CrossMark

LCI METHODOLOGY AND DATABASES

Impact of the selection of functional unit on the life cycle assessment of green concrete

Daman K. Panesar[1] · **Karina E. Seto**[1] · **Cameron J. Churchill**[2]

Abstract

Purpose The objectives of this study are to evaluate life cycle assessment (LCA) for concrete mix designs containing alternative cement replacement materials in comparison with conventional 100% general use cement concrete and to evaluate the interplay and sensitivity of LCA for four concrete mix designs and six functional units which range in degrees of complexity and variables.

Methods Six functional units with varying degrees of complexity are included in the analysis: (i) volume of concrete, (ii) volume and 28-day compressive strength, (iii) volume and 28-day rapid chloride permeability (RCP), (iv) volume and binder intensity, (v) volume and a combination of compressive strength and RCP and (vi) volume and a combination of binder intensity and RCP. Four reference flows are included in the analysis: three concrete mix designs containing slag, silica fume and limestone cement as cement replacement and one concrete mix design for conventional concrete.

Results and discussion All three alternative mix designs were evaluated to have lower environmental impacts compared with the base 100% general use cement and so are considered to be 'green' concrete. Similar LCA results were observed for FU$_1$, FU$_2$ and FU$_4$, and relatively similar results were obtained for FU$_3$, FU$_5$ and FU$_6$. LCA conducted with functional units which were a function of durability exhibited markedly different (lower) LCA compared with the functional units that did not capture long-term durability.

Conclusions Outcomes of this study portray the interplay between concrete mix design materials, choice of functional unit and environmental impact based on LCA. The results emphasize (i) the non-linearity between material properties and environmental impact and (ii) the importance of conducting an LCA with a selected functional unit that captures the concrete's functional performance metrics specific to its application and expected exposure conditions. Based on this study, it is recommended that a complete LCA for a given concrete mix design should entail examination of multiple functional units in order to identify the range of environmental impacts or the optimal environmental impacts.

Keywords Compressive strength · Concrete · Durability · Functional unit · Life cycle assessment · Limestone cement · Rapid chloride permeability · Silica fume · Slag

✉ Daman K. Panesar
d.panesar@utoronto.ca

[1] Department of Civil Engineering, University of Toronto, 35 St. George St, Toronto, ON M5S 1A4, Canada

[2] Engineering and Society Program, McMaster University, 1280 Main St W, Hamilton, ON L8S 4L7, Canada

1 Introduction and background

In life cycle assessment (LCA) studies, a functional unit 'defines the quantification of the identified functions (performance characteristics) of the product' (International Organization for Standardization (ISO) 2006). The selection of a functional unit is an important step in defining the scope of an LCA study. The purpose of the functional unit is to provide a basis for the quantification of all inputs and outputs (i.e. a reference point for which data is collected) and to allow for comparison of LCA results based on equivalent functional performance of different processes or products. The challenge

for practitioners is how to select a functional unit when a product or process has multiple identified functions and ultimately how to determine the influence of such a choice on the results.

1.1 General guidance for the selection of a functional unit

Despite the fundamental importance of the functional unit in LCA studies, the ISO standards that relate to LCA (ISO 14040 and ISO 14041) provide only general guidance. For example the International Organization for Standardization (ISO) (1998) states that functional units shall be (i) consistent with the goal and scope of the study and (ii) clearly defined and measurable. The International Organization for Standardization (ISO) (1998) also briefly refers to scenarios where more than one function is performed by a system, stating that when two systems are compared, it must be ensured that the functional units for each system account for the same number of functions. The ISO standards, however, are meant to serve as a framework and not as explicit guidelines for LCA studies and so, appropriately, they provide general guidance only with regard to functional unit selection. LCA studies by nature need to be framed within the context of highly specific geography, technology and time periods. Any selected functional unit must reflect this context, and so general statements as in the ISO documents do not necessarily always provide sufficient guidance. A more nuanced discussion of the selection of the functional unit is required when specific LCA studies are developed.

1.2 Selection of the functional unit for LCA of concrete materials

North American Product Category Rules have been developed to be used to evaluate the environmental impact of concrete (Carbon Leadership Forum 2012). The Product Category Rules state that the 'declared unit' shall be defined as 1 m^3 or 1 yard^3 of concrete. It is explicitly stated that the 'declared unit' characterises a reference flow of material quantity and is used instead of a 'functional unit' as the Product Category Rules do not address the use or end-of-life phase for concrete. There have, however, been many LCA studies (including both cradle-to-gate and cradle-to-grave analyses) that have focused on concrete materials and have based their analysis on a functional unit. Table 1 presents a summary of functional units that pertain to LCA conducted on cement and concrete materials and products. However, it should be noted that these studies vary from each other in other ways, for example in the choice of system boundary or in the geographical context, but for the purposes of this review, the focus is on the choice of functional unit. The review is categorised based on three levels of complexity of the functional unit, namely, (i) 'simple' functional unit is composed of a single variable; (ii) 'moderately

complex' functional unit is composed of two variables; and (iii) 'complex' functional unit is composed of three or more variables. Some of the commonly used functional units reported in the literature pertaining to cement and concrete include: volume of concrete, mass of cement, volume of aggregate, compressive strength of concrete, service life, binder intensity and carbon dioxide content (Brown et al. 2014; Gursel and Ostertag 2017; Van den Heed and De Belie 2012; Chen et al. 2010a, b; Nisbet et al. 2002; Knoeri et al. 2013; Yang et al. 2015; De Schepper et al. 2014).

Considering the simple functional unit category, the use of a unit of concrete volume or weight is a straightforward approach for measuring the overall environmental impact of the concrete material or concrete product. However, using the unit of weight or volume may not necessarily be the most appropriate choice because it is not typically the primary function of the concrete. Rather, the compressive strength of concrete is often seen as a functional requirement. For example casting concrete cylinders for testing and evaluation of the 28-day compressive strength (or 56-day compressive strength for some exposure classes (Canadian Standards Association (2016) is a basis for material acceptance. However, given that plain (unreinforced) concrete has a relatively lower tensile strength, it is typically reinforced with steel bars to provide the tensile strength capacity. The service life of the steel-reinforced concrete system is typically associated with the initiation of the corrosion process of the steel (depassivation of the reinforcement). For example a recent study by Mistry et al. (2016) examined the LCA and life cycle cost of a two reinforced concrete piers, one designed with carbon steel and the other designed with stainless steel for reinforcement. The design was based on equivalent structural properties of the reinforcement, the same type of concrete, and both piers had equal amounts of steel and concrete. The only difference between the two types of steel is their durability (ability to resist corrosion). Therefore, service life was chosen as a suitable functional unit (Mistry et al. 2016). Durability is multi-dimensional, and for concrete applications can include resistance to damage as a result of abrasion, freeze-thaw cycles, sulphate attack and chloride ingress. Often, durability of concrete is correlated to the permeability of the materials, as the transport of deleterious substances through concrete is a critical issue that may negatively influence the service life of concrete (Muller 2016). This is particularly the case for reinforced concrete applications where the protection of reinforcing steel from corrosion is critical to maintaining the integrity of the structural system. The rapid chloride permeability test in accordance with ASTM C1202 (ASTM International 2012) is a common test that primarily measures conductivity as an indicator of permeability and durability of concrete. The rapid

Table 1 Literature review of functional units pertaining to cement and concrete LCAs

Source	Functional unit
I. Simple functional unit (single variable)	
Celik et al. (2015)[a]	1 m^3 of ready-mixed self-consolidating concrete
Chen et al. (2010a)[a]	1 kg of cement
Collins (2010)	Concrete bridge (40 MPa, 100 years. life + recycling, CO_2 carbonation included)
Huntzinger and Eatmon (2009)[a]	907 kg (2000 lb) of cement × 4 types: traditional, blended (natural pozzolans), cement + sequestration in waste materials, cement + recycled CKD
Lee and Park (2005)[a]	1 kg of cement clinker, cement, slag powder, silicate fertiliser
Marinkovic et al. (2010)[a]	1 m^3 of ready-mixed natural aggregate and recycled aggregate concrete
Nisbet et al. (2002)[a]	1 m^3 of ready-mixed concrete, 100 concrete masonry units, 1 m^3 of precast concrete
Tosic et al. (2015)[a]	1 m^3 of ready-mixed natural and recycled aggregate concrete
Xing et al. (2008)[a]	1 m^2 building area, steel and concrete office structures
II. Moderately complex functional unit (two variables)	
Athena (2005)	1 m^3 of 15, 20 or 30 MPa ready-mixed concrete; precast double 'T' beam, precast hollow deck, standard concrete blocks, cement mortar
Chen et al. (2010a, b)	1 kg of binding equivalent fly ash, slag and CEM 1
Hassan (2009)	5 mm thick surface mix of ultrafine TiO_2 anatase, cement, filler, and water (0.1:1:3:0.4) applied on 1 lane-kilometre of pavement surface
Jonsson et al. (1998)	1 m^2 floor area for seven frame cases over the lifetime of a building
Knoeri et al. (2013)	1 m^3 of a specific strength class of concrete (lean, indoor and outdoor)
Li et al. (2015)	1 t of Portland cement, 1 t of Portland cement with 42.5 MPa of strength
Prusinski et al. (2004)	1 m^3 and 1 yard^3 of 20 and 35 MPa ready-mixed concrete, 50 and 70 MPa precast concrete, concrete block mix
III. Complex functional unit (three or more variables)	
Anderson and Silman (2009)	kg CO_2 m^{-2} $year^{-1}$
Crossin (2012)	1 m^3 of AS 1379/2007 40 MPa concrete for 50 years
De Schepper et al. (2014)	Mass of concrete for 1 MPa of strength and 1 year of service life
Garcia-Segura et al. (2014)	25 MPa reinforced concrete building column (3 × 0.3 × 0.3 m) during its lifetime
Kawai et al. (2005)	Pre-stressed concrete bridge, overflow dike of dam, retaining wall, secondary lining in tunnel with specific strength requirements and service lives
Yang et al. (2014)	Binder intensity and CO_2 intensity concepts (Damineli et al. 2010) in terms of the unit strength (1 MPa) of concrete
Wang et al. (2013)	4047 m^2 of permeable pavement and other types of runoff systems sized for runoff associated with 2.5 cm of rainfall generated over a 0.4 ha (1 acre) watershed

[a] Sources that base their LCA analysis and calculations on a 'functional unit' that do not represent a function but rather appear to be a reference flow

chloride permeability value is a basis for material acceptance by the Ministry of Transportation for many applications such as high-performance concrete, overlays and precast elements.

Close review of the studies reported in Table 1 also exposed some scenarios where the selection of a particular functional unit for a particular application had a potential to yield unclear or misleading, or variable or incomparable LCA results. Three important aspects that are distilled from the literature review (Table 1) and warrant attention include: (i) the selection of a functional unit based on physical characteristics; (ii) distinction between functional units and reference flows; and (iii) justification and sensitivity analysis of the selected functional unit.

(i) Selection of a functional unit based on physical characteristics: the interpretation of LCA results may be perplexing when the functional unit of concrete is based on physical characteristics. For example the objective of the Lee and Park (2005) study is to quantify the environmental credit of granulated blast furnace slag recycling and to propose the best recycling option. The analysis is based on four functional units that correspond to physical, rather than functional, characteristics: 1 kg of cement clinker, 1 kg of Portland cement, 1 kg of slag powder and 1 kg of silicate fertiliser. As a result of choosing four different functional units, four independent analyses were performed with no apparent basis for functional equivalency. Consequently, it is a challenge to directly compare the LCA results for the different materials. The study does, however, present the relative environmental performance of various recycling options despite that the results are not exactly aligned with the definition of the functional unit. Although choosing a physical characteristic may seem to correspond with the intent of the product category rules for a cradle-to-gate analysis, using these functional units make it difficult to interpret the LCA results. The authors also tend

to refer to these parameters as 'functional units' and not 'declared units', which is not consistent with the product category rules.

(ii) Lack of distinction between functional units and reference flows: in some studies, the lack of distinction between functional units and reference flows can lead to challenges with interpretation of the results. Marinkovic et al. (2010) set the functional unit as 1 m^3 of ready-mixed natural aggregate concrete and 1 m^3 of recycled aggregate concrete. The challenges associated with the choice of volume as a functional unit is described in the discussion of Lee and Park (2005) (in point (i)). However, in addition, the concrete mix designs for the natural aggregate concrete and the recycled aggregate concrete are different. LCA results are calculated for these two different mix designs, and conclusions are drawn with regard to the relative environmental performance. The complexity appears to be that the selected functional units do not describe nor quantify functional properties of the product (such as compressive strength) but rather the means by which the function is achieved. This is actually better correlated to the definition of reference flows, which 'translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis' (Weidema et al. 2004). As a result, the comparison of the environmental impact of the different materials is not made on the basis of a common functional equivalency. Furthermore, the results may be interpreted as being relevant to only the specific mix design presented, with very little latitude for comparison. This is problematic given the fact that many concrete mix designs can achieve the same or similar functions. Reference flows and functional units should be clearly distinguished in LCA studies.

Note that in Table 1, references which base their LCA analysis and calculations on a functional unit that does not represent a function, but rather appears to be a reference flow, are indicated with a superscripted lowercase letter 'a'. The conflation between functional unit and reference flow is a common issue of the LCAs of concrete.

(iii) Lack of explanation and sensitivity analysis for choice of functional unit: for most of the concrete material studies reported in Table 1, the functional unit is simply stated as part of the study goal and scope definition. There is little to no explanation for why any particular functional unit was selected. Furthermore, none of the studies present a sensitivity analysis for varying functional units. Given the importance of the functional unit in establishing the basis for the entire LCA analysis, the selection of the functional unit need be thoughtful, rigorous and well-documented. Furthermore, for materials such as concrete which meet more than one function, the sensitivity of LCA results to the choice of various functional units should be assessed in order to ensure robustness of results and completeness of interpretation.

1.3 Motivation and objectives

The wide range of types of functional units, listed in Table 1 as applied in the literature, partially reflect the fact that over the past two decades, efforts have been made to green the concrete industry from material selection, manufacturing and application of sustainable concrete products. Concrete has developed and continues to develop into a multi-faceted construction material, and in parallel, the construction industry is under pressure to design resilient structures with higher strengths, longer lives and lower environmental impacts than ever before (Tait and Cheung 2016; Celik et al. 2015; Churchill and Panesar 2013; Hossain et al. 2016; Berndt 2009; Hajek 2016). However, the current challenge we are faced with is not only to advance construction building material technologies but to choose among the variety of cement-based material options available on the market while balancing cost, environmental impacts, ease of constructability, mechanical properties and long-term durability performance (Shi et al. 2011). Conducting an LCA which captures concrete's specific properties can prove to be powerful and well aligned with performance-based specifications which are becoming more and more prevalent in concrete and cement specifications world-wide (Muller 2016; Fernandez-Ordonez 2016; Alexander 2016). Therefore, there is a need to investigate the interplay between concrete mix designs containing alternative green materials, the material properties and long-term performance and implications on environmental impacts. Aligned with the motivation and gaps in the literature, the objectives of this study are threefold: (i) to evaluate LCA for concrete mix designs containing alternative cement replacement materials in comparison with conventional 100% general use cement concrete; (ii) to develop six functional units that range in complexity, from simple (one variable) to complex (three or greater variables), which are a function of volume, binder intensity, compressive strength and durability; and (iii) to evaluate the interplay and sensitivity of LCA for four concrete mix designs and six functional units.

2 Goal and scope definition

2.1 LCA goal

The selection of an appropriate functional unit in the context of LCA of concrete materials is explored by evaluating the LCA results and their sensitivity of six functional units of varying degrees of complexity. It should be noted that the compressive strength and rapid chloride permeability measurements are taken at 28 days for all cases.

i.   Volume of concrete
ii. Volume of concrete and compressive strength

iii. Volume of concrete and rapid chloride permeability
iv. Volume of concrete and binder intensity (defined as amount of cementing materials per unit of 28-day compressive strength)
v. Volume of concrete and a combination of compressive strength and rapid chloride permeability and
vi. Volume of concrete and a combination of binder intensity and rapid chloride permeability.

2.2 LCA scope definition

2.2.1 Mix designs

The four concrete mix designs considered in this study are shown in Table 2 along with their corresponding experimental results for the 28-day compressive strength and rapid chloride permeability. The concrete mix presented in the left-most column is labelled as 100GU which is concrete with 100% general use (GU) cement. In this study, the 100GU mix is considered the base case. The second concrete mix (GU-25SL) contains general use cement with 25% slag (SL) as cement replacement. The third concrete mix (GUL-25SL) is made with general use limestone (GUL) cement (contains 12% limestone) and 25% slag as cement replacement. The fourth concrete mix (GU-8SF-25SL) is a ternary blend composed of general use cement with 8% silica fume (SF) and 25% slag as cement replacement. The four mix designs are used by the Ministry of Transportation of Ontario in transportation infrastructure and represent the reference flows for this study, as defined by the International Organization for Standardization

(ISO) (1998), linking the actual concrete component flows to the functional performance of the overall system (i.e. the functional unit). It should be noted that the mix designs are all created based on a standard volume of 1 m^3 of concrete but that they vary in their proportions of the concrete components. This is aligned with the definition of a reference flow presented in Section 1.2; the mix design translates the six functional units explored in this paper into specific product flows (i.e. cement, aggregate, water, silica fume, slag and limestone cement).

2.2.2 System boundary

The cradle-to-grave system boundary for LCA of conventional concrete, which is composed of 100% general use cement, fine and coarse aggregate and water, is identified in Fig. 1. The system boundary was designed to align with the flow of materials and energy through each system and present a high-level view of the activities that are and are not included in the analysis. The processes for conventional concrete represent the baseline system boundary. Each process is composed of input and output data such as energy use, raw material use and emissions to air, land and water, which correspond to the activities described as follows. The *water treatment* process is the extraction and processing of water. *Cement production* is the extraction and transportation of raw materials and the manufacturing of cement including blending, grinding and pyroprocessing and cement transportation. *Aggregate production* includes the extraction, processing and transport of fine and coarse aggregates. *Concrete plant operations* include batching and mixing activities and transport of concrete

Table 2 Mix designs and hardened properties used as input for the LCA and functional unit calculations

Quantity (kg/m³)	Mix design identification			
	$j^a = -$ 100GU[b]	$j^a = 1$ GU-25SL	$j^a = 2$ GUL-25SL	$j^a = 3$ GU-8SF-25SL
Water	180	155	150	140
General use cement (GU)	429	300	–	276
General use limestone (GUL) cement	–	–	300	–
Slag (SL)	–	53	54	100
Silica fume (SF)	–	–	–	24
Coarse aggregate	900	1064	1071	1000[c]
Fine aggregate	875	779	781	800[c]
Air-entraining admixture (mL kg⁻¹ of cementing material)	52	–	–	–
28-day compressive strength (MPa)	48.5	36	34.7	56.5
28-day rapid chloride permeability (C)	3186	2135	1969	421

[a] Index values corresponding to Eqs. (1) to (6)

[b] Base case scenario (Dolatabadi 2013)

[c] Aggregate quantities are estimated based on typical Ministry of Transportation proportions
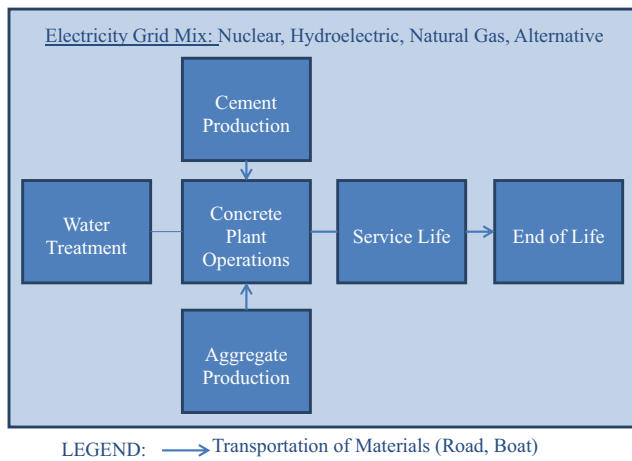
Fig. 1 System boundary for LCA of general use cement concrete products

to the site where it will be placed. *Service life* includes maintenance activities such as repair. *End of life* is the in-place rubblising of concrete. The electricity grid mix composition, which includes nuclear, hydroelectric, natural gas and alternative means of energy production is also shown. The life cycle iunventory (LCI) data used to create the model is documented in Section 3.2.

In order to model the concrete mix designs containing slag, silica fume and general use limestone cement as cement replacement materials, the system boundary presented in Fig. 1 is modified as follows:

- To model silica fume, a silica fume transportation process is added as described in Section 3.2.6.
- To model slag, a slag processing and transportation process is added using the same methodology as for silica fume transportation, as described in Section 3.2.7.
- To model general use limestone cement, the general use limestone production was substituted for general use cement production as described in Section 3.2.8.

3 Life cycle inventory

The creation of an LCI is a foundational step for any further assessment of environmental impacts. Generally, every input or output of materials or energy included within the system boundaries needs to be identified and quantified. There are several factors that can influence the quality of an LCI, with the primary concern being the quality of the data itself. Sources of data can be diverse and may originate from governments, academic institutions, industry organisations or corporations, among others. This data may represent a wide variety of geographical regions or time periods. Some of this

data may also be sensitive or proprietary. The quality of the LCI used for an LCA study can greatly influence the results.

3.1 LCI methodology

The collection of high-quality data is a particularly important and challenging stage of LCA. It is the foundation for the entire LCA, and errors in LCA can often be attributed to errors in the LCI (Coulon et al. 1997). Data quality is multi-dimensional and not necessarily quantitative. Many LCAs and LCIs use the semi-quantitative matrix developed by Weidema and Wesnaes (1996), as shown in Table 3. Further research (De Barba Junior et al. 2014) established data-quality indicator thresholds for excellent (<10) and very good (<12) data quality, where the best score (cumulative of five indicators where 1 is the strongest score and 5 is the weakest score) is 5 and the worst score is 25. Note that 'unknown' conditions merit the worst scores. This highlights the difficulty of working with datasets that are poorly documented.

The data-quality pedigree matrix shown as Table 3 was applied to evaluate data quality and assess potential LCI datasets for this research. A data-quality ledger which contains the results of this analysis is included in Appendix B of the Electronic supplementary material.

3.2 Life cycle inventory documentation

By applying the data collection methodology described in Section 3.1, LCI data was collected for all major processes (as shown in Fig. 1) included in the system boundaries for each type of concrete. This section describes the sources, limitations and assumptions associated with each dataset selected.

3.2.1 Cement production process

A report released by the Athena Sustainable Materials Institute titled *Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates: Cement and Structural Concrete Products* (Athena 2005) contains detailed LCI data for the production of cement. The raw material, energy use, atmospheric emissions, liquid effluent and water usage data presented in this report was used to create the cement production process in all of the LCA models. This dataset is meant to provide an overview of the Canadian Portland cement industry and is based on data from specific regions of the industry. The Central Canada (Manitoba and Ontario) data was used for this research as it is most relevant to the jurisdiction of the Ministry of Transportation. As the data was collected for this region specifically, it reflects the production technology, raw material characteristics and transportation distances and modes that are typical to the Ontario industry.

Table 3 Data quality pedigree matrix (reproduced from Weidema and Wesnaes 1996)

| Indicator	1 (strongest)	2	3	4	5 (Weakest)
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified measured data	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data from a smaller number of sites/shorter periods or incomplete data from adequate number of sites	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	<3 years difference to year of study	<6 years difference	<10 years difference	<15 years difference	Age unknown or >15 years difference
Geographical correlation	Data from area under study	Average data from larger area in which the study area is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

3.2.2 Electricity grid mix process

The Electricity Grid Mix process is based on the Canadian electricity grid mix processes from the GaBi Extension database XVII: Full US. That process was developed specifically for Canada in 2011 and includes biogas, biomass, hard coal, heavy fuel oil, hydropower, natural gas, nuclear, photovoltaics, wind and waste to energy. In order to increase the level of geographical and temporal correlation to the scope of this work, the ratio of the individual types of generation was modified to reflect the supply mix of Ontario in 2014 (shown in Fig. 2).

3.2.3 Water treatment process

Racoviceanu et al. (2007) used the economic input-output life cycle assessment model and the GHGenius model to quantify the energy use and greenhouse gas emissions for the City of Toronto municipal water treatment system. Several stages were considered including chemical manufacturing, chemical transportation and water treatment facility operation. Although the scope of the study was somewhat limited, given that only energy use and greenhouse gas emissions were considered, a review of the National Pollutant Release Inventory has shown that there are no emissions recorded for the four Toronto water treatment plants (which are Harris, Clark, Horgan and Island). Therefore, as reported in the National Pollutant Release Inventory, none of the 363 substances (including NO_x, SO_2 or particulate matter) are released at these facilities (Environment Canada 2013).

3.2.4 Aggregate processes

Four aggregate processes are integrated in the LCA model: (i) fine aggregate production, (ii) coarse aggregate production, (iii) fine aggregate transportation and (iv) coarse aggregate transportation. To build each of these processes, data for energy requirements, raw material requirements, atmospheric emissions and liquid effluents were collected for the extraction, processing and transportation of the fine and coarse aggregates (Athena 2005). Based on an Athena (2005), road transportation by diesel-powered truck requires 1.18 MJ/t-km. Emission factors for road transportation by truck are taken from Athena (2005) and are shown in Table 4. For all
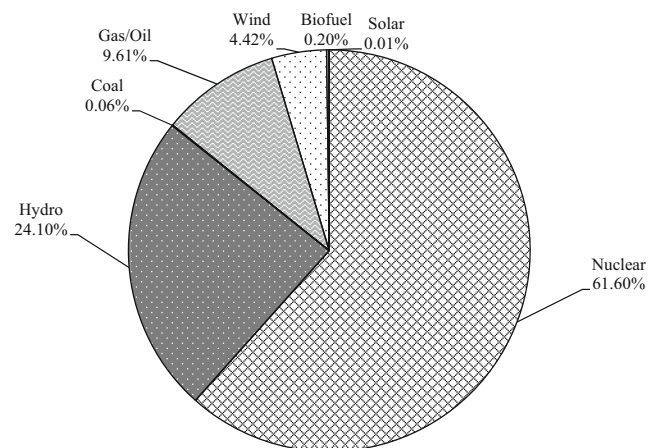
Fig. 2 Ontario's electricity supply mix for 2014 (Independent Electricity System Operator (IESO) 2015)

Table 4 Energy emission factors for the calculation of transportation energy consumption and emissions (Athena 2005)

Energy emissions factors (kg GJ^{-1})

CO_2	SO_2	NO_x	VOC	CH_4	CO
70.7	0.102	0.807	0.0869	0.0217	0.443

transportation processes in this model, potential routes were mapped out in consultation with the Ministry of Transportation of Ontario and based on the locations of pre-qualified suppliers that are on the Ministry of Transportation of Ontario's Designated Sources for Materials list. For each material, the worst-case transportation scenario, corresponding to the route that has the highest environmental impact, was then selected as shown in Table 5. For this analysis, where all the transportation processes use the same mode (truck), the route with the longest distance indicates the worst-case transportation scenario.

3.2.5 Admixture production processes

Data for admixtures, including superplasticising and air-entraining admixtures has been gathered from product declarations prepared by the European Federation of Concrete Admixtures Associations (2010). The environmental product declaration includes the raw materials, emissions to air, emissions to soil and emissions to water.

3.2.6 Silica fume transportation processes

Silica fume is a by-product of silicon production. It is a very fine substance that does not require further processing before it is incorporated into concrete. Upstream energy, raw materials and emissions are not included in this process, which is a common, conservative assumption. Silica fume transportation is modelled based on silica fume sources and modes of transportation that are typical for the Ministry of Transportation of Ontario. The corresponding emissions factors are shown in

Table 4, and the worst-case transportation scenario is shown in Table 5.

3.2.7 Slag processing and transportation processes

Slag is a by-product of the steel industry, which requires processing before it can be incorporated into concrete. Energy and emissions for this processing are quantified by Marceau et al. (2006). Upstream energy, raw materials and emissions for the production of the slag as a by-product of steel production are not included in this process. As described in the literature review, this is because these waste materials are generated regardless of whether they are incorporated into concrete, disposed of in a landfill or any other usage. Using them in concrete is environmentally beneficial, and so not including any upstream processes is conservative. This is an assumption commonly used in concrete LCAs. Slag transportation is modelled based on slag sources and modes of transportation that are typical for the Ministry of Transportation of Ontario. The corresponding emissions factors are shown in Table 4, and the worst-case transportation scenario is shown in Table 5.

3.2.8 General use limestone cement processes

For general use limestone cement production, transportation of raw materials is not included. This is because cement production facilities are typically located at limestone quarries, and so there is no transportation requirement for these materials (CANMET and Radian Canada 1993). As a result, the only added process for general use limestone cement production is the grinding of raw materials (Athena 2005).

3.2.9 Concrete plant operations process

The concrete production process represents the stage in the life cycle where the various concrete 'ingredients', including water, cement, fine aggregate, coarse aggregate and the various green alternative concrete materials, are combined in order to create concrete. The mix proportions were entered into the parameterised model according to the mix designs described

Table 5 Worst-case transportation scenarios for slag, silica fume and aggregate (based on Ministry of Transportation of Ontario)

Material	Route	Total distance (km)	Mode of transportation
Slag	Hamilton, Ontario to Picton, Ontario; Picton, Ontario to Toronto, Ontario	498	Truck
Silica fume	Niagara Falls, New York to St Basile, Quebec City; St Basile, Quebec City to Toronto, Ontario	1623	Truck
Coarse aggregate	Typical route	200	Truck
Fine aggregate	Typical route	200	Truck

in Table 2. In addition to the raw material requirements, the batching and mixing processes require energy. The energy requirement for the concrete plant operations was extracted from Prusinski et al. (2004), who calculated a value of 247 MJ for the production of a cubic metre of concrete. This value was consistent even with the addition of supplementary cementing materials (i.e. slag and silica fume), and the same assumption was used in this study.

3.2.10 Concrete maintenance process

Concrete maintenance activities are highly dependent on the specific concrete application and environmental conditions that the concrete is exposed to over its life. In terms of LCA, however, they can be represented as additional quantities of materials and energy that are required over the entire life of the concrete. As operational and cost considerations are not within the scope of this research, it is appropriate to combine all maintenance activities into a single activity. In order to estimate these impacts, the concept of a maintenance factor was used, where a maintenance factor of 20% means that over the entire life of the concrete, 20% more of the materials and energy required for initial placement must be input in order to maintain the concrete. A value of 20% was selected in consultation with the Ministry of Transportation of Ontario (Rhead and Schell, personal communication, 4 December 2014) and is applied to all of the mix designs included in this study.

3.2.11 End of life process

'End of life' is the final stage in a cradle-to-grave LCA. Potential disposal options for concrete products include recycling, landfill and reuse. Ministry of Transportation infrastructure is typically crushed in place for reuse as fill (i.e. rubblisation) (Rhead and Schell, personal communication, 4 December 2014). This activity is assumed to be powered by diesel. The energy required to crush 1 tonne of concrete is estimated as 34 MJ (Wilburn and Goonan 1998). This energy requirement was calculated based on the density of the concrete mix and was modified to reflect the density of each mix design. The emissions resulting from the use of diesel were estimated using emission factors from Athena (2005), as shown in Table 4.

4 Methodology

4.1 Life cycle impact assessment methodology

GaBi 6 software package (PE International 2014) is used to compile the LCI data and conduct the impact assessment. This software package was selected based on the critical comparison and evaluation of five software packages with application to concrete by Seto et al. (2016). GaBi 6 is packaged with several impact assessment methods, including the International Reference Life Cycle Data System method which was used for this study (European Commission-Joint Research Centre 2011). This method was selected because the International Reference Life Cycle Data System method was developed based on a rigorous and thorough assessment of existing life cycle impact assessment (LCIA) methods (including IPCC, ReCiPe, TRACI, EcoIndicator 99 and others) in the context of seven main criteria: completeness of scope, environmental relevance, scientific robustness and certainty, documentation transparency and reproducibility, applicability, overall evaluation of science-based criteria and stakeholder acceptance (European Commission-Joint Research Centre 2011). The guidance provided by the International Reference Life Cycle Data System 'is intended to support life cycle impact assessment on a global level recommending default characterisation models and associated factors for each impact category' (European Commission-Joint Research Centre 2011). As a result, it was determined that this method was the most appropriate approach to use in this study.

GaBi offers several options for impact categories such as global warming, ozone depletion, human toxicity, acidification, eutrophication, ecotoxicity, resource depletion (water) and resource depletion (mineral, fossil and renewable). Not every potential impact category, however, has international consensus with regard to classification and characterisation. Although international consensus is not the only factor to consider upon selecting relevant impact categories for a given application, it is however a relative measure of how often the category is used, and how well developed the methodologies are. The 'international consensus' information is based on a report compiled by the Danish Ministry of the Environment (Stranddorf et al. 2005). As is commonly reported in LCA literature, 'classification' means assigning LCI results to relevant impact categories and 'characterisation' refers to the science-based conversion factors used to model LCI impacts. Furthermore, based on Stranddorf et al. (2005), the level of international consensus of classification and characterisation of each category and discussion with the Ministry of Transportation of Ontario, four impact categories were assessed as priorities for this study, namely, acidification, global warming potential, resource depletion and water depletion. Table 6 presents a description of each impact category as well as the characterisation factor used in the analysis. In LCA, characterisation factors are science-based factors that are used to convert LCI data to actual environmental impacts (Scientific Applications International Corporation 2006). Raw LCIA results are presented in Appendix A of the Electronic supplementary material.

Table 6 Impact categories

	Impact category	Description	Characterisation factor
$i^a = 1$	Acidification	Release of protons and leaching out of anions from a system	Acidification potential (mole H+ ion equivalents)
$i^a = 2$	Global warming	Effect of increasing temperature in the atmosphere due to the reflection of radiation by greenhouse gases back to the surface	Global-warming potential (kg CO_2 equivalents)
$i^a = 3$	Resource depletion	Depletion of abiotic non-water resources (e.g. minerals or fossil fuels)	Resource-depletion potential (kg of antimony (Sb) equivalents)
$i^a = 4$	Water depletion	Water use (reuse, degradation or incorporation into final product)	Water-depletion potential (volume of water used (m^3))

^{a} Index values corresponding to Eq. (7)

4.2 Functional unit calculation

In this section, the methodology for calculating functional units (FU) is described. Equations (1) to (6) are given for the calculation of the six functional units. The six functional units considered in this study vary in complexity as a result of the number of variables that are considered simultaneously. The calculated functional units for each scenario are summarised in Table 7.

In the equations that follow, the index 'i' refers to the four impact categories included in this study, as indicated in Table 6. The index 'j' refers to the four mix designs included in this study, as indicated in Table 2. The index 'x' refers to the six functional units included in this study, as indicated in Table 7.

4.2.1 FU_1: volume (1 m^3 of concrete)

Volume is not a truly *functional* unit for LCA studies of concrete materials, as it provides information only about the physical properties of a particular product, rather than the performance of that product. However, it is included in this study to recognise that despite its limitations, it is simple to employ and is one of the most common functional units used in cement and concrete LCAs (as shown in Table 1). Equation 1 shows how FU_1 is calculated based on the relative volumes of the base material and each alternative concrete material that is modelled. In this study, the mix designs are all created based on a standard volume of one cubic metre of concrete but that they vary in their proportions of the concrete components (and therefore FU_1 is equal to 1). It should however be noted that the base material is in the denominator because a higher volume of concrete is worse for the environment due to the additional materials required. Therefore, if the alternative concrete requires more material it should increase the value of the functional unit.

$$FU_{(1,j)} = \frac{\text{volume } (m^3)_{(\text{alt.material}j)}}{\text{volume } (m^3)_{(\text{base material})}} = 1 \qquad (1)$$

where j corresponds to each alternative (alt.) mix design, as described in Table 2

4.2.2 FU_2: volume and compressive strength

Compressive strength is one of the most important performance characteristics of concrete, and 28-day compressive strength is a value that is commonly specified and evaluated to ensure the quality of concrete products. Equation 2 shows how FU_2 is calculated based on the relative 28-day compressive strength values (for 1 m^3 of concrete) of the base material

Table 7 Calculated functional units (FU)

		Variables included	Degree of complexity	Functional units (FU)		
				GU-25SL	GUL-25SL	GU-8SF-25SL
$x^a = 1$	FU_1	Volume	Simple	1	1	1
$x^a = 2$	FU_2	Volume and compressive strength	Moderately complex	1.10	1.05	0.86
$x^a = 3$	FU_3	Volume and rapid chloride permeability	Moderately complex	0.44	0.46	0.13
$x^a = 4$	FU_4	Volume, binder content and compressive strength	Complex	1.03	0.98	0.80
$x^a = 5$	FU_5	Volume, compressive strength and rapid chloride permeability	Complex	0.48	0.49	0.11
$x^a = 6$	FU_6	Volume, binder content, compressive strength and rapid chloride permeability	Complex	0.45	0.45	0.11

^{a} Index values corresponding to Eq. (7)

and each alternative concrete material that is modelled. It should be noted that the value for the alternative concrete material is in the denominator because a higher compressive strength is a more desirable performance characteristic for concrete. Concrete typically provides a compressive strength capacity in structural systems, and using higher strength concrete has the potential to both improve functional performance and reduce the amount of concrete needed to obtain the same performance (De Schepper et al. 2014). Therefore, if the alternative concrete has a higher compressive strength, this should lower the value of the functional unit.

$$FU_{2,j} = \frac{\text{strength (MPa)}_{\text{base material}}}{\text{strength (MPa)}_{\text{alt.material } j}} \qquad (2)$$

where j corresponds to each alternative (alt.) mix design, as described in Table 2

4.2.3 FU$_3$: volume and durability

As with compressive strength, durability is a critical performance characteristic of concrete, particularly when the concrete is steel reinforced, or when it is exposed to harsh conditions such as freeze-thaw cycling or the presence of ions such as chlorides or sulphates. The 28-day rapid chloride permeability is measured in Coulombs (C) (ASTM C1201) and is a measure of the durability of the concrete. Equation 3 shows how FU$_3$ is calculated based on the relative 28-day rapid chloride permeability test (RCPT) values (for 1 m^3 of concrete) of the base material and each alternative concrete material that is modelled. The value for the base material is in the denominator because a higher rapid chloride permeability value represents a worse performance for concrete. Therefore, if the alternative concrete has a lower rapid chloride permeability value, this should lower the value of the functional unit.

$$FU_{3,j} = \frac{\text{RCPT}(C)_{\text{alt. material } j}}{\text{RCPT}(C)_{\text{base material}}} \qquad (3)$$

where j corresponds to each alternative (alt.) mix design, as described in Table 2

4.2.4 FU$_4$: volume and binder intensity

Binder intensity is the ratio of the mass of binder material in a concrete mix design (kg) to the compressive strength of the concrete (MPa), for 1 m^3 of concrete. This combines physical characteristics (volume and mass) with a performance characteristic (compressive strength). Equation 4 shows how FU$_4$ is calculated based on the relative binder intensities of the base material and the alternative concrete material. The value for the base material is in the denominator because a higher volume of concrete is worse for the environment due to the

additional materials required to achieve a unit quantity of 28-day compressive strength. Therefore, if the alternative concrete requires more material, it is a less desirable scenario and should raise the value of the functional unit.

$$FU_{4,j} = \frac{\text{binder intensity (kg/MPa)}_{\text{alt. material } j}}{\text{binder intensity(kg/MPa)}_{\text{base material}}} \qquad (4)$$

where j corresponds to each alternative (alt.) mix design, as described in Table 2

4.2.5 FU$_5$: volume, compressive strength and durability

FU$_5$ represents one of the most complex types of functional units, as it combines three variables, two of which are important performance characteristics for concrete materials. This allows the functional unit to capture multiple dimensions of these materials, which are representative of the Ministry of Transportation of Ontario concrete acceptance criteria. Equation 5 illustrates how FU$_5$ is calculated by multiplying together the values for FU$_2$ and FU$_3$. As a result, the functional unit has its lowest and most desirable value when the strength value is higher and the rapid chloride permeability value is lower.

$$FU_{5,j} = FU_{2,j} \times FU_{3,j} \qquad (5)$$

where j corresponds to each alternative (alt.) mix design, as described in Table 2

4.2.6 FU$_6$: volume, binder intensity and durability

FU$_6$ represents one of the most complex types of functional units, as it combines four variables, two of which are important performance characteristics for concrete materials. This allows the functional unit to capture multiple dimensions of these materials, which are representative of acceptance criteria. Equation 6 illustrates how FU$_6$ is calculated by multiplying together the values for FU$_3$ and FU$_4$. As a result, the functional unit has its lowest and most desirable value when both the binder intensity (kg of cementing material per MPa of 28-day compressive strength) and the rapid chloride permeability are lower.

$$FU_{6,j} = FU_{3,j} \times FU_{4,j} \qquad (6)$$

where j corresponds to each alternative (alt.) mix design, as described in Table 2

4.3 LCA methodology

The raw LCIA results are factored to eliminate the various units used for the different impact categories such that the results can be more easily compared. The raw LCIA results

for each alternative material are divided by those for 100GU, the base case mix design, which has no alternative constituents, as shown in Eq. 7. The results for 100GU are placed on the numerator, because greater LCIA results (e.g. higher acidification, higher global warming potential) are less desirable. Therefore, a factored result that is lower than one corresponds to a material that is less environmentally impactful than the 100% general use cement base mix. By factoring relative to this value, it can quickly be determined whether a material has a higher or lower environmental impact compared with the base case.

Equation 7 calculates LCA results for each impact category which incorporate LCIA results and are specific to each mix design and functional unit. This method is consistent with a previous LCA of a sustainable concrete material (De Schepper et al. 2014) and allows for the combination of environmental impact (as measured by the LCIA results) and functional performance (as measured by the various functional units).

$$
\text{LCA result}_{i,j}
$$
$$
= \frac{\text{LCIA result}_{\text{impact category } i, \text{alternative material } j}}{\text{LCIA result}_{\text{impact category } i, \text{base material}}} * FU_{x,j} \qquad (7)
$$

where $i = 1$ to 4 and corresponds to impact category, as described in Table 6.

$j = 1$ to 3 and corresponds to each alternative mix design, as described in Table 2.

and $x = 1$ to 6 and corresponds to each functional unit, as described in Table 7.

5 Results and discussion

The LCA results for all four mix designs using the six functional units are presented in Fig. 3. LCA of alternative concrete materials (slag, silica fume and general use limestone cement) not only captures the effect associated with the reduction in cement content, but it also has potential to capture the physical and chemical implications these alternative materials have on mechanical properties, transport properties and durability.

Figure 3a–d presents the LCA results corresponding to the impact categories: acidification, global warming potential, resource depletion and water depletion, respectively. Each plot presents the vertical axis which is the LCA result which is factored to the base case mix design. All of the LCA results presented in Fig. 3a–d are factored to the results of the base case mix design. And therefore, all values of the 100% GU concrete mix design are equal to one. The horizontal axis of Fig. 3 presents the six functional units (FU$_1$–FU$_6$) that were used in this analysis and correspond to Eqs. 1–6, respectively. Examination of the results in Fig. 3 reveals the interplay

between the four concrete mix designs and the selected functional unit on the LCA result.

5.1 Effect of alternative mix constituents on LCA

Irrespective of the functional unit applied (FU$_1$–FU$_6$) or the complexity of the functional unit (simple, moderately complex, complex), the LCA results show that all alternative concrete mix designs (GU-25SL, GUL-25SL and GU-25SL-8SF) exhibit lower LCA values (less than 1) compared with the base case mix design (100% general use cement (100GU)) (equal to 1) for all four impact categories considered. This observation supports that the 'alternative' mix designs are indeed green mix designs. One common aspect between the three alternative mix designs is that they all contain 25% slag as cement replacement. Beyond the obvious benefits that partial replacement of cement by industrial by-products has on reducing CO_2 emissions, energy and resources, the use of slag and also yield beneficial effects on the transport properties of concrete and in turn positively affects long-term durability (as reflected by the properties reported in Table 2).

The effect of replacing general use cement with general use limestone cement can be isolated by comparing the LCA results of concrete mix GU-25SL to GUL-25SL. Although, in all cases shown in Fig. 3a–d, the LCA result for the GUL-25SL concrete is slightly lower than the GU-25SL mix with one exception, where LCA results are actually equal. This is supported by the fact that the cement contents (GU and GUL) in the mix designs are equal (300 kg/m^3) and in addition, the compressive strength (36 and 34.7 MPa) and rapid chloride permeability values (2135 and 1969 C) are also relatively similar to each other.

Although the implications of cement type had a modest effect based on the materials used in this study, the effect of an 8% silica fume addition was markedly more significant. This is apparent by comparing mix GU-25SL to mix GU-8SF-25SL for all functional units and for all impact categories shown in Fig. 3a–d. Part of the explanation is due to the fact that silica fume is typically added to concrete owing to its ability to achieve high early compressive strengths as well as its contribution towards developing a dense microstructure with very low transport properties which are beneficial for long-term resistance and durability to outdoor exposure conditions (i.e. freeze-thaw, salt scaling etc.). In fact, the mix containing silica fume and slag (GU-8SF-25SL) has the lowest LCA result of all the mix designs with one exception related to FU$_1$. The LCA result calculated using FU$_1$ is slightly higher (0.76) for concrete mix GU-8SF-25SL compared with the mix GUL-25SL (0.73) and mix GUL-25SL (0.67) which is likely attributed to the transportation of materials for silica fume. It should also be noted, however, that in this outlying case, FU$_1$ is only a physical characteristic functional unit (volume). When performance characteristics are taken

a

b
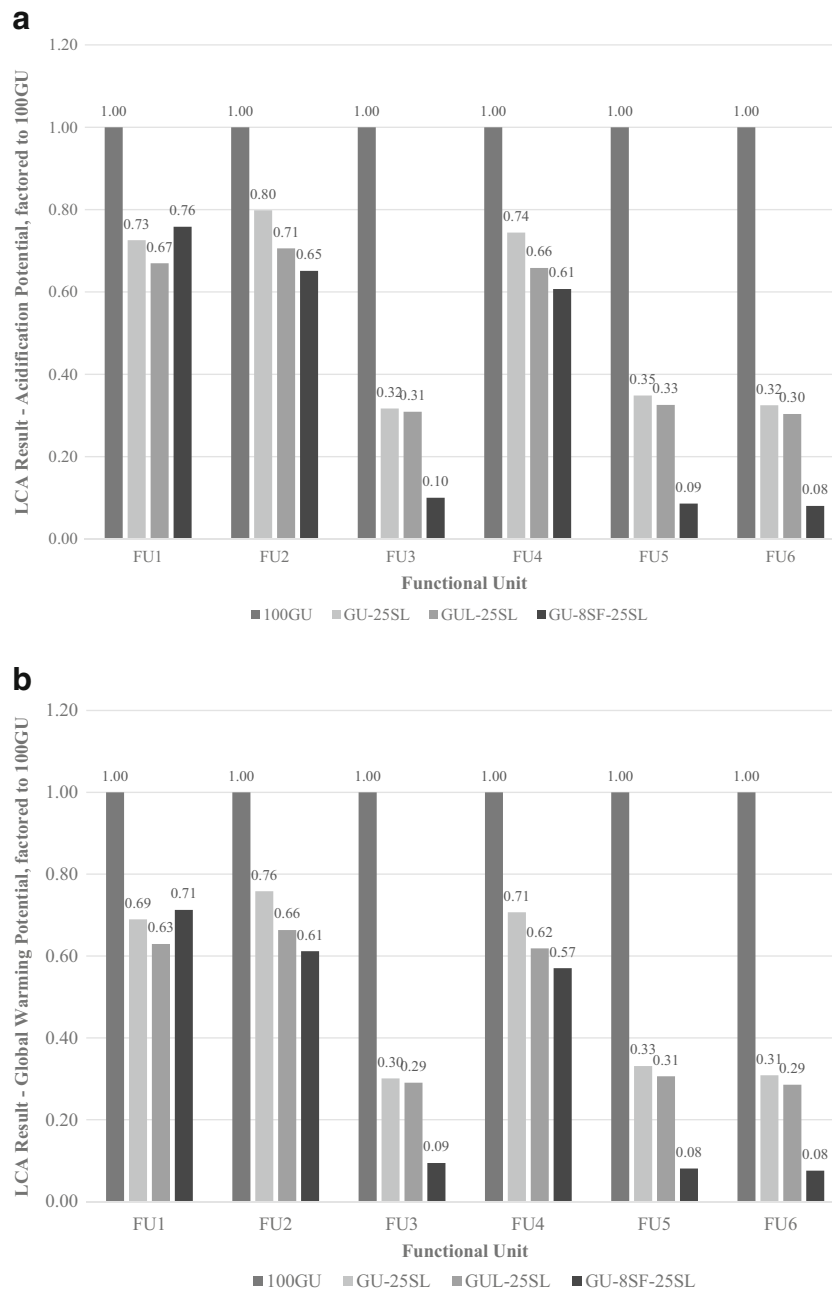
Fig. 3 Effect of functional unit on LCA results for four concrete mix designs in four different impact categories: **a** acidification potential, **b** global-warming potential, **c** resource-depletion potential and **d** water-depletion potential

into account, as in FU_2, FU_3, FU_4, FU_5 and FU_6, it is clear that the concrete mix containing silica fume has a superior environmental performance.

It is useful to examine the functional unit results in more detail to explain the large improvement in environmental performance of GU-8SF-25SL. As shown in Table 7, for FU_3, FU_5 and FU_6 in particular, the functional units are approximately four times higher for GU-8SF-25SL than for the other materials included in this study.

For outdoor concrete infrastructure where long-term durability is a concern, then FU3, FU5 and FU6 should be considered as they capture the durability component. Use of silica fume has a beneficial effect on refining the materials microstructure as a result of its pozzolanic, latent hydraulic properties, as well as chloride binding ability which positively impacts the long-term durability and longevity of the concrete. As can be seen from the relatively lower rapid chloride permeability value (Table 2) compared with all other mixes. These results show the importance of using functional units that incorporate performance characteristics, and where relevant, multiple performance characteristics, and are not limited to physical characteristics.
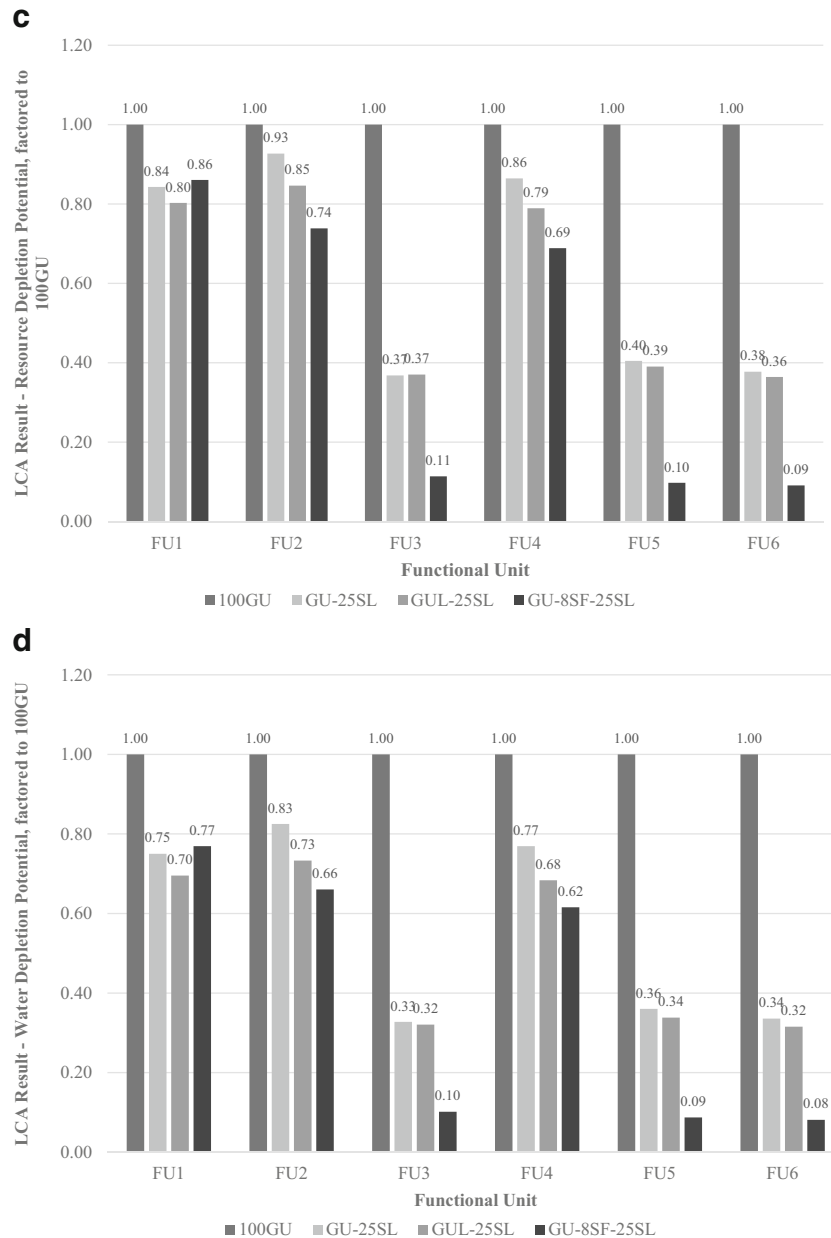
c

d

Fig. 3 continued.

5.2 Role of the degree of complexity and selection of different functional units

The LCA result for each alternative mix design (GU-25SL, GUL-25SL and GU-8SF-25SL) varies for each of the different functional units (FU1–FU6) evaluated in this study. However, examination of Fig. 3a–d reveals that for a specific mix design, the LCA results are relatively similar for FU_1, FU_2 and FU_4. At the same time, the LCA results are observed to be relatively close for FU_3, FU_5 and FU_6. For example from Fig. 3a, considering the alternative mix GU-25SL, the LCA results are 0.73, 0.80 and 0.74 for FU_1, FU_2 and FU_4, respectively, and 0.32, 0.35 and 0.32 corresponding to FU_3, FU_5 and

FU_6, respectively. The LCA results when FU_3, FU_5 and FU_6 are used in the calculation are reduced by more than 50% when compared with the LCA results when FU_1, FU_2 or FU_4 is used. Still considering Fig. 3a which presents the LCA for acidification potential, a similar trend is observed for alternative mix GUL-25SL. The LCA results are 0.67, 0.71 and 0.74 for FU_1, FU_2 and FU_4, respectively, and the results are 0.31, 0.33 and 0.30 corresponding to FU_3, FU_5 and FU_6, respectively, and the latter LCA results (for FU_3, FU_5 and FU_6) are more than 50% of those measured when LCA uses FU_1, FU_2 and FU_4. The alternative concrete mix design GU-8SF-25SL yields the lowest LCA results but also has the same trend as the other two alternative concrete mix

designs being that the LCA results are close (Fig. 3a), for FU$_1$, FU$_2$ and FU$_4$ are 0.76, 0.65 and 0.61 and LCA results when FU$_3$, FU$_5$ and FU$_6$ are 0.10, 0.09 and 0.08, respectively. These general trends are observed based on Fig. 3a, the trends are also true and observed for the other environmental impacts as shown in Fig. 3b–d, respectively. However, it is observed that the LCA result is the lowest for global-warming potential, slightly higher for acidification potential, slighter higher for water depletion and the highest for resource depletion.

To explain these observations, closer examination of the variables that control the functional unit needs to be considered. But before that, it should be noted that a functional unit that is considered to be simple (FU$_1$) can yield similar LCA results as a functional unit that is 'moderately complex' (FU$_2$) and even complex (FU$_4$). Similarly, the FU$_3$ which is moderately complex yields similar LCA analysis carried out when complex functional units (FU$_5$ and FU$_6$) are used. One variable that can be identified which differentiates FU$_1$, FU$_2$ and FU$_4$ from FU$_3$, FU$_5$ and FU$_6$ is the incorporation of durability by way of the rapid chloride permeability value. The physical and chemical contributions benefit the slag, silica fume and limestone have on pore refinement, and chloride binding, and in turn long-term durability is reflected by the relatively lower rapid chloride permeability value reported in Table 2 which have a strong influence on the LCA results (Aqel and Panesar 2016; Panesar and Francis 2014; Panesar and Chidiac 2009). This observation is supported by other researchers whose analysis reveals that an adequate understanding of the durability of alternative concrete materials is necessary to compute the environmental impacts correctly 'If not, the environmental benefit of replacing more cement with a supplementary material can be cancelled out due to additional manufacturing over time' (Van den Heede and De Belie 2010).

Table 8 shows the percentage difference for each mix design between the LCA results for each functional unit, as compared with the results for FU$_1$. For each mix design, it is observed that the least variation of the LCA results is observed for LCA analysis based on FU$_2$ and FU$_4$ (compared with FU$_1$). The range of percentage difference between the LCA

Table 8 Percentage difference between LCA results for functional units (FUs) incorporating performance characteristics vs. FU$_1$ (volume)

	Percentage difference between LCA results calculated using FU$_1$ and FU$_x$ (%)		
	GU-25SL	GUL-25SL	GU-8SF-25SL
FU$_2$	9.98	5.43	−14.2
FU$_3$	−56.3	−63.9	−86.8
FU$_4$	2.54	−1.69	−20.0
FU$_5$	−52.0	−51.4	−88.7
FU$_6$	−55.2	−54.6	−89.4

results for GU-25SL, GUL-25SL and GU-8SF-25SL are (2.5 to 10), (−1.7 to 5.4) and (−14 to −20), respectively. In contrast, markedly greater differences are observed between the LCA results based on FU$_1$ and the LCA results based on FU3, FU5 and FU6. In particular, for mixes GU-25SL, GUL-25SL and GU-8SF-25SL, the range of percent difference between FU$_1$ and FU$_3$ and FU$_5$ and FU$_6$ are (−52 to −56), (−55 to −64) and (−87 to −89), respectively. This highlights the importance of the selection of the functional unit, in particular for concrete with high-performance characteristics (strength and durability) such as concrete containing silica fume. However, it should be noted that in some concrete applications and in some geographic climates, it could be appropriate and reasonable not to capture a variable that is resistant to corrosion processes.

6 Conclusions

Today more than ever, concrete designers, engineers and the construction industry are faced with important decisions related to material selection and design of structures that are sustainable, cost effective and durable. In the past decades, concrete materials have advanced in order to achieve unique fresh properties, hardened properties and durability to last for longer service lives than ever before. In order to make environmentally responsible design decisions, it is necessary to examine the interplay between concrete materials, their properties and functional requirements and the implications on environmental impacts. The four impact categories considered in this analysis are acidification, global warming potential, resource depletion and water depletion. This study conducts an LCA analysis for four concrete mix designs based on six functional units. One of the concrete mix designs is the base case composed of 100GU. The other three mix designs contain some percentage replacement of the cement with slag and/or silica and/or general use limestone cement and are referred to as GU-25SL, GUL-25SL and GU-8SF-25SL. Six functional units are developed to capture the effect of the volume and material properties of each mix design. The defined functional units applied in this study are volume of concrete (FU$_1$), volume of concrete and compressive strength (FU$_2$), volume of concrete and rapid chloride permeability (FU$_3$), volume of concrete and binder intensity (defined as amount of cementing materials per unit of 28-day compressive strength) (FU$_4$), volume of concrete and a combination of compressive strength and rapid chloride permeability (FU$_5$) and volume of concrete and a combination of binder intensity and rapid chloride permeability (FU$_6$).

Key outcomes from this study pertain to the selection, complexity and sensitivity of the functional unit on LCA analysis in the context of concrete containing alternative cement-replacement materials.

- For the concrete mix designs considered in this study, the LCA results for all six functional units (FU$_1$–FU$_6$) revealed that the incorporation of the alternative cementing materials, namely slag, silica fume and general use limestone cement, reduced the environmental impact compared with the base mix of 100% general use cement. Therefore, this outcome reveals that all three of the alternative concrete mix designs are indeed green. It should be noted, that the alternative mix designs, GU-25SL and GUL-25SL exhibited lower environmental impact compared with 100GU even though they had lower 28-day compressive strength values. This outcome emphasises the non-linearity of the effect of material properties on quantification of environmental impacts.

- The LCA results were computed as a function of six functional units which have varying degrees of complexity (simple (FU$_1$), moderately complex (FU$_2$, FU$_3$) and complex (FU$_4$, FU$_5$, FU$_6$)). Relatively similar results were observed when comparing the LCA results for FU$_1$ (volume), FU$_2$ (volume and compressive strength) and FU$_4$ (volume and binder intensity were used). Relatively similar results were observed when comparing the LCA results when FU$_3$ (volume and rapid chloride permeability), FU$_5$ (volume and a combination of compressive strength and rapid chloride permeability) and FU$_6$ (volume and a combination of binder intensity and rapid chloride permeability). This outcome indicates that irrespective of the degree of complexity of the functional unit, for the concrete considered in this study (which has applications to transportation infrastructure), the rapid chloride permeability which is a direct indicator of durability strongly controls the LCA. This illustrates the importance of conducting an LCA with a selected functional unit that captures the concrete's functional performance metrics specific to its application and expected exposure conditions.

- The LCA results for the mix designs considered in this study are very sensitive to the choice of functional unit. In comparison with FU$_1$ which is only a function of the volume of concrete, LCA analysis based on FU$_2$ and FU$_4$ only varied within 1.7–20% (for all the alternative (green) mix designs). However, in comparison with FU$_1$ (volume only), the LCA results based on FU$_3$, FU$_5$ and FU$_6$ varied between 52 and 89% (for all three of the alternative (green) concrete mix designs). This outcome highlights the sensitivity of functional units on the LCA results. It is suggested that a complete LCA for a given concrete mix design should entail examination of multiple functional units in order to identify the range of environmental impacts or the optimal environmental impacts.

References

Alexander MG (2016) Performance-based concrete durability design and specifications in South Africa—background, implementation, and quo nunc? Fib Symposium Performance-Based Approaches for Concrete Structures. Editor: H. Beushausen. pp 52–62

Anderson JE, Silman R (2009) A life cycle inventory of structural engineering design strategies for greenhouse gas reduction. Struct Eng Int 283–288

Aqel M, Panesar DK (2016) Hydration kinetics and compressive strength of steam-cured cement pastes and mortars containing limestone filler. Construct Build Materials 113:359–368

ASTM International (2012) Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. ASTM C1202-12. West Conshohocken, PA: ASTM International

Athena (2005) Cement and structural concrete products: life cycle inventory update #2. Athena Sustainable Materials Institute, Ottawa

Berndt ML (2009) Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. Const Build Mats 23:2606–2613

Brown D, Sadiq R, Hewage K (2014) An overview of air emission intensities and environmental performance of grey cement manufacturing in Canada. Clean Technol Environ Pol 16:1119–1131

Canadian Standards Association (2016) Obtaining and testing drilled cores for compressive strength testing. Ontairo, Canada. Retrieved from http://applications.roadauthority.com/Standards/?Id=DF6091DB-C63E-4FAF-8570-3E9690BF50AD

CANMET and Radian Canada (1993) Raw material balances, energy profiles and environmental unit factor estimates: cement and structural concrete products. Ottawa: Athena sustainable materials institute

Carbon Leadership Forum (2012) North American Product Category Rules (PCR) for ISO 14025 Type III Environmental Product Declarations (EPDs) and/or GHG Protocol Conformant Product 'Carbon Footprint' of Concrete. Seattle: University of Washington College of Built Environments Department of Architecture

Celik K, Meral C, Gursel A, Mehta P, Horvath A, Monteiro P (2015) Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended Portland cements containing fly ash and limestone powder. Cement Concrete Comp 56:59–72

Chen C, Habert G, Bouzidi Y, Jullien A (2010a) Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. J Clean Prod 18:478–485

Chen C, Habert G, Bouzidi Y, Jullien A, Ventura A (2010b) LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete. Resour Conserv Recy 54:1231–1240

Churchill C, Panesar DK (2013) Life-cycle cost analysis of highway noise barriers designed with photocatalytic cement. Struct Infrastruct Eng 9(10):983–998

Collins F (2010) Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint. Int J Life Cycle Assess 15:549–556

Coulon R, Camobreco V, Teulon H, Besnainou J (1997) Data quality and uncertainty in LCI. Int J Life Cycle Assess 2(3):178–182

Crossin E (2012) Comparative life cycle assessment of concrete blends. Centre for Design RMIT University, Melbourne

Damineli BL, Kemeid FM, Aguiar PS, John VM (2010) Measuring the eco-efficiency of cement use. Cement Concrete Comp 32:555–562

De Barba Junior DJ, de Oliveira Gomes J, Bork CA (2014) Reliability of the sustainability assessment. 21st CIRP Conference on Life Cycle Engineering, pp 361–366

De Schepper M, Van den Heede P, Van Driessche I, De Beile N (2014) Life cycle assessment of completely recyclable concrete. Materials 7:6010–6027

Dolatabadi M (2013) Properties and performance of photocatalytic concrete. Library and Archives Canada, Toronto

Environment Canada (2013) Summary of national pollutant release inventory reporting requirements. Retrieved from Environment Canada-Pollution and Waste: https://www.ec.gc.ca/inrp-npri/default.asp?lang=en&n=629573FE-1

European Commission-Joint Research Centre (2011) ILCD handbook: recommendations for life cycle impact assessment in the European context. Luxemburg: Publications Office of the European Union

European Federation of Concrete Admixtures Associations (2010) EFCA Publications. Retrieved January 10, 2015, from EFCA: http://www.efca.info/publications.html

Fernandez-Ordonez D (2016) Sustainability and performance design of structures with precast elements. Fib Symposium Performance-Based Approaches for Concrete Structures. Editor: H. Beushausen, pp 13–21

Garcia-Segura T, Yepes V, Alcala J (2014) Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int J Life Cycle Assess 19:3–12

Gursel AP, Ostertag C (2017) Comparative life-cycle impact assessment of concrete manufacturing in Singapore. Int J Life Cycle Assess 22:237–255

Hajek P (2016) Sustainable concrete and concrete structures—challenge for a sustainable future. Fib Symposium Performance-Based Approaches for Concrete Structures. Editor: H. Beushausen, pp 91–100

Hassan M (2009) Life-cycle assessment of titanium dioxide coatings. Building a sustainable future—Proceedings of the 2009 Construction Research Congress. 2, pp. 836–845. Seattle: American Society of Civil Engineers

Hossain MU, Poon CS, Lo IMC, Cheung JCP (2016) Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach. Int J Life Cycle Assess 21:70–84

Huntzinger D, Eatmon T (2009) A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. J Clean Prod 17:668–675

Independent Electricity System Operator (IESO) (2015) Supply overview. Retrieved 10 February 2015, from IESO: http://www.ieso.ca/Pages/Power-Data/Supply.aspx

International Organization for Standardization (ISO) (1998) Environmental management—life cycle assessment—goal and scope definition and inventory analysis. ISO, Geneva

International Organization for Standardization (ISO) (2006) Environmental management—life cycle assessment—principles and framework. ISO, Geneva

Jonsson A, Bjorklund T, Tillman A-M (1998) LCA of concrete and steel building frames. Int J Life Cycle Assess 3(4):216–224

Kawai K, Sugiyama T, Kobayashi K, Sano S (2005) Inventory data and case studies for environmental performance evaluation of concrete structure construction. J Adv Concr Technol 3(3):435–456

Knoeri C, Sanye-Mengual E, Althaus H-J (2013) Comparative LCA of recycled and conventional concrete for structural applications. Int J Life Cycle Assess 13(5):909–918

Lee K-M, Park P-J (2005) Estimation of the environmental credit for the recycling of granulated blast furnace slag based on LCA. Resour Conserv Recy 44:139–151

Li C, Cui S, Nie Z, Gong X, Wang Z, Itsubo N (2015) The LCA of Portland cement production in China. Int J Life Cycle Assess 20:117–127

Marceau M, Nisbet M, Van Geem M (2006) Life cycle inventory of Portland cement manufacture. Portland Cement Association, Skokie

Marinkovic S, Radonjanin V, Malesev M, Ignjatovic I (2010) Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manag 30:2255–2264

Mistry M, Koffler C, Wong S (2016) LCA and LCC of the world's longerst pier: a case strudy on nickel- containing stainless steel rebar. Int J Life Cycle Assess 21:1637–1644

Muller C (2016) Durability requirements for concrete nowadays and on the future—key parameters for performance concepts. Fib Symposium Performance-Based Approaches for Concrete Structures. Editor: Beushausen H, pp 42–51

Nisbet MA, Marceau ML, VanGeem MG (2002) Environmental life cycle inventory of Portland cement concrete. Portland Cement Association

Panesar DK, Chidiac SE (2009) Capillary suction model for characterizing salt scaling resistance of concrete containing GGBFS. Cement Concrete Compo 31:570–576

Panesar DK, Francis J (2014) The effect of saturated limewater and sodium chloride solution on the pore structure of cement paste using MIP and DWVS. Constr Build Mater 52:52–58

PE International (2014) GaBi 6.0

Prusinski JR, Marceau ML, VanGeem MG (2004) Life cycle inventory of slag cement concrete. Eighth CANMET/ACI Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete

Racoviceanu A, Karney B, Kennedy C, Colombo A (2007) Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems. J Infrastruct Syst 13(4):261–270

Scientific Applications International Corporation (SAIC) (2006) Life cycle assessment: Principles and Practice. Retrieved September 20, 2013. http://www.cs.ucsb.edu/~chong/290NW10/EPAonLCA2006.pdf

Seto K, Panesar DK, Churchill CJ (2016) Criteria for the evaluation of life cycles assessment software packages and life cycle inventory data with application to concrete. Int J Life Cycle Assess. doi:10.1007/s111367-016-1060-6

Shi C, Jimenez AF, Palomo A (2011) New cements for the twenty-first century: the pursuit of an alternative to Portland cement. Cement Concrete Res 41:750–763

Stranddorf H, Hoffman L, Schmidt A (2005) Update on impact categories, normalisation and weighting in LCA. Environmental Protection Agency, Danish Ministry of the Environment

Tait MW, Cheung WM (2016) A compative cradle-to-gate life cycle assessment of three concrete mix designs. Int J Life Cycle Assess 21:847–860

Tosic N, Marinkovic S, Dasic T, Stanic M (2015) Multicriteria optimization of natural and recycled aggregate concrete for structural use. J Clean Prod 87:766–776

Van den Heede P, De Belie N (2010) Durablity related functional units for life cycle assessment of high-volume fly ash concrete. Second International Conference on Sustainable Construction Materials and Technologies.Volume 3 of 3, pp 583–594

Van den Heede P, De Belie N (2012) Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations. Cement Concrete Comp 34:431–442

Wang R, Eckelman M, Zimmerman J (2013) Consequential environmental and economic life cycle assessment of green and gray stormwater infrastructures for combined sewer systems. Environ Sci Technol 47:11189–11198

Weidema B, Wesnaes M (1996) Data quality management for life cycle inventories—an example of using data quality indicators. J Clean Prod 4(3–4):167–174

Weidema B, Wenzel H, Petersen C, Hansen K (2004) The product, functional unit and reference flows in LCA. Danish Ministry of the Environment, Danish Environmental Protection Agency

Wilburn D, Goonan T (1998) Aggregates from natural and recycled sources. US Geological Survey, US Department of the Interior. Denver: US Geological Survey

Xing S, Xu Z, Jun G (2008) Inventory analysis of LCA on steel- and concrete-construction office buildings. Energ Buildings 40:1188–1193

Yang KH, Jung YB, Cho MS, Tae SU (2014) Effect of supplementary cmeneting materials on reductin of CO2 emissions from concrete. J Clean Prod 1–10

Yang K-H, Jung Y-B, Cho M-S, Tae S-U (2015) Effect of supplementary cementitious materials on reduction of CO_2 emissions from concrete. J Clean Prod 103:774–783