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How environmentally sustainable are fibre reinforced alkali-activated concretes?

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ABSTRACT

Alkali-activated concretes have been receiving increasingly attention as they are identified to be key components towards achieving sustainable construction in future. A detailed comparative environmental assessment study of different mix-designs of fibre reinforced alkali-activated concretes (FRAAC), conventional concrete (CC) and steel fibre reinforced conventional concrete (SFRCC), was conducted using Life cycle assessment (LCA) methodology. LCA study was conducted to determine the environmental performance of the different FRAACs when compared to CC and SFRCC, and also to identify the most important contributing factors to their environmental burdens. Results from the contribution analysis conducted indicated that sodium silicate solution was the major contributing material in the different FRAACs mix-designs. This is because, in addition to the high amount of energy required in the production of sodium silicate solution, high quantities of the solution is required in the development of the alkali-activated concretes. Furthermore, sensitivity analysis conducted indicated that there is a high variability in the environmental assessment results when different life cycle inventory (LCI) data sources of sodium silicate solution are used. Thus, amount of constituents and source of LCI data used, can hugely influence the overall results of the LCA study. As a result, constituent materials required in the development of FRAACs (especially ones which result in higher environmental burdens in FRAACs e.g. sodium silicate) should be cautiously utilised. Alternatively, they can be substituted with materials of lower environmental impacts where applicable, while ensuring the mechanical properties of the alkali-activated concretes are not compromised upon.

1. Introduction

The distinctive properties of concrete in terms of its availability, usability, and price, among other benefits, makes it the most commonly used construction material (Petrillo et al., 2016). Thus, making cement in high demand, as it is the principal binder material used in concrete production (Mehta, 2002). With the excellent properties of concrete comes the drawbacks, and it is considered one of the highest causes of environmental impacts due to factors such as increasingly production of concrete, emissions of CO_2 from calcination of limestone and a high energy consumption during cement production (Mehta, 2002; Turner and Collins, 2013). On a global scale, the construction industry depletes about two-fifths of raw stone, sand, and gravel, one-fourth of virgin wood, 16% of water, and 40% of energy annually; making the industry one of the largest exploiters of the earth's natural resources (Dixit et al., 2010).

According to the European Cement Association, an estimation of 4.7 billion tonnes of cement was produced globally in 2016 (CEMBUREAU, 2017). In 2016, greenhouse gas (GHG) emissions of CO_2 production was estimated to be 1.45 ± 0.2 Gt $CO_{2,\ eq.}$ contributing about 8% of global GHG emissions (Andrew, 2018). The CO_2 emissions usually result from two processes in cement production. The first process is the chemical reaction process required in the production of clinker during the thermal decomposing of $CaCO_3$ to CaO to produce cement; while the second process is emissions derived from combustion of fossil fuels to generate energy for heating raw materials needed in cement production (Andrew, 2018). Other environmental burdens besides CO_2 emissions, also emanate during cement and concrete production such as loss of agricultural land, resource extraction, usage of potable water to wash aggregates and to suppress dust, noise and vehicle pollution, dust emissions, water pollution, and landscape degradation (Zainudeen and Jeyamathn, 2004). Nonetheless, it should be noted that if cement were produced on a lesser scale at a reduced consumption, the environmental burdens would be reduced (Mehta,

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2002). As such, durability and lastingness of buildings and other construction products, will lead to a lesser need for virgin materials and resource extraction.

The concern for a more sustainable environment has led to increased research in alternative ways of reducing environmental burdens caused by cement production and by large, concrete production. This has led to possibilities of fusing methods such as material recycling in the concrete industry. This is achieved by recycling waste products from one industry to be used as raw materials in another industry (Mehta, 2002). Traditionally, many industries use the conventional linear economic model 'take-make-consume-throw away' (Brennan et al., 2014), which makes many industrial side-streams landfilled. The advent of sustainable development has led to more recycling and reusing of waste products. Thus, in some concrete industries, some industrial side-streams are recycled and reused as supplementary cementitious materials (SCMs) as a partial replacement for cement. Some additional trends in introducing sustainability to concrete industry also include the use of alkali-activated binders as a substitute to cement.

Alkali-activated binders are synthesized by reacting an alkali silicate/alkali hydroxide solution with an aluminosilicate powder and water (Singh et al., 2015). SCMs with a high Si/Al (aluminosilicate) ratio can be used as source materials. Aluminosilicate SCMs that have demonstrated good results include but are not limited to coal fly ash, granulated blast furnace slag (GBFS), natural pozzolans and calcined clay (Provis, 2017). A comprehensive knowledge of these SCMs' chemical compositions must be carried out to determine the potential of the source materials (Mehta and Siddique, 2016). Aluminosilicate precursors differ from region to region making it very versatile and locally adaptable. They differ in terms of availability, reactivity, cost and value. Thus, not making them a standardised material with respect to Portland cement. When considering developing alkali-activated binders for construction purposes, one key factor that should be taken into account is the local availability (minimised transportation) of suitable raw materials to enhance its sustainability prospects (Provis, 2017).

Barriers to utilisation of SCMs include inconsistency in compositions of materials. This is because the properties of SCMs can vary significantly over time, for example in the case of coal fly ash, they vary from plant to plant due to factors such as type of coal combusted, source of coal, and mixing of fly ash with other particles or materials during post-production phase (Wescott et al., 2010). Other barriers include; market barriers - as SCMs are yet to have widespread market acceptance. In addition, availability of supply for SCMs in the long-term is of great concern because the growth of coal plants for instance, might be hindered due to advent of renewable energy, stringent environmental regulations, and incorporation of sustainable measures to industries (Bouzoubaâ and Fournier, 2005; Wescott et al., 2010).

Alkali-Activated binders (AABs) can be produced using two main pathways namely; one-part mix (dry powder with water) (Duxson and Provis, 2008; Luukkonen et al., 2018) and two-part mix (using liquid activator) (Duxson et al., 2007). The two-part mix is the most common and the focus of this study. However, one-part mix may be more scalable in future due to less difficulty in handling and transporting when compared to liquid activators (Luukkonen et al., 2018).

Alkali-activated concretes (AACs) is produced by a mixture of AAB with fine and coarse aggregates, and water. They can be quite brittle, and this makes them sensitive to cracking, thereby forming micro-cracks when loaded which eventually leads to macro-cracks, deterioration and failures, making them unable to withstand additional load (Al-mashhadani et al., 2018; Ganesan et al., 2015). As a result of this drawback, the durability of AACs are undermined. To overcome this limitation and to enhance its ductility, toughness and limit the tendency of cracking, AACs are reinforced with fibres (Alomayri, 2017a). The fibres transmit stress between fibre and matrix through the interfacial bond by crossing the paths of potential cracks (Alomayri, 2017a). The use of Fibre-Reinforced Alkali-Activated Concrete (FRAAC) has attracted much attention among researchers due to the superior physical and mechanical properties that can be achieved (Alomayri, 2017a) as compared to ordinary AAC. However, it should be noted that the characteristics of fibre reinforced concrete depend on many factors such as size, type, elastic properties etc. (Ganesan et al., 2015). Thus, the type of fibre used as well as the pattern of dispersion of fibres in the alkali-activated matrix can affect the mechanical properties. As a result, the type and form of fibre, surface and matrix properties have to be taken into consideration (Alomayri et al., 2013).

There have been different studies carried out on the influence of the fibres on concretes (Al-mashhadani et al., 2018; Alrefaei and Dai, 2018; Assaedi et al., 2017; Behera et al., 2018; Bhutta et al., 2017; Mohseni, 2018; Shaikh et al., 2018). Polyvinyl alcohol micro-fibres as reinforcement in concrete composites have shown to significantly increase ductility which led to increase in toughness and energy absorption of the concrete (Hamoush et al., 2010). A study by Alomayri (2017b) showed that the inclusion of glass micro-fibre as reinforcement material in AAC enhanced the post cracking response of the geopolymer composite (Alomayri, 2017b). Flexural strength and modulus properties and toughness were also enhanced. The increased toughness increased the energy absorption properties of the concrete (Alomayri, 2017b). Steel reinforcement in AAC has shown to improve strength, crack resistance, energy absorption, impact resistance, ductility and modulus of elasticity while decreasing brittleness (Ganesan et al., 2015).

Furthermore, there have been studies comparing environmental performance of conventional concretes to AACs (Davidovits, 2015; Habert et al., 2011; Marinković et al., 2017; McLellan et al., 2011; Ouellet-Plamondon and Habert, 2015; Passuello et al., 2017; Petrillo et al., 2016; Teixeira et al., 2016; Van Den Heede and De Belie, 2012; Yang et al., 2013). Habert et al. (2011) concluded that with respect to global warming, AAC had a slightly lower impact than Ordinary Portland Cement (OPC) concrete. Also, the study revealed that AAC had higher environmental impact than OPC conrete in other impact categories majorly due to the presence of sodium silicate in AAC. McLellan et al. (2011) estimated a 44–64% improvement of greenhouse gas emissions of AAC over OPC. Yang et al. (2013) estimated that CO_2 reduction rate of AAC with respect to OPC concrete was in the range of 55–75%. However, the CO_2 reduction depended on the type, concentration and dosage of alkali activators. The environmental performance results of these studies conflict and vary because of differences in aspects such as different system boundaries, functional units, inventory data etc. Thus, it will be difficult to compare these results. However, most importantly, these studies shed light to different contributing factors to the environmental burdens of AACs.

Environmental performance of different FRAACs has substantially been less investigated. One of the few papers that features environmental performance of FRAACs is by Ohno and Li (2018). The results of the study showed that the significant contributors to the embodied energy and global warming intensity are the alkaline activator and polyvinyl alcohol (PVA) fibre. In addition, it was stated from the results that FRAAC had greater total energy consumption than conventional concrete due to the addition of PVA fibre. However, FRAAC had a lower global warming impact in comparison to conventional concrete (Ohno and Li, 2018).

Although, FRAACs seem promising for construction purposes in the efforts to reuse waste, to lower CO_2 emissions and generally achieve environmental improvements in the concrete industry, there is still a need for a comprehensive environmental assessment done on FRAACs to determine if it they are a more environmentally sustainable alternative with respect to conventional concrete. Due to the lack of in depth studies on the environmental performance of FRAACs, this paper will be focussing on comparing the environment performance of different FRAACs with respect to conventional concrete in addition to identifying the most important factors contributing to their environmental burdens.

2. Materials and method

According to ISO 14040:2006, “Life cycle assessment (LCA) addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal” (EN ISO 14040, 2006). The method utilised in this study follow the phases of LCA, which are: (1) goal and scope definition, (2) inventory phase, (3) impact assessment phase, and (4) interpretation phase. Besides these four compulsory phases, other optional steps include classification, characterisation, normalisation, grouping, and weighting. To establish confidence in LCA results, some evaluation procedures such as completeness check, consistency check and sensitivity check, are recommended (EN ISO 14040, 2006).

The different materials considered in this study include materials such as cement, sand, gravel and water for the conventional Concrete (CC) mix-design while SFRCC has included in it steel fibre. For the FRAACs, the major input materials are fly ash, sodium hydroxide pellets, sodium silicate solution, sand, gravel, steel fibre, glass fibre and polypropylene fibre; where sodium hydroxide and sodium silicate are used as activators.

Steel fibres used as reinforcement in concrete demonstrates properties such as shrinkage control of concrete, temperature resistance, high fatigue strength resistance to impact, erosion and abrasion resistance to splitting (Rai and Joshi, 2014). The degree of improvement gained by steel fibres in concrete depends on concrete mix and age, fibre content and volume fraction and fibre geometry and orientation. They have been generally known to improve compressive, tensile, flexural fatigue and impact strength (Rai and Joshi, 2014). Steel fibre reinforced concrete can be applied when constructing new pavements and in the repair of existing pavements. It can also be applied in hydraulic structures, industrial floors, tunnel linings, shotcrete linings, refractory concrete, and precast application and in structural applications (Behbahani et al., 2013).

Inclusion of glass fibres to concrete results in improved tensile and impact strength of the concrete. Due to ability of glass fibre to get brittle with time, alkali resistant glass fibre have been introduced to help combat the drawbacks of the former (Rai and Joshi, 2014). Glass fibre concretes are mainly applied as architectural precast concrete and in exterior building façade panels. They can also be applied in building renovation works, water and drainage works, bridge and tunnel lining panels, acoustic barriers and screens (Rai and Joshi, 2014).

Polypropylene (PP) fibre reinforced concrete leads to increased impact resistance, increased tensile strength and energy absorption (Jain et al., 2011). Polypropylene fibre reinforced concrete have been applied in structural applications such as foundation piles, piers, highways, industrial floors, bridge decks, facing panels, heavyweight coating for underwater pipes and floatation units for walkways (Najimi et al., 2009). They are also applied for controlling shrinkage and temperature cracking, rigid pavement. Due to the usefulness of PP fibre reinforced concrete in controlling shrinkage and fine cracks, it can also be applied in structural applications such as airports and industrial floors (Najimi et al., 2009). From these studies, it can be seen that these fibre reinforced concretes (steel, glass and polypropylene) can be implemented in similar structural applications.

2.1. Goal and scope definition

The object of analysis in this study is fibre-reinforced alkali-activated concrete (FRAAC) and the overall goal of this study is to perform an environmental assessment of different types and mix-designs of FRAACs in comparison to conventional concrete (CC) and steel fibre reinforced conventional concrete (SFRCC). This is required to determine the environmental performance of the FRAACs, estimate and compare the impacts of the different concretes while also identifying the main factors contributing to their environmental burdens that could be taken into account in future development.

In accordance to the goal of the study, the system boundary was determined as shown in Fig. 1. Heat Curing was included in the

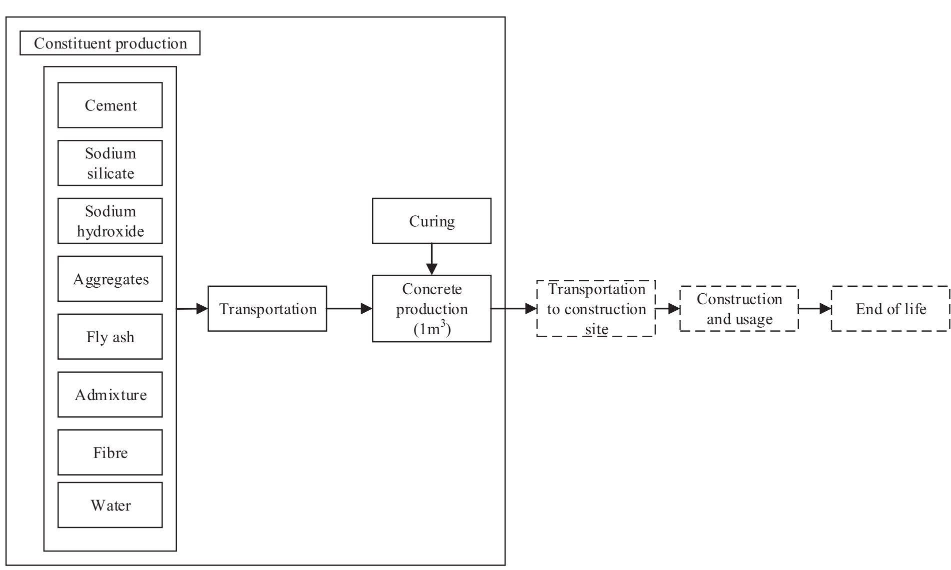

Fig. 1. LCA system boundary illustrating production of 1 m^3 Concrete.

concrete production phase for some of the FRAACs. Transportation of raw materials to concrete production site was omitted from the assessment since similar distances was assumed for transportation of the raw materials and similar impacts were expected. In addition, similar applications and impacts were expected from the Use phase, hence, omitted from the assessment. The End-of-life phase was also omitted from assessment as it was assumed that the End-of-life phase (where part of the waste is recycled and part is disposed in landfill) of the different concrete mixes are comparable. The omitted phases are outside the system boundary as shown in Fig. 1.

Since this study is primarily focussed on concrete production, the unit processes will be limited to the production stage as shown in Fig. 1. Based on the system boundary, the unit processes illustrated are associated with the different raw material constituents used in the production of CC, SFRCC and FRAAC. The functional unit of this study is defined as the environmental impact generated due to the activities involved in the production of 1 m^3 of concrete. As a result of these different concrete mix-designs having the possibility of multiple specific applications in structural engineering, thus, a singular function cannot be selected (Habert et al., 2011; Passuello et al., 2017).

2.2. Life cycle inventory (LCI)

2.2.1. Data collection

This is the phase where material inputs (e.g. energy) and outputs (e.g. emissions) within the system boundary are quantified (Teixeira et al., 2016). A detailed literature review was conducted to obtain mix-designs of concrete and FRAACs and these are presented in Table 1.

The mix-designs are grouped as follows:

- Conventional concrete (CC)
- Steel fibre reinforced conventional concrete (SFRCC)
- Steel fibre reinforced alkali-activated concrete (SFRAAC)
- Glass fibre reinforced alkali-activated concrete (GFRAAC)
- Polypropylene fibre reinforced alkali-activated concrete (PPFRAAC)

Conventional concrete acts as the reference scenario. Steel fibre reinforced conventional concrete was included in the assessment to observe how steel fibre influences the strength of the concrete and also see how it compares in terms of environmental performance with the FRAACs. The different mix-designs were collected as directly reported from different literature studies (analysed and tested).

The FRAACs mix-designs were grouped according to the type of fibre reinforcement (steel fibre, glass fibre and polypropylene fibre) as shown in Table 1. Each group have in them different quantities of constituent materials to observe how varied quantities of these materials affects the strength of the concrete. All FRAAC mix-designs as shown in Table 1 are analysed to determine the mix-design that is most environmentally optimal, which will be further analysed in section 3. The result of the environmental assessment of all mix-designs in Table 1 can be found in the supplementary material.

Table 1
Mix-designs for conventional concrete, steel fibre reinforced conventional concrete and fibre reinforced alkali-activated concretes.

	Cement kg/m^3	Fly ash kg/m^3	GBFS kg/m^3	NaOH pellets kg/m^3	Na_2SiO_3 solution kg/m^3	Sand kg/m^3	Silica sand kg/m^3	Gravel kg/m^3	Super-plasticizer kg/m^3	Water kg/m^3	steel fibre kg/m^3	glass fibre kg/m^3	PP fibre kg/m^3	Comp. Strength MPa	REF
Conventional concrete															
CC	360					598		1266		192				35	[1]
SFRCC	360					598		1266	4	192	38.64			39.5	[1]
Steel fibre reinforced alkali-activated concrete															
S_1		408		16.4	103	600		1248	10.2	16	19.32			38.4	[1]
S_2		408		16.4	103	600		1248	14.5	16	38.64			41.2	[1]
S_3		408		16.4	103	600		1248	14.5	18	57.95			42.5	[1]
S_4		408		16.4	103	600		1248	16	18	78.28			43.8	[1]
S_5		412	276	56.51	294.3		1100				78			74	[2]
S_6		412	276	56.51	294.3		1100				117			74	[2]
S_7		412	276	56.51	294.3		1100				156			82	[2]
S_8		450	60	24	175		1237.5				31.4			61.67	[3]
S_9		450	60	24	175		1237.5				62.8			61.97	[3]
S_10		450	60	24	175		1237.5				94.2			62.52	[3]
S_11	39.43	354.87		14.38	101.39	554.4		1293.4	11.83	55.18	19.63			42.44	[4]
S_12	39.43	354.87		14.38	101.39	554.4		1293.4	11.83	55.18	39.25			43.09	[4]
S_13	39.43	354.87		14.38	101.39	554.4		1293.4	11.83	55.18	58.88			47.46	[4]
Glass fibre reinforced alkali-activated concrete															
GF_1		400		18.27	143	540		1260				13,3		66	[5]
GF_2		400		18.27	143	540		1260				19.9		60	[5]
GF_3		400		18.27	143	540		1260				26.5		54	[5]
GF_4		400		18.27	143	540		1260				33.1		70	[5]
GF_5	39.43	354.87		14.38	101.39	554.4		1293.4	11.83	55.18		0.268		35.97	[6]
GF_6	39.43	354.87		14.38	101.39	554.4		1293.4	11.83	55.18		0.536		32.08	[6]
GF_7	39.43	354.87		14.38	101.39	554.4		1293.4	11.83	55.18		0.804		40.73	[6]
Polypropylene fibre reinforced alkali-activated concrete															
PP_1		450	60	24	175		1237.5						3.64	60.97	[3]
PP_2		450	60	24	175		1237.5						7.28	60.44	[3]
PP_3		450	60	24	175		1237.5						10.92	59.78	[3]
PP_4		368.91		21.3	132.14	581.03		1171.29		31.9			14.19	39.21	[7]

CC- conventional concrete; SFRCC – steel fibre reinforced conventional concrete; GBFS – granulated blast furnace slag; NaOH – sodium hydroxide; Na_2SiO_3 – sodium silicate: PP – polypropylene.
[1] Ganesan et al. (2015), [2] Khan et al. (2018), [3] Al-mashhadani et al., 2018, [4] Vijai et al. (2012a), [5] Nematollahi et al. (2014), [6] Vijai et al. (2012b), [7] Patil and Patil (2015)..

2.2.2. Data sources

The data utilised in this study were gathered from published literature and the LCA modelling was carried out using GaBi software system LCA tool. The Gabi database, which PE International, has provided and checked for consistency, are primarily concerned with material and energy flow required in the production process of a material. GaBi professional database with extensions 2018 served as the main data sources for collecting the LCI of some materials utilised in this study such as cement, sand, gravel, silica sand, transportation, electricity, water, sodium hydroxide, glass fibres and polypropylene fibres.

Life cycle inventory (LCI) for sodium silicate solution was not available in the GaBi database. Hence, it was sourced from the article Life cycle inventories for the production of sodium silicates (Fawer et al., 1999). Sodium silicate with weight ratio of 2.0 was used in this study and it is produced by hydrothermally dissolving silica sand in sodium hydroxide solution (Fawer et al., 1999). Fly ash is considered to have a very small environmental footprint because fly ash mostly does not require beneficiation. (Lemay, 2017; Marceau et al., 2007). Thus, only transportation impacts will be attributed to fly ash. For steel fibres, there is no direct LCA information in the Gabi database and due to insufficient LCA data on steel fibre from literature, the material will be modelled based on the unit process steel sheet stamping and bending. Steel sheet stamping and bending is a part production in making steel metal parts and since it has similar input material as required in making steel fibres, the unit process was adopted. Thus, the impacts associated with 1 kg of steel sheet stamping and bending will for now be assumed to equal 1 kg of steel fibre. Inventory data for the admixture used (superplasticizer) was also not available in GaBi database, but was otherwise sourced from the environmental product declaration (EPD) owned by the European Federation of Concrete Admixtures Associations Ltd. (EFCA). The base materials for the superplasticizer contain lignosulphonate, naphthalene sulphonate, melamine sulphonate, polycarboxylate, additives and water. The result of the LCA of the superplasticizer was selected from the product with the highest environmental impact for a worst-case scenario and is limited to the production stage (cradle to gate). There were no allocations applied for production and the data quality was considered to be good (EFCA, 2015).

The LCI sources for the different material inputs are summarised in Table 2. In general, LCI for this study was made using a combination of information from different sources (Gabi, EPD and literature). The inventory data gotten from literature were transferred to the GaBi software version of 8.6.0.20 to ensure quality of data interpretation.

Table 2
Sources of LCI datasets.

Type of data	Source
Polypropylene fibre	GaBi database 2018
Steel fibre	GaBi database 2018 (steel sheet stamping and bending)
Glass fibre	GaBi database 2018
Sodium hydroxide	GaBi database 2018 (sodium hydroxide, 100% caustic soda)
Sodium silicate	Fawer et al. (1999); (sodium silicate 2.0, hydrothermal liquor, 48% solid)
Sand	GaBi database 2018 (sand 0/2)
Gravel	GaBi database 2018 (gravel 2/32)
Silica sand	GaBi database 2018 (excavation and processing)
Superplasticizer	EFCA (2015)
Water	GaBi database 2018 (tap water)
Electricity	GaBi database 2018 (electricity grid mix)
Transportation	GaBi database 2018 (truck-trailer, Euro 5, 34-40t gross weight/27t payload capacity)
Cement	GaBi database 2018 (Portland cement CEM I)
Diesel	GaBi database 2018 (diesel mix at refinery)

2.3. Life cycle impact assessment (LCIA)

The impact assessment categories used in this study in assigning LCI results to specific environmental issues, are namely; global warming potential (GWP 100 years), ozone layer depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), abiotic depletion potential (ADP elements), abiotic depletion potential (ADP fossil), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), photochemical Ozone Creation Potential (POCP) and terrestrial ecotoxicity potential (TETP). These indicators are according to Centrum voor Milieukunde Leiden (CML) 2015 indicators and provide information on the environmental issues associated with inputs and outputs of the product system (EN ISO 14040, 2006). The CML impact assessment method is a widely adopted method due to its robustness, and limiting uncertainties by restricting quantitative modelling to the early stages in the cause-effect chain, when compared to other impact assessment methods (Turk et al., 2015; Deviatkin et al., 2016).

2.3.1. Normalisation

Normalisation is an optional step used in the “calculation of the magnitude of the category indicator results relative to some reference information” (EN ISO 14040, 2006). There are difficulties associated with comparing and ranking impact categories, especially when they have different standardisations. As a result, normalisation is applied to help compare different impact category indicators (Aymard and Botta-Genoulaz, 2017). Normalised impact is the impact of the studied system (in a certain category) divided by the estimated environmental impact of a reference region (Aymard and Botta-Genoulaz, 2017). Equation (1) illustrates how normalisation is calculated.

$$N_i = S_i/R_i \tag{1}$$

where, i is the impact category, N_i is the normalised impact for a specific impact category, S_i is the characterised impact of the impact category i of the system under study, and R_i is the estimated environmental impact of a reference region. The normalisation values R_i, used in this study is the global equivalents from CML 01–2015 (including biogenic carbon) sourced from GaBi software and are shown in Table 3 below.

Table 3
Global equivalents reference values for estimated environmental impact of each impact category from GaBi software.

Impact category	R_i
Abiotic depletion potential (ADP elements) - kg Sb eq.	3.61E8
Abiotic depletion potential (ADP fossil) - MJ	3.8E14
Acidification potential (AP) - kg SO2 eq.	2.39E11
Eutrophication potential (EP) - kg Phosphate eq.	1.58E11
Freshwater aquatic ecotoxicity potential (FAETP) - kg DCB eq.	2.36E12
Global warming potential (GWP 100 years) - kg CO2 eq.	4.18E13
Human toxicity potential (HTP) - kg DCB eq.	2.58E12
Marine aquatic ecotoxicity potential (MAETP) - kg DCB eq.	1.94E14
Ozone layer depletion potential (ODP) - kg R11 eq.	2.27E8
Photochemical ozone creation potential (POCP) - kg Ethene eq.	3.68E10
Terrestrial ecotoxicity potential (TETP) - kg DCB eq.	1.09E12

2.3.2. Contribution analysis

To get started with interpretation of results, it is essential to identify the key processes that contribute the most to the LCA results (Ciroth et al., 2017) by decomposing the total LCA results into individual process contributions (Liikanen et al., 2017). Once these key processes have been identified, further checks such as sensitivity analysis can be conducted to evaluate the overall robustness of the LCA study (Zampori et al., 2016). The benefits of contribution analysis includes focussing on processes to improve environmental performance of the system of study (Zampori et al., 2016).

2.3.3. Sensitivity analysis

Sensitivity analysis "is a procedure to determine how changes in data and methodological choices affect the results of the LCIA" (EN ISO 14040, 2006). There are two reasons for conducting sensitivity analysis; 1) Sensitivity analysis is conducted to identify the key parameters influencing the system and how they change under different systems conditions (Guo and Murphy, 2012). 2) Sensitivity analysis can be used to study how uncertainty in a model output can be apportioned to different sources of uncertainty in a model input. In this study, the sensitivity analysis will be carried out to determine how the system changes under different conditions.

3. Results and discussion

As presented in section 2.2.1, the data collected (Table 1) were analysed to determine the most environmentally optimal mix-design for each respective group of the FRAACs (SFRAAC, GFRAAC and PPFRAAC) and this was carried out using GaBi software tool. Details of the results can be found in the supplementary material. S_1, PP_4, and GF_5 were the most environmentally optimal mix-design in each group of the different FRAACs. For meaningful comparisons during analysis, it was also ensured that these chosen mix-designs were based on having equivalent compressive strength of 38 ± 2 MPa at 28 days. Furthermore, it was ensured that the chosen mix-designs had equivalent amounts of constituent materials except in the quantities of fibres, where the amount varied a bit. These careful considerations were put in place for ease of environmental performance comparison and most importantly to actualise the main goal of the study.

These mix-designs (S_1, PP_4 and GF_5) as shown in Table 4 will represent the different scenarios analysed with respect to CC and SFRCC to establish their environmental performance.

The LCIA results of these scenarios were generated and normalisation (as explained in 2.3.1) was carried out. The normalised results as illustrated in Fig. 2, cannot be summed up because they

Table 4
Chosen mix-designs representing the different scenarios analysed in this study.

Scenarios	Cement kg/m^3	Fly ash kg/m^3	NaOH pellets kg/m^3	Na_2SiO_3 solution kg/m^3	Sand kg/m^3	Gravel kg/m^3	Super-plasticizer kg/m^3	Water kg/m^3	steel fibre kg/m^3	glass fibre kg/m^3	PP fibre kg/m^3
CC	360				598	1266		192			
SFRCC	360				598	1266	4	192	38.64		
S_1		408	16.4	103	600	1248	10.2	16	19.32		
PP_4		368.91	21.3	132.14	581.03	1171.29		31.9			14.19
GF_5	39.43	354.87	14.38	101.39	554.4	1293.4	11.83	55.18		0.268	

CC — conventional concrete, SFRCC - Steel fibre reinforced conventional concrete, S_1 - Steel fibre reinforced alkali-activated concrete, PP_1 - Polypropylene fibre reinforced alkali-activated concrete, GF_5 - Glass fibre reinforced alkali-activated concrete.

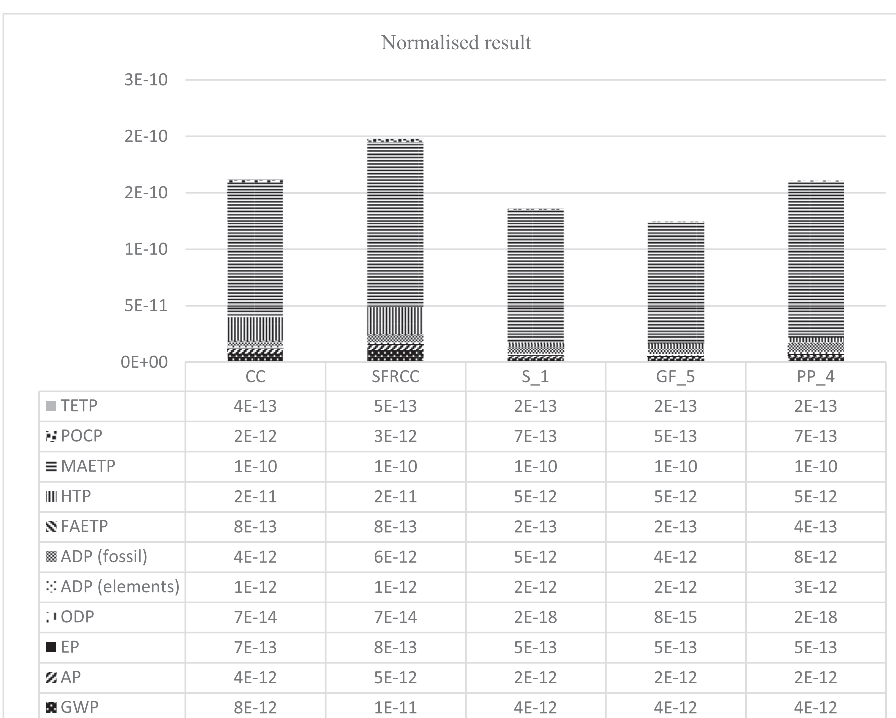

Fig. 2. Normalised results of the studies scenarios.

are shares of global impact of different impact categories. Thus, the graph is a way to visualise the normalised impacts and the importance of the different impact categories as compared to one another.

All three FRAACs S_1, GF_5 and PP_4 had decreased emissions of 16%, 23% and 0.8% respectively, when compared to CC, and decreased emissions of 32%, 37% and 19%, respectively, when compared to SFRCC (see supplementary information for weighted results). From these results and from the quantities of the different constituent materials as shown in Table 4, it can be seen that GF_5 was the most environmentally sustainable among the FRAACs despite having a small amount of cement (39.43 kg/m^3) in its mix-design. However, the low amount of sodium silicate (101.39 kg/m^3) and sodium hydroxide (14.38 kg/m^3) compensated for the inclusion of cement. PP_4 was the least environmentally sustainable among the FRAACs as a result of having the highest amount of sodium silicate (132.14 kg/m^3) and sodium hydroxide (21.3 kg/m^3).

3.1. Contribution analysis

As discussed in section 2.3.2, contribution analysis is to identify the processes significantly contributing to the LCA results. Thus, the total result is decomposed into individual process contributions. The contribution analysis will be based on MAETP, HTP, ADP (fossil), GWP and AP environmental impact categories, since they are the most relevant impact categories in this study (Fig. 2).

Sodium silicate was the highest contributor to these impact categories followed by steel fibre and sodium hydroxide. Steel fibre had the highest process contribution in the category of fibres. However, the amount of steel fibre used (19.32 kg/m^3), was 1.4

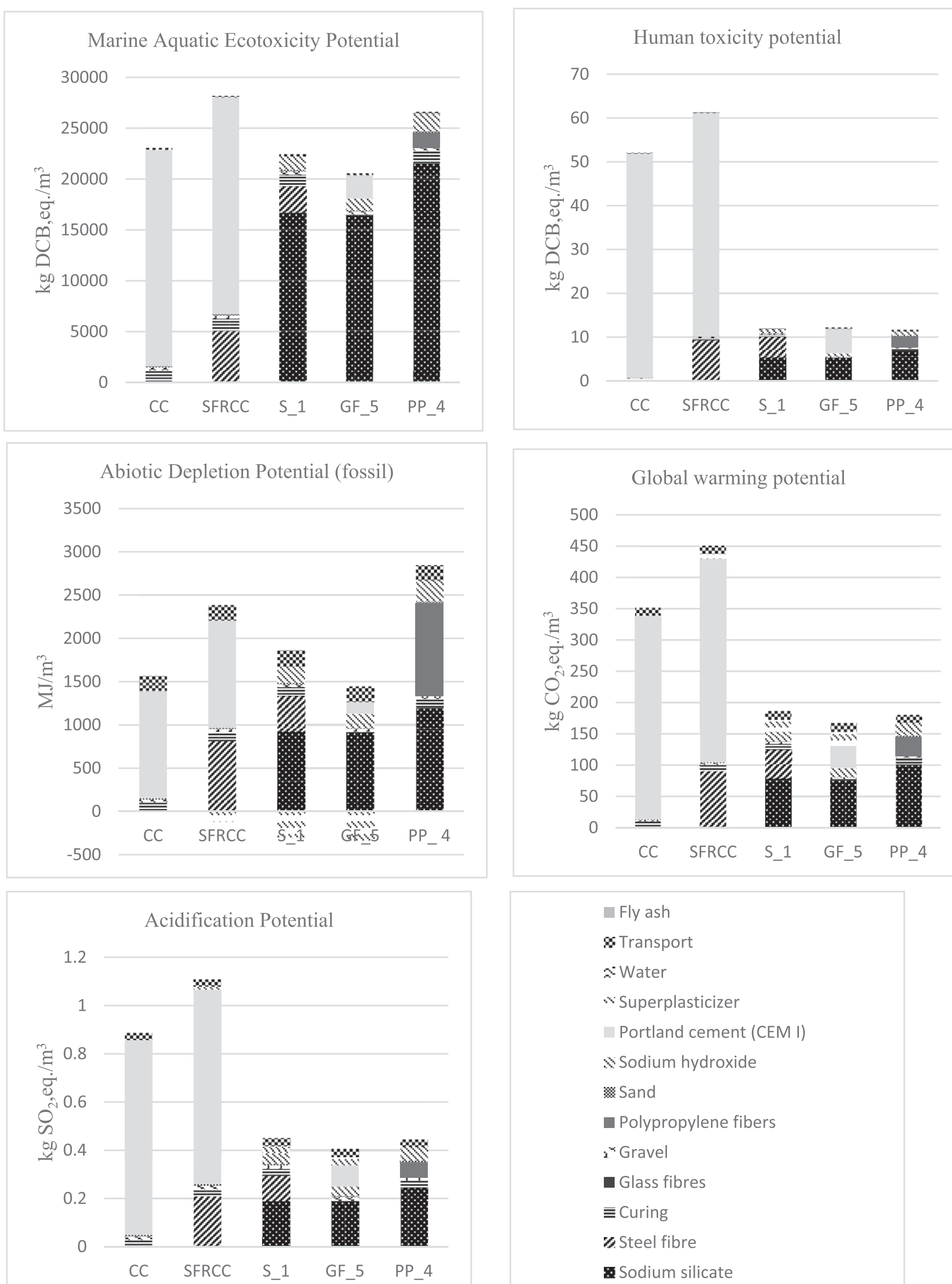

Fig. 3. Contribution of the different processes to MAETP, HTP, ADP (fossil), GWP and AP for the studied scenarios.

times the amount of polypropylene fibre (14.19 kg/m^3) and 72 times the amount of glass fibre (0.268 kg). This has an effect on the overall results based on the differences in fibre quantities. Nevertheless, comparing 1 kg of steel fibres to glass and polypropylene fibres shows steel fibres have a higher environmental impact (see supplementary material). Therefore, factors such as the amount of steel fibre used in comparison to other fibres to actualise similar strength of material, can increase the environmental impact of the alkali-activated concrete.

For sodium silicate, as much as it was the process with the highest contribution, it was observed that a higher quantity of sodium silicate was used (between 101.39 and 132.14 kg/m^3) when compared to sodium hydroxide (between 14.38 and 21.3 kg/m^3) in making the alkali solution. Therefore, the quantity of sodium silicate used in the development of FRAAC (in addition to sodium silicate having a higher environmental impact when compared to other constituent materials except for some of the fibres and sodium hydroxide) made it the process with the highest burden. Thus, quantities of constituent materials especially the alkali activators used can make the FRAAC more or less environmentally sustainable than CC or SFRCC.

Heat curing, transportation (diesel and truck), sand (0/2), fly ash, gravel and water had minimal contribution (less than 10%) to the respective impact categories. Fly ash is considered to have a very small environmental footprint because fly ash mostly does not require beneficiation. (Lemay, 2017; Marceau et al., 2007). Thus, only transportation impacts was attributed to fly ash. Curing is essential for initiating chemical reaction of alkali-activated concretes at first instance. The FRAACs required curing except GF_5. CC and SFRCC also did not require curing. Curing consumed 86.4 MJ (Bai et al., 2014) of electricity for 24 h at 85 °C. Transportation was constant for all the different mix-designs, as it is assumed the different concrete types were locally produced within a distance of 100 km between raw material production and concrete production. In situations of higher distances, impacts related to transportation will also increase.

GF_5 had the lowest overall process contributions to the impact categories as a result of having the least amount of constituent materials and also did not consume extra energy needed for curing.

With respect to GWP, GF_5, S_1 and PP_4 are 52%, 47% and 49% respectively, lower than CC, and 63% and 58% and 60% lower than SFRCC. With respect to MAETP, GF_5 and S_1 are 11% and 3% respectively, lower than CC, and 27% and 20% lower than SFRCC, while PP_4 is 15% higher than CC and 6% lower and SFRCC. With respect to HTP, GF_5, S_1 and PP_4 are 76%, 77% and 78% respectively, lower than CC, and both GF_5 and S_1 are 80% lower than SFRCC while PP_4 is 81% lower than SFRCC. With respect to ADP (fossil), GF_5 and S_1 are 29% and 0.4% respectively, lower than CC and 51% and 31% lower than SFRCC, while PP_4 is 80% and 26% higher than CC and SFRCC respectively. Finally, with respect to AP, GF_5, S_1 and PP_4 are 54%, 49% and 50% respectively, lower than CC, and 63%, 59% and 60% lower than SFRCC (see Fig. 3).

Based on these results, the significant contributor to the FRAACs is the sodium silicate which correlates with study by Ohno and Li (2018), which acknowledges alkaline activator (majorly sodium silicate) as significant contributors to embodied energy and global warming intensity. Others studies such as Ouellet-Plamondon and Habert (2014), Passuello et al. (2017) and Turner and Collins (2013), also acknowledges alkali activator as the greatest contributor to the environmental impact of alkali activated concretes. Although, the focus of these studies was on alkali activated concrete without fibre reinforcement.

3.2. Sensitivity analysis

3.2.1. Sodium silicate

The results of research performed so far on LCA of alkali-activated concretes are contradictory. This is mostly the consequence of different LCI data used for alkali activators (Marinković et al., 2017). In this section, the effect of different inventory data for sodium silicate on the overall results is discerned.

For all the impact categories featured in the contribution analysis, sodium silicate was consistently the highest contributor to the different impact categories for the different FRAACs. Thus, sensitivity analysis as described in section 2.3.3 was carried out on sodium silicate solution by collecting LCI data of sodium silicate from two different sources in addition to the reference sodium silicate data (Fawer et al., 1999) used for the main LCIA results. These two additional LCI sources are from Ecoinvent database and best available technique (BAT) for the manufacture of large volume inorganic chemicals (IPPC, 2007). Furthermore, fuel substitution was carried out on the reference sodium silicate data sourced from Fawer et al. (1999) by replacing fossil fuel used in producing sodium silicate with biogas renewable energy (LCI biogas data was sourced from GaBi database).

From Fig. 4, it is seen how using different LCI sources of sodium silicate can influence the overall LCIA results. When the fossil fuel used in producing sodium silicate (Fawer_FE) is substituted with biogas (Fawer_RE), ADP emissions reduced by 23%, 32% and 17% for S_1, GF_5 and PP_4 respectively. Emission reduction between 15% and 20% was observed for GWP. MAETP had a reduction between 40% and 43% and HTP had a reduction between 18% and 25%. Only AP had an increase between the range of 18% and 20%. When comparing BAT to Fawer_FE, ADP (fossil) had a reduction in the range of 23%–44% for the different FRAACs, AP had a reduction between 18% and 40%, GWP had a reduction between 25% and 33%, HTP had a reduction between 30% and 42%, and MAETP had a reduction between 62% and 68%.

Sodium silicate data from Ecoinvent database gave the highest LCIA results. This is because the major raw materials (silica sand and sodium hydroxide) used in production of sodium silicate using the hydrothermal process, was twice higher in Ecoinvent when compared to Fawer_FE (Fawer et al., 1999) and BAT (IPPC, 2007). Besides, energy used in production of sodium silicate using BAT data consumed about 6.9 times less when compared to Fawer_FE and 1.2 times less when compared to Ecoinvent.

It should be noted that BAT result is when sodium silicate is produced with the best available technique and technologies with the best practicable environmental option. To reduce dust emissions, measures such as using fabric filters, electrostatic precipitators, low sulphur fuel, low NO_x burners, adopting primary measures such as reducing air/fuel ratio and reducing combustion air temperature among other factors are taken into consideration to achieve environmental benefits.

These different LCI sources of sodium silicate solution shows how variability in data can significantly change the outcome of LCIA results. If BAT was used as the reference LCI for sodium silicate to determine the normalised LCIA results, the overall results of the different FRAACs would have shown a much higher environmental performance than CC and SFRCC, as compared to when FAWER_FE is used. Conversely, this would have been otherwise if Ecoinvent data was used as the reference LCI data.

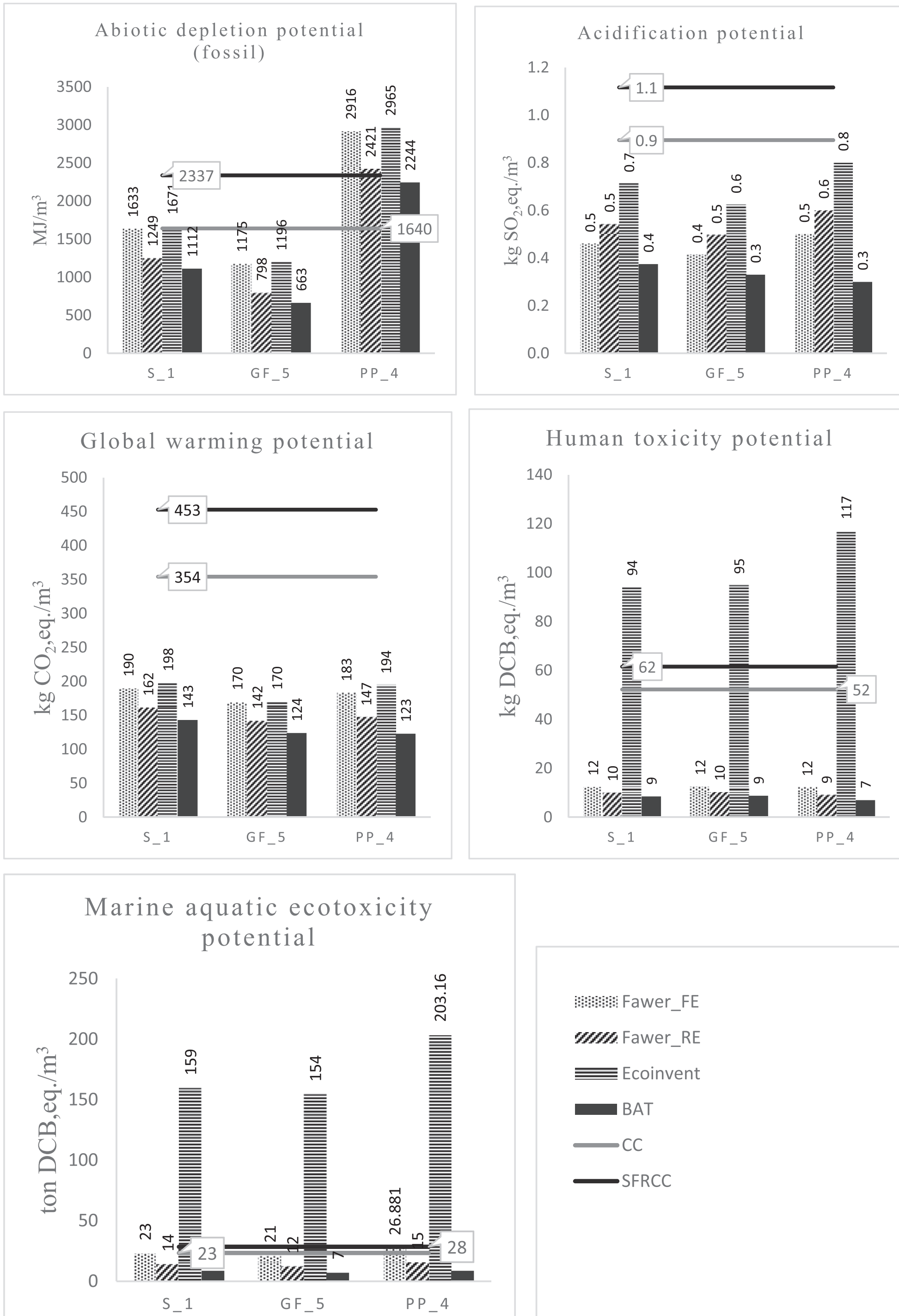

Fig. 4. Sensitivity analysis of sodium silicate. Where; **Fawer_FE** – LCI data for sodium silicate (hydrothermal process) from Fawer et al. (1999) using fossil fuel (Reference scenario); **Fawer_RE** - LCI data for sodium silicate (hydrothermal process) from Fawer et al. (1999) using biogas renewable energy; **Ecoinvent** – LCI data for sodium silicate (hydrothermal process) from Ecoinvent database; **BAT** - LCI data for sodium silicate (hydrothermal process) from best available technique (BAT) for the manufacture of large volume inorganic chemicals (IPPC, 2007).

4. Conclusions

This study used Life Cycle Assessment methodology to carry out a detailed environmental assessment of fibre reinforced alkali-activated concretes (FRAACs) in comparison to conventional concrete (CC) and steel fibre reinforced conventional concrete (SFRCC). This was conducted to estimate and compare the environmental impacts of the different concretes while also identifying the major constituent material behind the environmental burdens that could be taken into account in the future development of FRAACs.

The results showed that the FRAACs studied (GF_5, S_1 and PP_4), had lower environmental impacts than CC and SFRCC in all the impact categories studied except in Abiotic Depletion Potential (fossil) and Marine Aquatic Ecotoxicity Potential where PP_4 was higher than CC and SFRCC. In the contribution analysis, sodium silicate solution was found to be the major contributing factor to the environmental burden of the different FRAACs. This is as a result of high energy consumption during the production of sodium silicate solution in addition to using a higher quantity of sodium silicate in the production of alkali solution for the development of FRAACs. Due to the heavy effects of sodium silicate solution, sensitivity analysis was carried out to observe how different LCI sources of sodium silicate affected the overall LCIA results. Results of the sensitivity analysis showed that using LCI data from best available technology (BAT) gave the most environmentally optimal results while LCI data from Ecoinvent database was the least optimal.

The study highlights that future research and development of FRAACs should focus on reducing uncertainty of secondary data, by using data from local databases encompassed with site-specific data and data quality information. This can be achieved by collaborative effort of local industries and LCA experts, such that LCA studies can be conducted on primary data related to production processes and this can be implemented in the local database for future use. Furthermore, by taking into account the mix-designs, and the effect, varying quantities of constituent materials (especially the alkali activators) have on the alkali-activated concrete, it is recommended that constituent materials such as sodium silicate should be cautiously used or substituted with a more environmental friendly activator while not compromising on the mechanical properties of the concrete.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.07.076.

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