERI) recycling facility in Plainfield, Indiana (US). The approach was refined collaboratively with ERI process engineers. ERI receives televisions, computer monitors, and other electronic waste from various sources. Products are sorted and disassembled by hand, separating the commodities, circuit boards, and plastic from the glass CRTs. The CRT panel glass is then detached from the CRT leaded glass. The leaded glass is shipped to other customers for use in new products and is not used in the pozzolan. The panel glass is processed into small chips and the CRT phosphor is removed. The panel-glass chips are packaged into bulk
super sacks with greater than one-ton capacity and shipped to Urban Mining Northeast LLC (UMNE) for further processing into a pozzolan powder. The inputs and outputs from each process step were identified and quantified, such as energy and waste.

Currently a significant volume of mixed-container glass is recycled at materials recovery facilities. This material is commonly known as MRF glass. MRF glass is recovered, crushed, cleaned, and processed to form glass cullet, which in turn can be melted down and reused in new glass containers and other products. At the end of the recovery process, the glass cullet is sent through a fine-mesh vibrating screen to filter out small particles, or “fines.” Glass fines that pass through the mesh are commonly considered a waste by-product from the cullet process and are typically sent to a landfill. Some of this glass fines waste by-product is instead packaged and shipped to UMNE for processing into UMNE’s trademarked pozzolan made from MRF glass powder, Pozzotive®. (Urban Mining Northeast, 2018)

The travel stage of cement, defined in ASTM’s PCR, concerns the transportation of raw materials from the suppliers to the final manufacturing site. Distances between the various sites were calculated using over-the-road mapping software. A significant finding that emerged: the raw-material life-cycle stage includes all material inputs: the cementitious materials of one of the three mixtures contained 20% by weight of the 5% CRT-MRF glass mixture and 85% MRF glass (UMNE, 2018). The second mixture had a ratio of 15% CRT panel glass and 85% MRF glass. The two CRT-MRF glass mixtures were characterized using scanning-electron microscopy (SEM), X-ray diffraction (XRD), and laser-particle-size distribution analysis (PSD) to determine the morphology, amorphous/crystalline nature, and the particle size distribution, respectively. The strength activity index was determined following ASTM C311 protocols for chemical and physical requirements.

Three concrete mixtures were tested to determine the functional feasibility of the glass mixtures. The cementitious materials of one of the three mixtures contained 20% by weight of the 5% CRT-MRF glass mixture and 80% by weight of the ordinary portland cement (OPC). The second of the three mixtures contained 20% by weight of the 15% CRT-MRF glass mixture and 80% by weight of OPC. The third mixture comprised solely of OPC and served as the control mix for the study. All three mixtures were prepared with a design compressive strength of 5500 psi. Batching, mixing, casting, curing, and testing were performed following the relevant ASTM standard protocols. The workability (slump), air content, density, and setting times of three concrete mixtures were determined in accordance with ASTM C143, C231, C138, and C173, respectively. The hardened properties including compressive, tensile, and flexure strengths, were determined in accordance with ASTM C39, C496, and C293, respectively. The sulfate resistance was measured for one year of exposure using ASTM C1012. Leaching resistance of heavy metals and toxic chemicals (if any) from hardened concrete was determined using toxicity-characteristic leaching procedure (TCLP), performed in accordance with EPA 1311 (U.S. Environmental Protection Agency, 2016).

2.2. Life-cycle assessment

The physical performance testing results were required to demonstrate functional feasibility and equivalence of concrete and cement with and without a portion of the cement replaced by the defined glass pozzolans. Demonstrating the functional equivalence enabled the definition of a common functional unit and a direct comparison of the various cement and concrete environmental impacts. We performed a life-cycle assessment (LCA) to understand the environmental impacts of using CRT panel glass pozzolans in cement and concrete. Each activity involved in the creation, use, maintenance, and disposal of a product results in environmental or human-health effects due to the consumption of resources, emissions, or other exchanges. LCA provides an accounting framework for estimating the cumulative environmental impacts of a product’s life cycle, giving a comprehensive view of how a complex system affects its environment (Scientific Applications International Corporation, 2006).

The LCA for the cement and concrete containing the CRT-MRF glass pozzolan mixture was performed in accordance with ISO 14040:2006(E) International Organization for Standardization (2006a) and ISO 14044:2006(E) International Organization for Standardization (2006b). We followed the guidelines outlined in the Product Category Rules (PCR) for Preparing an Environmental Product Declaration (EPD) for Portland, Blended Hydraulic, Masonry, Mortar and Plastic (Stucco) Cements, UN CPC 3744 (ASTM International, 2014). The public LCA report is contained in the supplementary documentation.

The LCA analyzed the glass pozzolans first, then the cements with and without glass pozzolans, and finally the concretes that were made with the various cements. The glass pozzolans evaluated included a baseline commercially available pozzolan made from 100% MRF glass and a mixed-glass pozzolan with 15% CRT panel glass blended with 85% MRF glass. The 5% CRT panel glass mixture, which was functionally tested, was not evaluated using LCA since the environmental performance would be bounded between the evaluated 0% and 15% CRT glass. The two glass pozzolans were also evaluated in cement mixtures with 20% of OPC replaced by the glass pozzolan. The baseline OPC impacts were defined by the Portland Cement Association Environmental Product Declaration (PCA EPD), which conforms to the same cement product category rule (UN CPC 3744) used to guide our LCA (Portland Cement Association, 2016). The results of the cement-impact assessment were incorporated into an LCA of concretes. To produce concrete, the various cements were mixed with aggregate, water, and other ingredients in a ratio defined during the functional testing. This analysis hierarchy is shown in Fig. 1.

The life-cycle system boundary defined by the cement PCR is a cradle-to-gate analysis, which considers the environmental impacts of the raw material, transportation, and product manufacturing. It therefore does not include consideration of use, maintenance, and end-of-life stages.

The raw-material life-cycle stage includes all material inputs: the MRF container-glass by-product, CRT panel glass, cement, and other ingredients to produce concrete. The environmental impacts for OPC were obtained from the PCA EPD. The declaration quantifies the environmental impact of OPC produced by 22 member companies at 64 manufacturing plants in the US. The data accounts for 56,280,413 metric tons of production by PCA members, representing 72.4% of the cement industry total for 2014. Each concrete used in this study was comprised of cement as defined by the PCA EPD, as well as glass pozzolan, aggregate, water, and other concrete ingredients in the specified proportions used to create the functional testing samples.

The travel stage of cement, defined in ASTM’s PCR, concerns the transportation of raw materials from the suppliers to the final manufacturing site. Distances between the various sites were calculated using over-the-road mapping software. A significant finding that emerged: CRT panel glass traveled over 800 miles from the ERI facility in Indiana to the UMNE facility in upstate New York.

The glass-pozzolan manufacturing-process stage was documented during a site visit to the UMNE upstate New York facility (as described earlier in this section). The MRF glass and CRT panel glass were processed using the same equipment and process settings. The type of fuel and mix-ratio for New York was obtained from the U.S. Energy Information Administration (U.S. Energy Information Administration,
As with all LCAs, there is a limit to the amount of primary data that can be collected. Often secondary data is required to complete an analysis, which can be found in data libraries or in literature. Our LCA was completed using SimaPro 8.0.4.26 multi-user LCA software. We used the tool to collect, model, and translate the life-cycle inventory data into environmental impacts with a significant portion of the secondary data obtained from the U.S. Life Cycle Inventory (LCI) Database (National Agricultural Library, 2012). The ecoinvent v3.1 database was also used to fill in any voids in the USLCI data set (Wernet et al., 2016). The life cycle inventory and data quality assessment can be found within the LCA report contained in the supplementary documentation.

Finally, the inputs and outputs associated with the glass, cement, and concrete life cycles were converted into environmental, human-health, and resource impacts through defined characterization models. We used the impact categories given by ASTM in their cement PCR (Table 3: Declaration of Environmental Category Indicator Results, Use of Resources, and Generation of Waste). Calculations were done using the characterization factors specified in version 2.1 of the EPA’s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.1) (Bare, 2012) as required by the cement PCR. Category indicators included: global-warming potential (GWP), acidification potential, eutrophication potential, smog-creation potential, and ozone-depletion potential. Total-energy (renewable energy and non-renewable) was also calculated using the cumulative-energy-demand (CED) impact assessment method (version 1.09) in SimaPro.

3. Results

3.1. Material characterization and functional feasibility

3.1.1. Material characterization

Fig. 2(a) and (b) shows the morphology of the 5% CRT-MRF and 15% CRT-MRF glass powders. These images show that the CRT-MRF glass powders have irregularly shaped particles, in a variety of sizes. Fig. 2(c) shows the PSD curves of both the mixtures in comparison with portland cement used in this study. The average particle sizes were 23, 7.7 and 7.3 μm for OPC, 5% CRT-MRF and 15% CRT-MRF, respectively. Although the PSD curves were very similar (between the 2 glass powders), the average particle sizes were different and hence the specific surface areas (fineness) were 324, 418 and 502 m²/kg for OPC, 5% CRT-MRF and 15% CRT-MRF, respectively. The fresh properties of concrete such as the workability and setting times and the hardened properties such as the strength are influenced by the morphology, specific surface area, and the particle size distribution of the pozzolanic materials.

Table 1 shows the ASTM C618 chemical requirement for CRT-MRF glass and Table 2 shows the complete oxide analysis as determined by X-ray fluorescence (XRF). As per ASTM C618, the sum of silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and iron oxide (Fe₂O₃) must be at least 70%. The sulfur trioxide (SO₃) content should not be greater than 4%, and moisture content should not be more than 3%. The loss on ignition (LOI) should not be more than 6%. As shown in Table 1, mixtures of 5% CRT panel glass with 95% MRF glass and 15% CRT panel glass with 85% MRF glass both met the ASTM C618 chemical requirements for Class C, F, and N pozzolan (ASTM International, 2017a, 2017b).

3.1.2. Physical requirements

Table 3 details test results for the physical requirements in accordance with ASTM C618. As defined by the ASTM C618 activity index requirement, the strength-activity index must be more than 75% at 7 and 28 days to be qualified as a pozzolanic material in concrete. Both the 5% and 15% blends of CRT-MRF glass powders met the physical requirements stipulated by ASTM C618 and are qualified as effective pozzolanic materials.

3.1.3. Compressive, tensile, and flexural strength

The compressive, tensile, and flexural strengths of concrete mixtures are presented in Fig. 3. The compressive strength of concrete mixtures (Fig. 3a) with 15% CRT-MRF glass powder is higher than that of 5% CRT-MRF glass powder at all curing periods. All three concrete mixtures achieved the designed compressive strength, 5500 psi, at 28 days. The compressive strength was lower than that of the OPC concrete up to 56 days. However, the compressive strength of the glass powder incorporated mixtures surpassed the OPC concrete compressive strength at one year (Fig. 3a).

As expected, tensile-strength (Fig. 3b) and the flexural-strength (Fig. 3c) development followed the same trend as that of compressive strength. At 28 days, the tensile and flexural strengths were approximately 10% and 20% of the compressive, respectively. The 15% CRT-MRF concrete exhibited higher compressive, tensile, and flexural strength values than the 5% CRT-MRF concrete at all ages. As discussed in Section 3.1.1, 15% CRT-MRF glass powder contained finer particles with higher specific surface area compared to 5% CRT-MRF glass powder. Generally, materials with higher specific surface areas result in higher compressive strength due to increased hydration rate. This may
be the reason for slightly better performance of 15% CRT concrete compared to 5% CRT-MRF powder with respect to the hardened strength and durability properties achieved by them.

3.1.4. Toxicity characteristic leaching test

The toxicity characteristic leaching test (TCLP) was carried out in accordance with EPA 1311 standards on 56-day-old concrete samples (Rashad, 2014). Table 4 presents the concentration of ions leached from the concrete samples and the maximum concentration of contaminants for toxicity characteristic. Sample concentrations were all lower than regulatory limits and show that MRF and CRT-MRF glass do not introduce hazardous metals into concrete.

3.1.5. Rapid chloride permeability test

The rapid chloride-permeability test (RCPT) results are presented in Table 5. The OPC mixture had the highest chloride permeability at both 28 and 56 days; however it still achieved a designation of “Low” permeability. Both concretes with CRT-MRF glass mixtures achieved a designation of “Very Low” chloride penetrability in accordance with ASTM C1202, and the resistance to chloride penetrability increased as the age of the concrete mixtures increased (ASTM International, 2017b).

3.1.6. Sulfate resistance

Fig. 4 summarizes the change in length of mortar bars when exposed to a sulfate solution using the testing standards set out by ASTM C1012 (ASTM International, 2018). The results show that mortar-bar length across all tested concrete mixtures changed by less than 0.024% at 56...
days. After one year, both the 5% CRT-MRF and the 15% CRT-MRF mixtures exhibited considerably better resistance to sulfate attack when compared to the OPC control mixture.

3.2. Life-cycle assessment results

The physical performance testing results presented in the previous subsection demonstrated functional equivalence of concrete and cement with and without a portion of the cement replaced by the defined glass pozzolans. Demonstrating functional equivalence enabled the definition of a common functional unit and a direct comparison of the various cement and concrete environmental impacts. This section highlights the LCA critical results found throughout the analysis hierarchical structure previously defined in Fig. 1. The full description and results can be found in the public LCA report contained in the supplementary documentation.

Table 3
Test results for physical requirements as defined by ASTM C618.

<table>
<thead>
<tr>
<th>Physical requirements</th>
<th>5% CRT + 95% MRF</th>
<th>15% CRT + 85% MRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness: Amount retain when wet sieved (45 μm sieve) max %</td>
<td>0.03</td>
<td>0</td>
</tr>
<tr>
<td>Strength activity index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- With OPC, at 7 days, minimum percent of control</td>
<td>77.9</td>
<td>80.9</td>
</tr>
<tr>
<td>- With OPC, at 28 days, minimum percent of control</td>
<td>80.3</td>
<td>91.6</td>
</tr>
<tr>
<td>- With OPC, at 56 days, minimum percent of control</td>
<td>83.3</td>
<td>97.7</td>
</tr>
<tr>
<td>Water requirement, maximum, percent of control</td>
<td>91.7</td>
<td>89.7</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Uniformity requirement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fineness, maximum variation from average %</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>Density, maximum variation from average %</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 3. Strength development of concrete mixtures: a) compressive (ASTM C39) b) tensile (ASTM C496), and c) flexural or the modulus of rupture (ASTM C293).

Table 4
Toxicity characteristic leaching test (TCLP).

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Sample Concentration (ppm)</th>
<th>Maximum level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPC 5% CRT + 95% MRF 15% CRT + 85% MRF</td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>&lt; 0.05 &lt; 0.05 &lt; 0.05</td>
<td>5</td>
</tr>
<tr>
<td>Barium</td>
<td>0.175 0.334 0.724</td>
<td>100</td>
</tr>
<tr>
<td>Cadmium</td>
<td>&lt; 0.01 0.025 0.022</td>
<td>1</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.034 0.025 0.022</td>
<td>5</td>
</tr>
<tr>
<td>Lead</td>
<td>&lt; 0.05 &lt; 0.05 &lt; 0.05</td>
<td>5</td>
</tr>
<tr>
<td>Selenium</td>
<td>&lt; 0.05 0.025 0.022</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3. Glass pozzolans compared to OPC

The results in Fig. 5 represent the relative impacts of each of the glass pozzolans and OPC on a per-metric-ton basis normalized to the OPC environmental impacts described in the PCA EPD. The numeric results are in Table 6.

The results above show that the commercially available MRF glass pozzolan and CRT glass powder both have significantly less impact than OPC across all environmental categories. The data suggest that replacing a portion of cement with the glass pozzolans we tested will significantly decrease the environmental impact of the resulting concrete.

3.4. OPC compared to OPC with a portion replaced by a glass pozzolan

The next step in our analysis was to compare the environmental impacts of standard OPC with OPC containing glass pozzolans. The first comparison cement was 80% by mass OPC with 20% commercial MRF glass pozzolan. The second comparison cement was modeled as 80% by mass OPC and 20% of the mixed-glass pozzolan (15% CRT panel glass, 85% MRF glass). This results in an absolute ratio of 80% by mass OPC, 17% by mass MRF glass, and 3% by mass CRT panel glass. Fig. 6 shows the impacts of the cements with glass pozzolans as compared to the environmental impact of OPC as described in the PCA EPD for portland cements. The numeric results are in Table 7.

Results show that both cements containing the glass pozzolan had at least a 14.6% reduction in all evaluated environmental impacts when compared to standard OPC. Moreover, the difference in impact between the two glass pozzolan cements was insignificant. The CRT-MRT mixed-glass pozzolan, replacing just 3% of cement by mass, has only a slightly higher impact of 1.2% than the glass pozzolan made with only MRF. The study confirms CSI’s roadmap lever that substituting a lower impact material with cementitious properties (such as mixed glass) for a higher impact cement will decrease the overall environmental impact of cement (OECD/International Energy Agency, 2009).

Table 6

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Total Charge Passed (Coulombs)</th>
<th>Remarks as per ASTM C1202</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 days</td>
<td>56 days</td>
<td></td>
</tr>
<tr>
<td>OPC</td>
<td>1562</td>
<td>Low</td>
</tr>
<tr>
<td>5% CRT + 95% MRF</td>
<td>294.5</td>
<td>Very Low</td>
</tr>
<tr>
<td>15% CRT + 85% MRF</td>
<td>301.7</td>
<td>Very Low</td>
</tr>
</tbody>
</table>

Fig. 4. Length change of the samples exposed to sulfate solution (ASTM C1012).

Fig. 5. Normalized life cycle impacts of glass pozzolans compared to OPC.
Finally, our analysis compared the environmental impacts of the concrete products made with OPC (as described in the PCA EPD) with those containing glass pozzolans mixed with OPC. The numeric results are in Table 8 (Fig. 7).

### Table 6
CRT panel glass, MRF glass, and OPC environmental impacts.

<table>
<thead>
<tr>
<th>Data per metric tonne of material</th>
<th>Unit</th>
<th>OPC EPD</th>
<th>MRF Glass</th>
<th>CRT Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Impact (TRACI 2.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global warming potential (100 years)</td>
<td>kg CO₂-eq.</td>
<td>1040</td>
<td>58.7</td>
<td>228</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₂-eq.</td>
<td>2.45</td>
<td>0.50</td>
<td>1.6</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg N-eq.</td>
<td>1.22</td>
<td>0.029</td>
<td>0.107</td>
</tr>
<tr>
<td>Formation potential of tropospheric ozone</td>
<td>kg O₃-eq.</td>
<td>48.8</td>
<td>3.59</td>
<td>24.8</td>
</tr>
<tr>
<td>Ozone depletion potential</td>
<td>kg CFC 11-eq.</td>
<td>2.61E-05</td>
<td>1.16E-07</td>
<td>1.66E-06</td>
</tr>
<tr>
<td>Total primary energy consumption (CED 1.09)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-renewable primary energy: Fossil</td>
<td>MJ</td>
<td>5250</td>
<td>1080</td>
<td>3310</td>
</tr>
</tbody>
</table>

### Fig. 6. Normalized life cycle impacts of various cements.

### Table 7
LCIA data for cements (per metric ton).

<table>
<thead>
<tr>
<th>Data per metric tonne of material</th>
<th>Unit</th>
<th>OPC EPD</th>
<th>EPD cement with 20% MRF</th>
<th>EPD cement with 17% MRF &amp; 3% CRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Impact (TRACI 2.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global warming potential (100 years)</td>
<td>kg CO₂-eq.</td>
<td>1040</td>
<td>844</td>
<td>849</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₂-eq.</td>
<td>2.45</td>
<td>2.06</td>
<td>2.09</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg N-eq.</td>
<td>1.22</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Formation potential of tropospheric ozone</td>
<td>kg O₃-eq.</td>
<td>48.8</td>
<td>39.8</td>
<td>40.4</td>
</tr>
<tr>
<td>Ozone depletion potential</td>
<td>kg CFC 11-eq.</td>
<td>2.61E-05</td>
<td>2.09E-05</td>
<td>2.09E-05</td>
</tr>
<tr>
<td>Total primary energy consumption (CED 1.09)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-renewable primary energy: Fossil</td>
<td>MJ</td>
<td>5250</td>
<td>4420</td>
<td>4480</td>
</tr>
</tbody>
</table>

### 3.5. Concrete

Finally, our analysis compared the environmental impacts of the concrete products made with OPC (as described in the PCA EPD) with those containing glass pozzolans mixed with OPC. The numeric results are in Table 8 (Fig. 7).

### Table 8
LCIA data for concretes (per metric ton).

<table>
<thead>
<tr>
<th>Data per metric tonne of material</th>
<th>Unit</th>
<th>Concrete with EPD cement</th>
<th>Concrete with EPD cement containing 20% MRF</th>
<th>Concrete with EPD cement containing 17% MRF &amp; 3% CRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Impact (TRACI 2.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global warming potential (100 years)</td>
<td>kg CO₂-eq.</td>
<td>189</td>
<td>155</td>
<td>156</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₂-eq.</td>
<td>0.476</td>
<td>0.408</td>
<td>0.413</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg N-eq.</td>
<td>0.232</td>
<td>0.191</td>
<td>0.191</td>
</tr>
<tr>
<td>Formation potential of tropospheric ozone</td>
<td>kg O₃-eq.</td>
<td>9.72</td>
<td>8.13</td>
<td>8.24</td>
</tr>
<tr>
<td>Ozone depletion potential</td>
<td>kg CFC 11-eq.</td>
<td>5.59E-06</td>
<td>4.67E-06</td>
<td>4.68E-06</td>
</tr>
<tr>
<td>Total primary energy consumption (CED 1.09)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-renewable primary energy: Fossil</td>
<td>MJ</td>
<td>1011</td>
<td>864</td>
<td>876</td>
</tr>
</tbody>
</table>
4.1. Need for further study

The cement life-cycle boundary followed the guidelines outlined in the ASTM’s PCR (ASTM International, 2014), which is a cradle-to-gate analysis only. It excludes assessment of use and end-of-life stages, which may limit the full understanding of the potential environmental benefits.

For example, there are indications that cement with the glass pozzolan may provide significant benefit during use. The experimental data showed favorable permeability performance of concrete with 20% glass pozzolans. Lower permeability may mean that the concrete has less interconnected pores and may therefore be more durable and last longer. Lower permeability may also decrease the negative effects of freezing and thawing, as well as limit the penetration of chloride from road salts or salt water. These potential effects highlight that there may be value in investigating the durability influence on the full life-cycle environmental impacts of concrete with glass pozzolan within the built environment.

ASTM’s cement PCR also provides guidance on how to model secondary materials. According to these rules, any allocation impacts of recycled or recovered materials prior to reprocessing shall be allocated to the original product. These rules were followed for this LCA and as such, the CRT life cycle, including the CRT end-of-life, was allocated to the original product (CRT television). However, changing the traditional CRT end-of-life disposition through processing into a pozzolan could reveal significant environmental benefit.

We recommend that future studies consider a system expansion or other environmental modeling techniques to evaluate the use phase of concrete products as well as the CRT end-of-life stage. Modeling expansion objectives to consider in future studies include examining the potential to (1) increase the useful life of concrete bridges exposed to salt water, (2) reduce the environmental risk of mass CRT storage, and, (3) reduce the environmental impacts associated with end-of-life transportation by processing CRTs locally.

The glass-panel component makes up about two-thirds of the whole CRT product unit by mass, making its recovery a significant step towards reducing the negative impacts of CRT storage and management (Koebler, 2017b). Even though this does not completely solve the whole of the CRT-glass-waste problem, it does provide a significant contribution while concurrent research focuses on methods for removing lead from funnel glass (Veit et al., 2015).

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Acknowledgements

Our research was performed consistent with the terms and purposes of the New York State Pollution Prevention Institute (NYSPP2I) agreement between Urban Mining Northeast LLC (UMNE) and Rochester Institute of Technology (RIT). It is funded in part by RIT through a grant from New York State. Additional funding was provided by RIT’s Staples Sustainable Innovation Laboratory and the Electronic Recyclers International specifically to understand the impacts of replacing a portion of the ordinary Portland cement (OPC) in concrete with cathode-ray tube (CRT) panel glass. Any opinions, findings, and/or interpretations of data contained herein are the responsibility of RIT and its NYSPP2I and do not necessarily represent the opinions, interpretations or policy of New York State.

We thank Louis Grasso Jr. and Dale Hauke from UMNE for supporting this project, providing the MRF glass pozzolhan Pozzotive®, crushing and providing production quantity and quality CRT glass powder, and for allowing access to the manufacturing process and equipment for the LCA data. We also thank Aaron Blum, Andrew Nunan, and the technical staff at Electronic Recyclers International for providing access to their manufacturing process and equipment. This work would not have been possible without the full support of the manufacturers involved. We also thank Christopher Whitebell for his assistance in preparing the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2019.104451.

References


