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Environmental life cycle assessment of concrete with different mixed designs

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ABSTRACT

To identify proper types of concrete with favourable mechanical and durability properties is necessary, which imposes minimum pollution into the environment. We collected information, based on the literature and consulting companies, by evaluating one cubic meter of five different types of concrete, including microsilica, Geopolymer, micro–nano bubble, nanosilica and using only ordinary Portland cement (OPC). After using a life cycle inventory (LCI) phase, according to the life cycle assessment (LCA) for cradle to gate, we applied SimaPro8.1 software using the collected information. The results indicated that global warming indicator in Geopolymer concrete was much lower than the other concretes and indicated a reduction of nearly 26% in comparison with ordinary Portland cement in concrete. Also, the global warming indicator increased approximately 56%, 17% and 38% in microsilica, nanosilica and micro–nano bubble concrete in comparison with OPC concrete, respectively. Common harmful environmental impacts that were associated with ecosystem damage, ecosystem quality, human health, climate change and global warming potential (GWP), human toxicity, acidification and eutrophication were observed in microsilica concrete, while OPC was the most environmentally friendly concrete in production stage due to its lowest level of environmental burdens.

Abbreviations: BEES; Building for Environmental and Economic Sustainability: CKD; Cement Kiln Dust: CML; Center of Environmental Science of Leiden University (Centrum voor Milieukunde Leiden): DB; Dichlorobenzene: DALY; Disability Adjusted Life Years: EFA; Electric furnace arc: GWP; Global warming potential: HPC; High-performance concrete: IPCC; The Intergovernmental Panel on Climate Change: LCA; Life cycle assessment: LCI; Life cycle inventory: NA; Natural aggregate: OPC; Ordinary Portland cement: PDF; Potentially Disappeared Fraction: RCA; Recycled concrete aggregate: RFC; Reactive powder concrete: SETAC; Society of Environmental Toxicology and Chemistry.

KEYWORDS

LCI; LC ordinary Portland cement (OPC); nanosilica; microsilica; Geopolymer; micro–nano bubble; concrete

Introduction

Due to the development acceleration in the construction industry, the effects of one of the human interventions in the environment are gradually emerging, and subsequent efforts to maintain favourable living conditions on the planet have begun. In the construction industry, concrete is involved in a high percentage of constructions and it plays a vital role in environmental pollution related to construction activities. Concrete materials are the major causes of releasing a large amount of CO_2 in the atmosphere (Meyer 2009). The current level of carbon dioxide (CO_2) in the atmosphere is close to 380 ppm (Feely et al. 2004). Approximately 6 billion tons of concrete are produced around the world each year (ISO 2005), where the contribution of ordinary Portland cement (OPC) concrete in the emission of carbon dioxide is about 5% to 7%, globally (Huntzinger and Eatmon 2009; Meyer 2009).

Since Iran is a developing country, it is not surprising to carry out many construction projects in which concrete is considered as one of their basic construction materials. The extraction of significant amounts of raw materials, high energy consumption and vast production has led researchers to indicate a high degree of willingness to identify the best concrete for the environment (Tait and Cheung 2016). Therefore, more studies are needed to improve this material to be more environmentally friendly.

Considering the importance of reducing greenhouse gas emissions, Iran has been committed in the Kyoto Protocol to reduce its greenhouse gas emissions up to 4% by 2030, and if sanctions imposed on Iran

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are removed and financial, technological and human resources capacities are provided, another additional 8% will be added to its commitments to reduce greenhouse gases (Protocol 2016). Therefore, more studies are needed to make this material more environmentally friendly to reduce greenhouse gases and other pollutions.

Various studies have been carried out on the life cycle assessment (LCA) of concrete and cement, such as the study of Huntzinger and Eatmon (2009) which assessed the environmental impacts of the production of four types of cement by using SimaPro 6 software. These types of cement included 1) traditional Portland cement, 2) blended cement (natural pozzolan), 3) cement which recycled 100% of waste cement kiln dust (CKD) into the kiln process and 4) Portland cement produced by using cement kiln dust. As a result, CKD reduced 5% of the environmental impact of cement. Van den Heede and De Belie (2012) compared the environmental burden of green concrete with traditional concrete. They evaluated the environmental impacts with problem-oriented CML 2002 method and the damage-oriented IMPACT 2002+ method. Their results indicated that the concrete produced from the slag of the furnaces (green concrete) imposes less contamination into the environment in comparison with the concrete made of Portland cement.

Habert et al. (2012) used a LCA methodology based on ISO14040 to compare high-performance concrete and traditional concrete in bridge construction, and finally, by using the SimaPro software and the Ecoinvent database, they concluded that according to two main methods of impact assessment (CML and IMPACT2002 +), high-performance concrete (HPC) indicated 10% less environmental impact relative to traditional concrete. Also, the application of HPC for the production of bridge construction materials reduced the emission of greenhouse gases up to 50%. Based on these observations, they concluded that applying HPC is more environmentally friendly.

According to the environmental LCA of reactive powder concrete (RFC) concrete and traditional concrete on a dam construction project in China, Liu et al. (2013) observed that RFC concrete had 64% and 55% reduction in greenhouse gases and energy consumption compared to traditional concrete, respectively. Furthermore, reduction of CO_2 was recorded in different phases (i.e. 72% in material production, 25% in transport, 51% in construction and 15.6% in operation and maintenance). Faleschini et al. (2014) used environmental LCA framework based on a cradle to gate approach for the recycled concretes containing an electric furnace arc (EFA) and concrete samples of natural aggregate (NA), which had the same strength and durability. The concrete containing EFA slag had 35% less emission than NA concrete.

Celik et al. (2015) reviewed the replacement of some parts of cement with fly ash and limestone powder. They concluded that the replacement of Portland cements up to 55% of the concrete volume of fly ash or limestone and grey powder, resulted in the production of a 28-day and 365-day efficient concrete, resistance to chloride penetration and reduction in global warming. Tait and Cheung (2016) studied the cradle to the gate of concrete containing 100% cement, 65% cement and 35% fly ash, 30% cement and 70% slag of the furnace, using SimaPro8 software, and Environmental impacts were assessed using Eco-indicator 99 and Eco points 97 methods. Their results indicated 62% and 32% reduction of CO_2, in second and third concrete, compared to the traditional concrete.

Marinković et al. (2014) carried out an environmental life assessment focusing on the evaluation of structural aggregates containing natural aggregates as well as structural concrete containing recycled aggregates based on the LCA method. The results indicated that recycled aggregates were more environmentally friendly than natural aggregates. Kleijer et al. (2017) studied the recycled concrete and traditional concrete. The information was obtained by Gravière Claire aux Moines company and the Ecoinvent database. The results of environmental LCA indicated a very low (1%) reduction in greenhouse gas emissions and a 4% reduction in energy consumption, and the ecological scarcity of Switzerland in 2006 reduced the environmental impacts up to 12%. Kurad et al. (2017) examined the effect of recycled aggregates and fly ash in concrete. Environmental impacts were assessed by the CML method to study the potential of global warming of concrete. Three mix families of 0% fine RCA, 50% fine RCA and 100% fine RCA were produced. Furthermore, 0% and 100% coarse RCA with 0%, 30% and 60% of fly ash without adding superplasticizer was considered. Average global warming potential (GWP) decreased by.91%, .02% and.91% per kg, respectively, and also by using 1% superplasticizer, it decreased by 2%.

The objective of our study was to compare the LCA of different concretes types including microsilica concrete, nanosilica concrete, Geopolymer concrete, micro–nano bubble concrete and OPC concrete using SimaPro8.1 software. LCA of the concretes includes

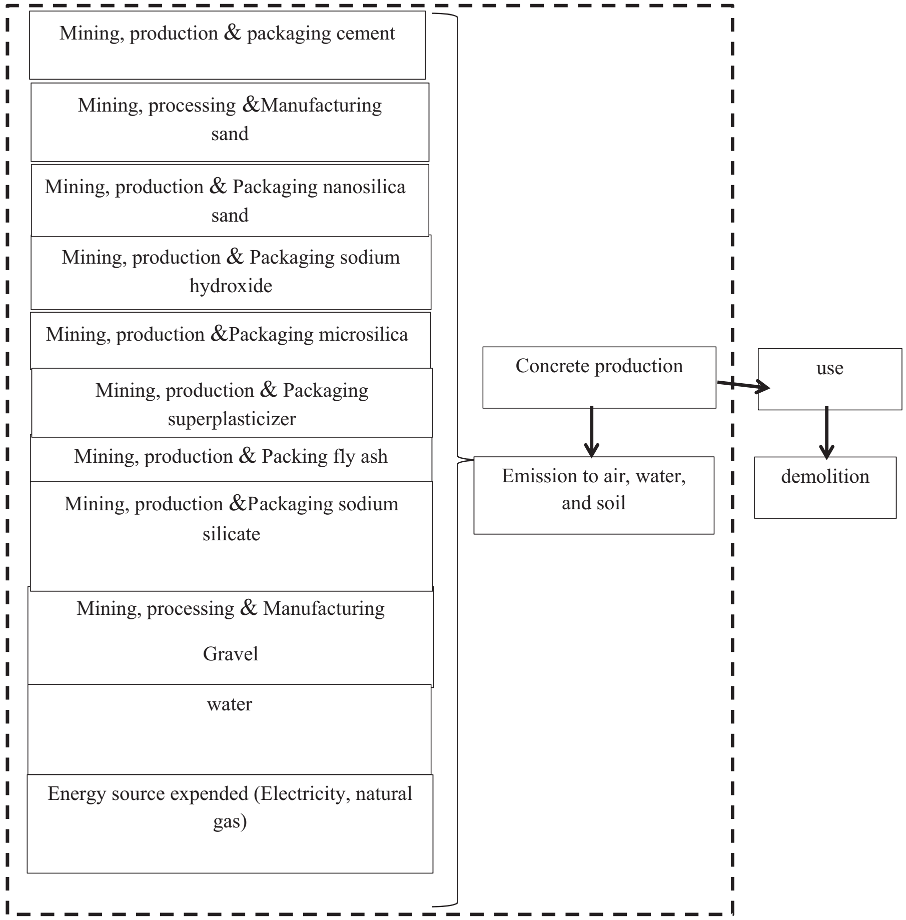

Figure 1. Concrete production system boundary.

ecosystem damage, ecosystem quality, human health, climate change and GWP, human toxicity, acidification and eutrophication categories.

Methodology

Life cycle assessment

The LCA method in this study focused on the environmental impacts related to the production of five types of concrete at different stages of the life cycle, namely the extraction of raw materials and the production of raw materials, the transfer of materials to the construction site and the producing process of concrete based on ISO 14040 standard. The LCA may help us for future environmental management strategies to produce concrete (Vahidi et al. 2015). According to ISO 14040, the LCA of the environment consists of four steps: definition of goal and the scope of the study, inventory analysis, impact analysis and finally the interpretation of the results (ISO I 14040 2006). The following describes these steps to evaluate the LCA of OPC concrete, nanosilica concrete, microsilica concrete, Geopolymer concrete and micro–nano bubble concrete.

Functional unit and system boundaries

The functional unit is defined as producing 1 m^3 of concrete, which unites constant for comparing different concretes made by OPC, nanosilica, microsilica, Geopolymer and micro–nano bubble with a 28-day compressive strength (approximately 40 MPa).

The study boundaries restricted to cradle to gate as indicated in Figure 1 and the stages in the life cycle are as follows: production and extraction of raw materials in concrete, transferring of raw materials to the concrete production site, concrete production at the site.

The life cycle inventory (LCI) for concrete considered in this research was based on the Ecoinvent database (Kellenberger et al. 2007). Also, we used expert's opinion, scientific bases and literature. The pressure-oriented method CML 2000 as a problem-oriented method (Guinée 2002) was used. CML method has the best and most common impact categories designed by the Society of Environmental

Table 1. Emissions and energy consumption a ton of nanosilica (Sabour et al. 2014).

Requirements	Unit	Amount
Emission to air		
CO_2	Kg	845
NO_X	Kg	0.12
SO_X	Kg	0.37
		Energy consumption
Electrical energy	KWh	1580

Toxicology and Chemistry (SETAC) (Faleschini et al. 2014) evaluate the environmental impacts. We considered the assignment of the results of the LCI to the CML 2000 category based on impact indicators for the assessment of environmental burdens. The environmental indicators of the CML method in this study are acidification, eutrophication, global warming, human toxicity. Also, by the damage-oriented method of Impact 2002+ (Jolliet et al.2003), the results of the LCI stage were evaluated in terms of human health, ecosystem quality, climate change and ecosystem damages.

Energy consumption and input information

- We calculated the amount of cement, sand, superplasticizer, sodium hydroxide and sodium silicate according to the Ecoinvent database.
- Nanosilica: The amount of direct and indirect emissions (at the factory and the relevant offices), as well as the equivalent electrical energy consumption of the Exonobel company for the production of nanosilica, is indicated in Table 1 (Sabour et al. 2014). Therefore, we used data of Table 1 including the emission and energy consumption as the input data for the SimaPro8.1 (2017) (Product ecology (Pre)consults 2017) using the nanosilica produced by the Swedish company of Exonobel.
- Fly Ash: fly ash is a by-product of coal power plants. Therefore, some studies have considered the contribution of greenhouse gas emissions from its production process zero (Turner and Collins 2013). We considered zero amount of greenhouse gas emissions.
- Microsilica: based on the weight per cent of output products in this study, 33% of the environmental burden of the ferrosilicium plant was considered as the production of microsilica and was modelled in SimaPro. The production capacity of this factory is 60,000 tons of ammonium ferrosilicium and about 20,000 tons of microsilica powder (Iran ferroalloy industry 2017).
- The second step is the process of transporting raw materials to the construction site, which includes the distance travelled, the type of loader vehicle and the fuel consumption of the vehicle. For transportation of the raw materials, sand and coarse aggregates in this study, the trucks with the capacity of 16 to 32 tons with EURO3 fuel were used. According to expert opinion, the distance travelled was considered 30 km for all materials.

Turner and Collins (2013) considered the comparison of emissions produced by the two types of Geopolymer and OPC concrete. They considered the concrete production of the Melbourne Concrete Plant for a bridge. The carbon dioxide emission factor during the manufacture and transfer of 1 m^3concrete was considered 0.0033 kg CO_2eq. Furthermore, the emission factor in the provision of temporary structural supports and access during producing, pumping and placement of concrete, final finishing and ultimately operation concrete engineering was calculated as 0.009 kg/m^3. We considered this emission factor for all scenarios (in production phase). In addition, the emission factor of 39.97 kg of CO_2 per m^3 was considered for the Geopolymer concrete for the emission of fuel which was used to increase the curing temperature of concrete (60 to 80°C). This concrete requires an increase in temperature over a period of 24 hours to reach the desired strength; however, OPC concrete cures at ambient temperature.

To produce bubble water for a micro–nano bubble concrete, a DAB pump with a power of 0.5 horsepower was used for 30 minutes. The overall energy of this machine was considered 6,500 KJ, and the energy needed to mix each concrete was 186.04 KW (Duxson et al.2007).

BEES software is designed by the National Institute of Standards and Technology (NIST) and based on information and standards in the United States. BEES combines the assessment of the environmental life cycle and the cost of construction materials and building performance.

It is also suitable for general use. BEES helps better decision-making by helping design, engineering or purchasing a product by making a balance between economic efficiency and the environment (Product ecology consultants 2013).

It is possible in this software that the user, considering the importance of environmental and economic effects, weighs the effects. The shortcomings of this software can be realized in the limited scope of building material cover (Bayer et al. 2010).

We encountered some limitations such as the lack of access to necessary information on the service life

Table 2. The result of acidification, eutrophication, global warming potential (GWP) and human toxicity of production of different types of concrete for one cubic meter.

Type of concrete	Unit Indicator	OPC concrete	Geo-polymer concrete	Microsilica concrete	Nanosilica concrete	Micro–nano bubble
Acidification	kg SO_2 eq.	0.84	1.11	1.55	0.96	0.89
Eutrophication	kg PO_4^{3-} eq.	0.159	0.183	0.572	0.185	0.175
Global warming potential (GWP)	kg CO_2 eq	386.44	286.85	605.32	453.31	424.17
Human toxicity	kg 1.4-DB eq.	35.68	72.35	182.52	41.04	37.45

of concretes which was selected scope of the study cradle-to-gate. We used the European database of Ecoinvent because of the lack of sufficient information related to emissions of some materials associated with the present study in Iran.

Results and discussion

Life cycle impact assesment (LCIA)

Table 2 indicates the results of the LCA of 1 $m^3$of different design of concrete, including OPC concrete, Geopolymer, micro–nano bubble, nanosilica and microsilica using the CML-IA baseline method.

As presented in Table 2, in the acidification category, different types of concretes containing microsilica, Geopolymer, nanosilica, micro–nano bubble and ordinary Portland Cement produced 1.55 kg SO_2 eq., 1.11 kg SO_2 eq., 0.96 kg SO_2 eq., 0.89 kg SO_2 eq. and 0.84 kg SO_2 eq., respectively. Also, microsilica concrete has the highest environmental impact in production. The significant impact indicator in microsilica concrete contains eutrophication (0.572 kg $PO_4{}^{3-}$ eq.), GWP (605.32 CO_2 eq.) and human toxicity (182.52 kg 1.4-DB eq.). Nanosilica concrete has second indicator value in the GWP category (453.31 CO_2 eq.) and the Eutrophication (0.185 kg $PO_4{}^{3-}$ eq.)

Geopolymer concrete is in the second rank in the Human Toxicity Group (kg1.4-DB eq is 72.35), while it produced the lowest greenhouse gas emission in the GWP group (286.85 kg CO_2 eq.). The results indicate that Geopolymer concrete, which does not contain cement, produces the minimum amount of environmental burden in GWP category. Turner and Collins (2013) examined emissions of OPC concrete and Geopolymer concrete. Based on their study, CO_2 emissions decreased up to 9%. Habert et al. (2010, 2011), Van Deventer et al. (2010) and McLellan et al. (2011) compared OPC concrete and Geopolymer concrete and indicated that CO_2 reduction could be up to 80%, although some studies demonstrated its reduction by 26%–45% (Lippiatt 2000) in Geopolymer concrete. These differences were stemmed from transportation consideration and curing temperature, which were not similar in these studies. In this study, the amount of CO_2 related to global warming associated with Geopolymer concrete decreased by 26% compared to OPC concrete by consideration of transportation as it mentioned before (EURO 3 fuel) and curing temperature (60 to 80°C (Turner and Collins 2013).

For confirmation of our results, we applied the BEES and IPCC method to determine the potential for acidification, eutrophication and GWP using SimaPro software. The BEES method expresses the potential of acid rain in terms of mole H +; however, the CML 2000 method reveals this potential based on Kg SO_2 eq. The IPCC also provides a list of ‘ provisional best estimates’ for GWP based on expert discussions around the world, which due to its extensive use and support was also used in LCA software databases (Maia de Souza et al. 2015). Table 3 indicates the results of the assessment of acidification, eutrophication and GWP using the BEES method. The comparison indicated in Table 3 is not based on the units of impact categories, and units are different. However, due to the difference in units of measurements, we compared two methods according to the contribution of each impact (in per cent) and it indicated that even by changing the measurement method, the overall results do not change.

Figure 2 indicates the comparison between the results of acidification, eutrophication, and GWP using BEES and CML 2000.

As indicated in Figure 2, the comparison between the results of eutrophication, acidification and the GWP of different types of the concrete mixture does not depend on the method of evaluation. In both BEES and CML 2000 methods (despite the differences in units of measurement), microsilica concrete has the highest environmental impact. Also, in the category of the GWP impact, different types of concretes containing microsilica, nanosilica, micro–nano bubble, OPC and Geopolymer produced, 28%, 21%, 20%, 18% and 13% CO_2, respectively. Figure 2 also describes an agreement between the results of GWP and acidification for all types of concrete using CML 2000 and BEES methods. The only small difference between the two mentioned methods belongs to eutrophication of

Table 3. Acidification potential of five concrete types based on the BEES method.

Impact category	Unit	OPC concrete	Microsilica concrete	Geopolymer concrete	Nanosilica concrete	Micro–nano bubble concrete
Acidification	H + mmole eq.	46217.83	83428.58	56566.27	52317.82	48987.72
Eutrophication	g N eq.	230.6112	1103.391	296.3896	273.6515	257.361
GWP	g CO_2 eq.	385366.9	599698.9	285626.6	452060.5	423015.593

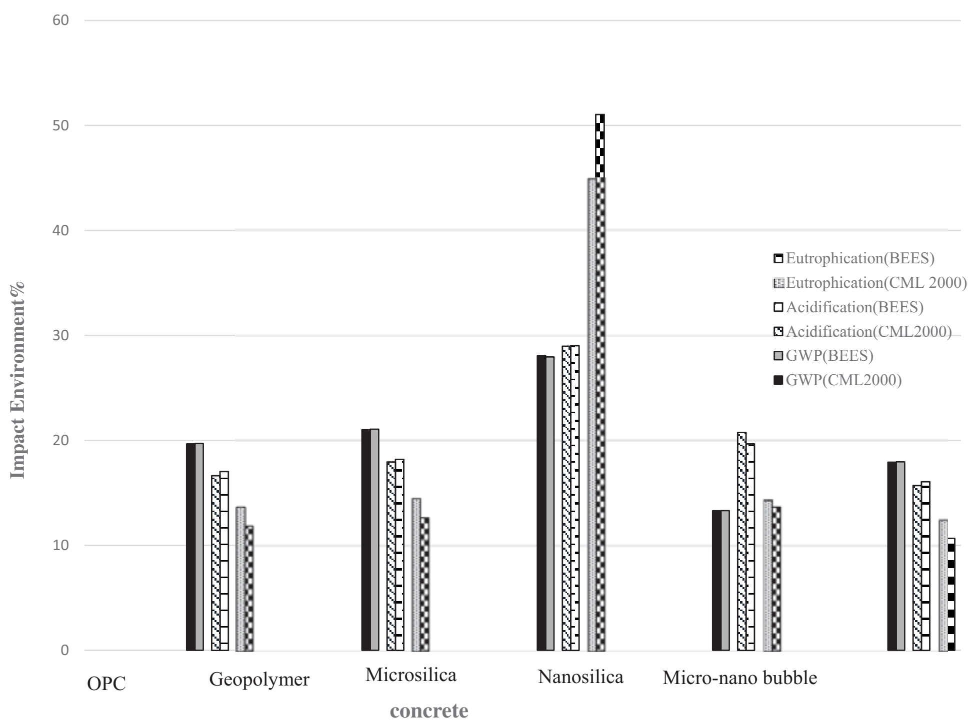

Figure 2. Comparison between results of acidification, eutrophication and GWP using BEES and CML2000 for five types of concrete.

Table 4. Comparison of the GWP results for five types of concrete using IPCC and CML-IA baseline (World 2000) method.

Type of concrete	GWP method of IPCC (kg CO_2eq.)	GWP method of CML-IA baseline (World 2000) (-(kg CO_2eq./kg)	Difference percentage (%)
OPC concrete	386.44	388.8463	0.6
Geopolymer concrete	286.85	289.543	0.9
Microsilica concrete	605.32	619.7306	2.4
Nanosilica concrete	453.31	456.0876	0.6
Micro–nano bubble concrete	424.17	426.7287	0.6

nanosilica concrete, which may be caused due to different methodology.

Table 4 indicates the results of the two CML 2000 and IPCC methods for the GWP. According to the Table 4, OPC concrete, nanosilica concrete and micro–nano bubble concrete have the same percentage of difference (0.6%); however, Geopolymer and microsilica concrete have 0.9% and 2.4% difference percentage, respectively. Therefore, the results of both CML and IPCC methods have an insignificant difference in the impact indicator of GWP. This result indicates that the evaluations do not depend on their methods.

Environmental damage assessment

Table 5 indicates the results of the environmental damage assessment for different types of concretes using impact 2002+ method. As indicated in Figure 5, silica concrete has the highest environmental damage. The environmental damage to silica concrete, including human health, ecosystem quality, climate change and ecosystem damage, was 0.000418 DALY, 57.37 PDF.m^2 yr, 586.16 kg CO2 eq and 8453.36 MJ surplus, respectively.

Geopolymer concrete has the second rank of environmental damage assessment, including human health (DALY of 0.000167) and ecosystem quality (39.59

Table 5. Results of environmental damage assessment for different types of concrete using IMPACT 2002+ method.

Impact category	Unit of measurement	OPC concrete	Geo-polymer concrete	Microsilica concrete	Nanosilica concrete	Micro-nano bubble
Human health	DALY	0.000137	0.000167	0.000418	0.000153	0.000142
Ecosystem quality	PDF. m^2yr	32.8	39.59	57.37	35.04	33.47
Climate change	kg CO_2 eq.	380.17	278.82	568.16	446.09	417.56
Ecosystem damage	MJ surplus	3460.05	3798.52	8453.36	3879.63	3581.85

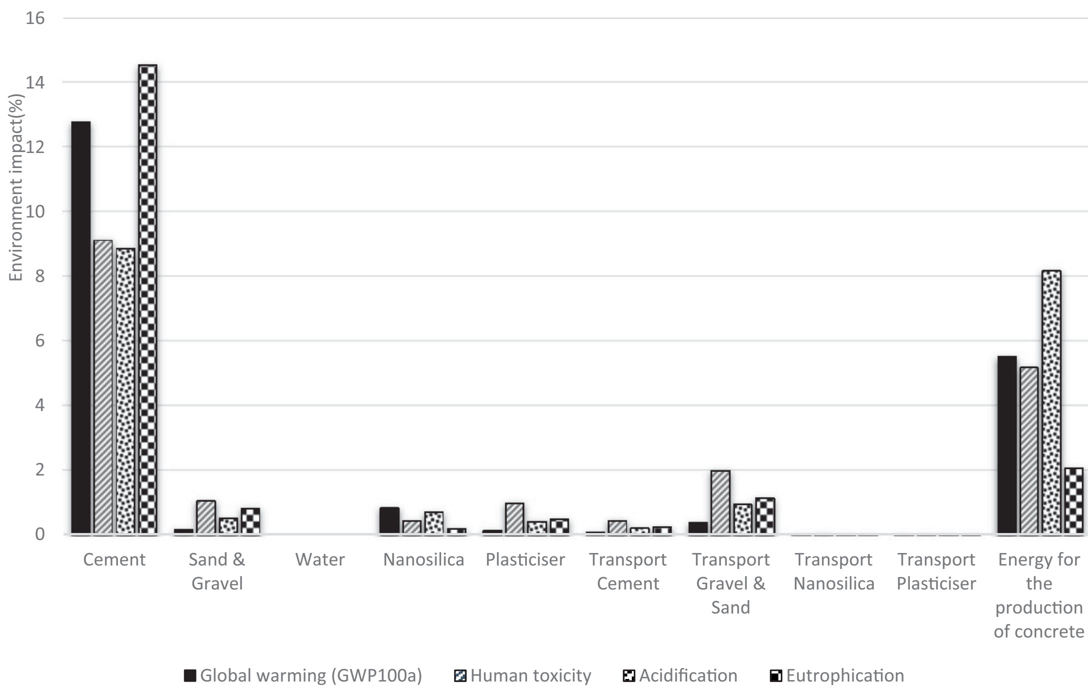

Figure 5. Impact of increasing each parameter by 20% on production of nanosilica concrete on global warming, human toxicity, acidification and eutrophication.

PDF[1]. m^2 yr). Also, nanosilica concrete is in the second range of climate change (446.05 kg CO_2 eq.) and ecosystem damage (3879.63 MJ surplus). The lowest environmental damage belongs to the OPC concrete. The impact indicator related to OPC concrete is human health equal to 0.000137 DALY, ecosystem quality is equal to 32.80 PDF. m^2 yr and ecosystem damage equal to 3460.05 MJ surplus. Despite the consumption of fuel for curing concrete samples, Geopolymer concrete has the lowest amount of damage of climate change (278.82 kg CO_2 eq.).

Maia de Souza et al. (2015) studied 1 m^2concrete and ceramic of roof coverage using IMPACT 2002+ method. They illustrated that concrete tiles have more impact than ceramic tiles on climate change (54%), resource depletion (35%) and water withdrawal (22%), whilst the difference between two other damage categories called human health (22%) and ecosystem quality (24%) was negligible over the whole life cycle of the tile product. The mentioned percentages in the pretenses demonstrate total impacts for each indicator.

Sensitivity analysis

To understand which types of material, energy and transportation in producing different types of concretes have a significant effect on the producing of GWP, human toxicity, acidification and eutrophication. Materials for the production of concrete included cement, gravel, sand, water, fly ash, sodium hydroxide, sodium silicate, superplasticizer, microsilica and nanosilica and also energy production and transportation were considered. We increased one of the materials in a concrete mix or energy or transportation by 20% without changing other material, energy and transportation. Then, Sima Pro software is run to determine its effect on GWP, human toxicity, acidification and eutrophication. Sensitivity analysis was performed for five different types of concrete. The results of sensitivity analysis are presented in Table 6, which indicates the details of these materials, energy and transportation

Figure 3 indicates the impacts of increasing 20% of each input parameter in the production of OPC

Table 6. Input parameters for sensitivity analysis.

Material/process/emission	Unit	OPC concrete	Geo-polymer concrete	Nanosilica concrete	Microsilica concrete	Micro-nano bubble
Portland cement	kg	328	_	390	450	381
Gravel	kg	1242	1202	1750	850	598.5
Sand	kg	781	647	_	800	1111.625
Sodium hydroxide	kg	_	41	_	_	_
Sodium silicate	kg	_	103	_	_	_
Plasticizer	kg	_	6	2.42	2	_
Fly ash	kg	_	408	_	_	_
Water	l	190	26	180	165	193
Microsilica	kg	_	_	_	39.6	_
Nanosilica	kg	_	_	10	_	_
Packing, cement	kg	328	_	390	450	381
Transport, cement	t.km	9.84	_	11.7	13.5	11.43
				52.5	25.5	17.955
		Transport, gravel	t.km	37.26	36.06	
Transport, sand	t.km	23.43	19.41	–	24	33.35
Transport nanosilica	t.km	–	–	0.33	–	–
Transport microsilica	t.km	–	–	–	3.6	–
Transport Fly ash	t.km	–	12.24	–	–	–
Transport, sodium hydroxide	t.km	–	1.23	–	–	–
Transport, sodium silicate	t.km	–	3.09	–	–	–
Transport, plasticizer	t.km	–	0.18	0.07254	0.06	–
Energy production	kWh	186.04	186.04	186.04	186.04	186.04
Water pump energy	kJ	–	–	–	–	670.5
CO_2 eq. concrete Batching	kg	0.0033	0.0033	0.0033	0.0033	0.0033
CO_2 eq. on site placement activities	kg	0.009	0.009	0.009	0.009	0.009
Emission for elevated temperature curing	kg	_	39.97	_	_	_

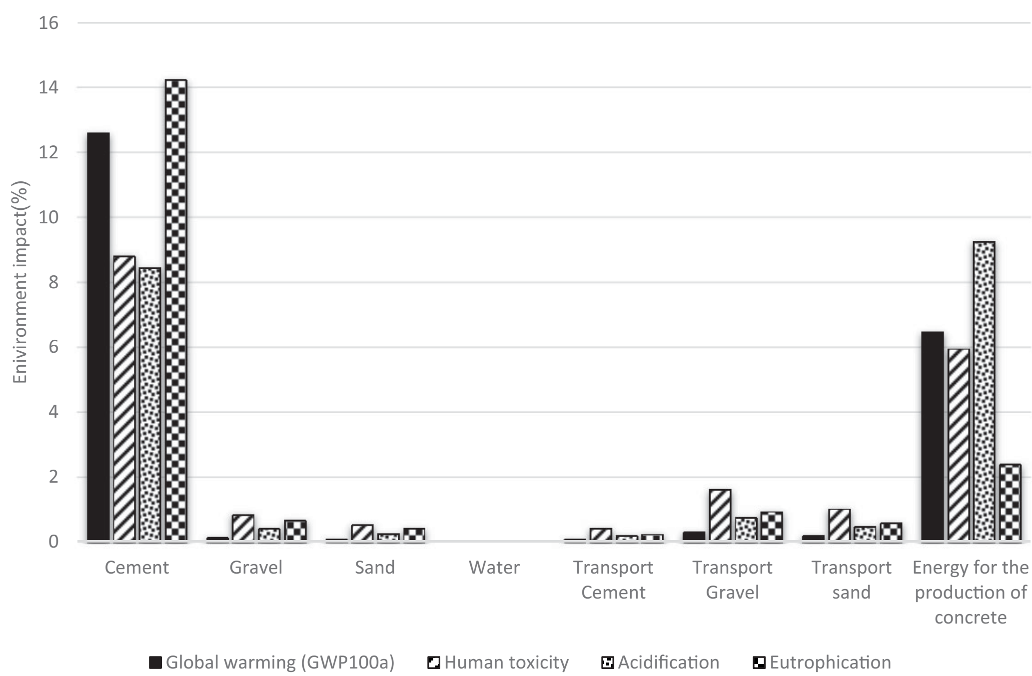

Figure 3. Impact of increasing 20% of each parameter in the construction of OPC concrete on global warming, human toxicity, acidification and eutrophication.

concrete on impact categories which include GWP, human toxicity, acidification and eutrophication.

As presented in Figure 3, cement and consumed energy are the most sensitive parameters in producing eutrophication, GWP and human toxicity, respectively. Increasing 20% cement consumption increased the eutrophication, GWP and human toxicity about14. 23%, 12.6% and 8.8%, respectively. Our results are similar to studies by Braga et al. (2017) and Blengini (2006), which identified cement as the most effective factor in global warming (Blengini 2006; Habert et al. 2010). Furthermore, Braga et al.

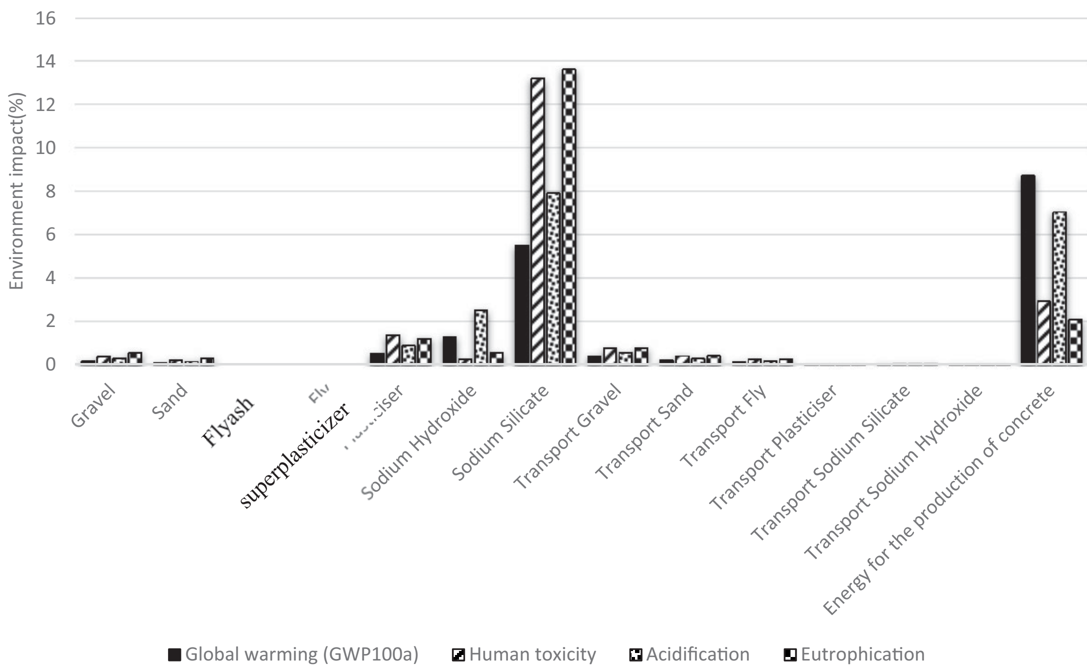

Figure 4. Impact of increasing 20 % of each parameter of Geopolymer concrete on global warming, human toxicity, acidification and eutrophication.

(2017) demonstrated environmental impacts related to 216 concrete mixing projects which were carried out and identified cement as the main cause of contamination and recycled aggregates as a prominent factor in reducing environmental pollution (Blengini 2006). However, by improving the efficiency of the cement industry, the amount of CO_2 released can be reduced up to 50% (Gäbel and Tillman 2005).

As indicated in Figure 3, the greatest impact on the acidification indicator is based on energy consumption in concrete production. Increasing the amount of energy consumption by about 20% can increase acidification of about 9%. Also, a 20% increase in the amount of cement increased the acidification groups by approximately 8.5% more. The least impact change is dedicated to water consumption (less than 1%). Therefore, despite the use of water in concrete, its contribution in the LCA is not taken into account due to the lack of specific relationship with the potential for environmental damage (Van den Heede and De Belie 2012).

Figure 4 represents the impact of increasing the parameters of Geopolymer concrete up to 20%, in $1m^3$of this concrete, on global warming, human toxicity, acidification and eutrophication. As presented in Figure 4, by increasing transporting of the raw materials (gravel, sand, fly ash, superplasticizer, sodium silicate, sodium hydroxide) up to 20%, we observed the greatest impact on the human toxicity (from 0.430% to 1.629%), eutrophication (from 0.249% to 0.941%), acidification (from 0.201% to 0.760%) and finally GWP (from 0.085% to 0.332%).

As indicated in Figure 4, in the production stage of Geopolymer concrete by increasing 20% of sodium silicate has the main effect on the value of eutrophication (13.64%), human toxicity (13.21%) and acidification (7.91%). At the next level, energy consumption has the main effect on GWP group (Figure 4). Energy consumption for concrete production in this scenario (Figure 4) is the major factor in GWP indicator. By increasing 20% of the energy for the production of concrete, the potential for global warming increased by about 8.7% (Figure 4).

As illustrated in Figure 4, sodium hydroxide consumption has the highest damaging effect on the acidification group (2.5%) and then the GWP (1.3%). Besides, the application of superplasticizer also increases human toxicity (1. 391%) and then Eutrophication (1.225).

Figure 5 indicates the impact of increasing 20% of each material and transportation in the production of $1m^3$ nanosilica concrete on global warming, human toxicity, acidification and eutrophication of one cubic meter of nanosilica concrete. In this scenario, cement and then energy consumption of concrete production are the most effective factors in environmental impacts.

As illustrated in Figure 5, by increasing the amount of cement consumption about 20% caused an increase of eutrophication (about 14.5%), GWP (about 12.8%), human toxicity (about 9%) and the acidification

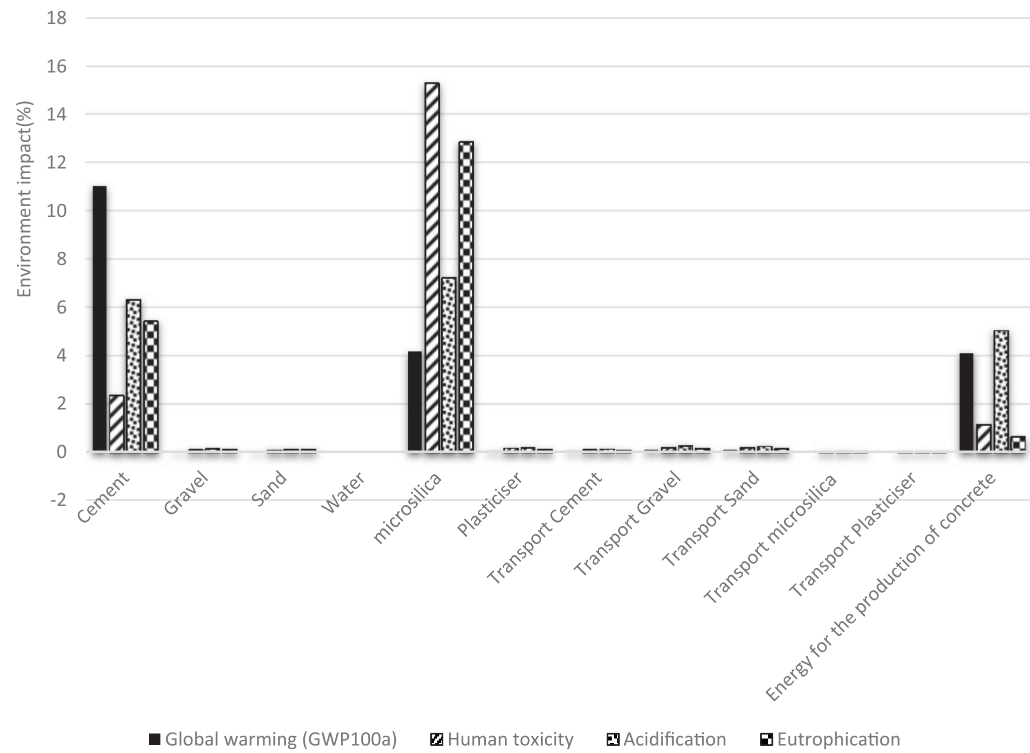

Figure 6. Impact of increasing 20% of each parameter in the production of microsilica concrete on global warming, human toxicity, acidification and eutrophication.

potential (about 8.8%). Increasing the amount of energy consumption of concrete production about 20% (for producing of concrete) caused an increase in the number of impact categories including global warming, eutrophication, human toxicity and acidification ranging from 2% to 8%. By increasing the amount of sand by 20%, GWP, human toxicity, acidification and eutrophication increased 0.226%, 0.419%, 0.301% and 0.428%, respectively. Also, by increasing the amount of gravel by 20%, the GWP, human toxicity, acidification and eutrophication increased 0.420%, 0.778%, 0.560% and 0.795%, respectively.

As indicated in Figure 6, increasing 20% of microsilica caused an increase in human toxicity (15.3%), eutrophication (12.86%), acidification (7.24%) and GWP by 4.5%.

Figure 7 indicates that increased 20% of each parameter in the production of $1m^3$ micro–nano bubble concrete results in the increase of global warming, human toxicity, acidification and eutrophication. As presented in Figure 7, increasing 20% of cement material in the production of micro–nano bubble concrete increases the eutrophication (15.028%), GWP (13.34%), human toxicity (9.76%) and the acidification potential (9.29%). The second prominent parameter in this scenario is energy consumption for concrete production. By increasing this parameter 20% to produce $1m^3$ micro–nano bubble concrete, acidification, GWP, human toxicity and eutrophication increased to 8.77%, 5.9%, 5.67% and 2.18%, respectively. A remarkable point in this scenario is energy consumption for producing bubble water. This parameter has the least sensitivity of footprint after the water in micro–nano bubble concrete.

Conclusions

We used the LCA methodology based on cradle-to-gate approach to carry out a detailed environmental impact for production of microsilica concrete, nanosilica concrete, Geopolymer concrete, micro–nano bubble concrete and OPC concrete. The key points of the results are as follows:

1. The 26% reduction in the GWP in Geopolymer concrete compared to the OPC concrete was achieved by CML 2000 method. Meanwhile, the GWP indicator increased by 56%, 17% and 38%, respectively, in the microsilica concrete, nanosilica concrete and micro–nano bubble concrete.
2. The results of sensitivity analysis illustrated that increasing 20% of cement had a significant impact on environmental burdens of the OPC concrete, nanosilica concrete and micro–nano bubble concrete. Furthermore, according to sensitivity analysis, 20% increase of sodium silicate and

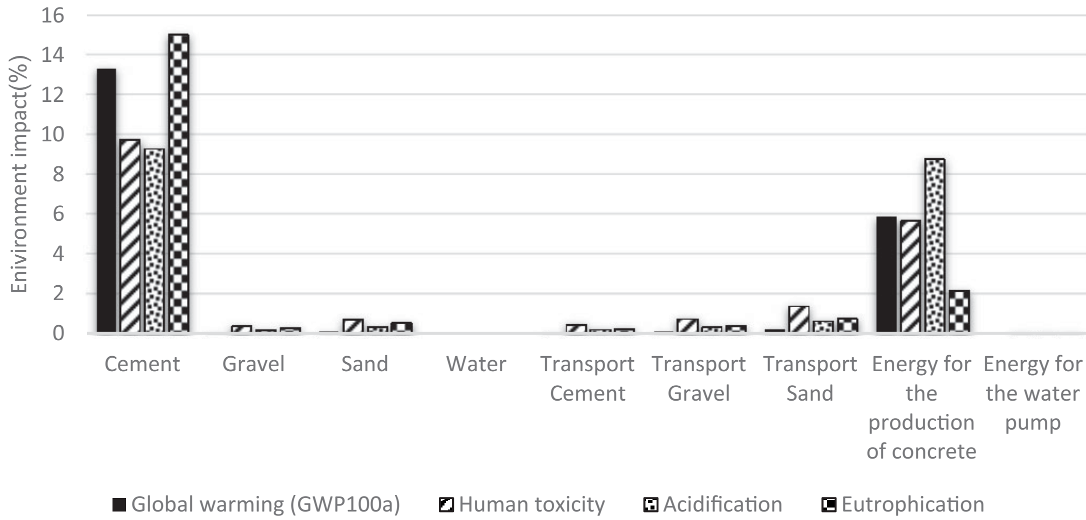

Figure 7. Impact of increasing each parameter up to 20% in the production of micro–nano bubble concrete on global warming, human toxicity, acidification and eutrophication.

microsilica results are the most effective factor in the impact categories associated with Geopolymer concretes and microsilica concrete, respectively.

3. Microsilica has the highest environmental impacts, and the results indicated increasing amounts of climate change (49.45%), ecosystem quality (6.8%) and human health (2 times), global warming (56.6%), human toxicity (more than 4 times), acidification (84.5%) and eutrophication (2.6 times) in comparison with OPC concrete.
4. The present study demonstrated that OPC concrete has the lowest environmental burden in the production stage except global warming, which is greater than Geopolymer concrete, and it is caused by cement consumption.
5. The results indicated that despite different unit measurement, environmental impacts are approximately the same in CML 2000 and BEES methods, and microsilica is the raw material which has the highest environmental impact in both methods.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

1. Potentially Disappeared Fraction

References

Bayer C, Gamble M, Gentry R, Joshi SAIA. 2010. Guide to building life cycle assessment in practice. Washington DC: The American Institute of architects, https://www.brikbase.org/sites/default/files/aiab082942.pdf

Blengini G. 2006. Life cycle assessment tools for sustainable development: case studies for the mining and construction industries in Italy and Portugal [Ph. D. Thesis]. Lisboa, Portugal: Universidade Técnica de Lisboa.

Braga AM, Silvestre JD, de Brito J. 2017. Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. J Cleaner Prod. 162:529.

Celik K, Meral C, Gursel AP, Mehta PK, Horvath A, Monteiro PJ. 2015. Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended Portland cement containing fly ash and limestone powder. Cem Concr Compos. 56: 59–72.

Duxson P, Provis JL, Lukey GC, Van Deventer JS. 2007. The role of inorganic polymer technology in the development of 'green concrete. Cem Concr Res. 37(12):1590–1597.

Faleschini F, De Marzi P, Pellegrino C. 2014. Recycled concrete containing EAF slag: environmental assessment through LCA. Eur J Environ Civil Eng. 18(9):1009–1024.

Feely RA, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ, Millero FJ. 2004. Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science. 305(5682): 362–366.

Gäbel K, Tillman A-M. 2005. Simulating operational alternatives for future cement production. J Cleaner Prod. 13(13–14):1246–1257.

Guinée JB. 2002. Handbook on life cycle assessment operational guide to the ISO standards. Springer Publishers.

Habert G, Billard C, Rossi P, Chen C, Roussel N. 2010. Cement production technology improvement compared to factor 4 objectives. Cem Concr Res. 40(5):820–826.

Habert G, De Lacaillerie JDE, Roussel N. 2011. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. J Cleaner Prod. 19(11):1229–1238.

Habert G, D'Espinose de Lacaillerie JB, Lanta E, Roussel N. 2010. Environmental evaluation for cement substitution

with geopolymers. In: Proceedings of the 2nd International Conference on Sustainable Construction Materials and Technologies; June 2010; Ancona, Italy. p. 1607–1615.
Habert G, Arribe D, Dehove T, Espinasse L, Le Roy R. 2012. Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges. J Cleaner Prod. 35:250–262.
Huntzinger DN, Eatmon TD. 2009. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. J Cleaner Prod. 17(7):668–675.
Iran ferroalloy industry [Internet]. 2017. [cited August 28, 2017]. http://ifi.co.ir/?lang=en.
ISO. 2005. Business plan ISO/TC 71 concrete, reinforced concrete and prestressed
ISO I. 14040. 2006. International standard. Environmental Management–Life Cycle Assessment–Principles and Framework, International Organisation for Standardization, Geneva, Switzerland.
Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R. 2003. IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess. 8(6):324.
Kellenberger D, Althaus H-J, Jungbluth N, Künniger T, Lehmann M, Thalmann P. 2007. Life cycle inventories of building products. Final Report Ecoinvent Data v2 No. 7.
Kleijer A, Lasvaux S, Citherlet S, Viviani M. 2017. Product-specific life cycle assessment of ready-mix concrete: comparison between a recycled and ordinary concrete. Resour Conserv Recycl. 122:210–218.
Kurad R, Silvestre JD, de Brito J, Ahmed H. 2017. Effect of incorporation of the high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete. J Cleaner Prod. 166:485–502.
Lippiatt BC. 2000. BEES 2.0 Building for Environmental and Economic Sustainability: Technical Manual and User Guide.
Liu C, Ahn CR, An X, Lee S. 2013. Life-cycle assessment of concrete dam construction: comparison of environmental impact of rock-filled and conventional concrete. J Constr Eng Manage. 139(12):A4013009.
Souza D. M D, Lafontaine M, Charron-Doucet F, Bengoa X, Chappert B, Duarte F, Lima L. 2015. Comparative life cycle assessment of ceramic versus concrete roof tiles in the Brazilian context. J Cleaner Prod. 89:165–173.
Marinković S, Malešev M, Ignjatović I. 2014. Life cycle assessment (LCA) of concrete made using recycled concrete or natural aggregates. Eco-efficient construction and building materials. Cambridge, UK: Elsevier; p. 239–66.
McLellan BC, Williams RP, Lay J, Van Riessen A, Corder GD. 2011. Costs and carbon emissions for geopolymer pastes in comparison to ordinary Portland cement. J Cleaner Prod. 19(9–10):1080–1090.
Meyer C. 2009. The greening of the concrete industry. Cem Concr Compos. 31(8):601–605.
Product ecology consultant. 2013. SimaPro database manual methods library, Netherlands: product ecology consultants report,version2.
Product ecology (PRe)consults. 2017. SimaPro life cycle assessment software package. Product ecology (PRe) consults. 8.1 ed. Amsterdam, The Netherlands.
Protocol K. 2016. United Nations framework convention on climate change. Kyoto Protocol, Kyoto. Mar; 7.
Sabour M, Yekkalar M, Nikravan M. 2014. Investigation of the effect of NANO-SIO2 consumption in concrete on its environmental and economic functions. Ferdowsi Univ Mashhad J Civil Eng. 25(2):67–78.
Tait MW, Cheung WM. 2016. A comparative cradle-to-gate life cycle assessment of three concrete mix designs. Int J Life Cycle Assess. 21(6):847–860.
Turner LK, Collins FG. 2013. Carbon dioxide equivalent (CO 2-e) emissions: a comparison between geopolymer and OPC cement concrete. Constr Build Mater. 43: 125–130.
Vahidi E, Jin E, Das M, Singh M, Zhao F. 2015. Comparative life cycle analysis of materials in wastewater piping systems. Procedia Eng. 118:1177–1188.
Van Deventer JS, Provis JL, Duxson P, Brice DG. 2010. Chemical research and climate change as drivers in the commercial adoption of alkali-activated materials. Waste Biomass Valor. 1(1):145–155.
Van den Heede P, De Belie N. 2012. Environmental impact and life cycle assessment (LCA) of traditional and green concrete: literature review and theoretical calculations. Cem Concr Compos. 34(4):431–442.