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Life cycle assessment of a low-height noise barrier for railway traffic noise

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ABSTRACT

Life cycle assessment (LCA) methodology was applied to assess five locally developed mix designs for a 20 m low-height noise barrier (LHNB) categorized as: precast Portland cement concrete (S0-baseline scenario), two precast geopolymer composites (S1; S2), and two additive-manufactured geopolymer composites (S3; S4). The objective of the study is to carry out a LCA study of the mix designs, to identify environmental hotspots and evaluate the influence of durability and service life on the LCA results. Environmental impact categories assessed are global warming potential (GWP), fossil depletion, photochemical ozone formation, and acidification. Results show that when a fixed service life of 40 years is chosen for all mix designs, S4 is the most environmentally sustainable with 73% reduced GWP when compared to S0. When sensitivity analysis was used to determine the effect of varying service life (10–40 years) on S1–S4; S4 shows equivalent to better environmental performance than S0. Carbonation was considered and result shows up to 8% of CO_2 uptake can be achieved. In conclusion, S4 depicts solutions and concepts that result in environmental improvement potentials for a LHNB from geopolymer composites. The results from this study supported decision-making and guided in the development a 20 m LHNB from 83% industrial side-streams and 0.3% alkali activator maintaining a 10 dB absorption capacity.

1. Introduction

Railway traffic noise, has become a recurrent but much underrated pollutant in modern-day environments and can cause negative effects such as communication interference, effects on social conduct, sleep disturbance, and hearing and concentration loss for neighboring residents (Valdebenito and Dahmen, 2013). Railway traffic noise arise from different sources, most significant is the amount of contact between the rail and the train wheel due to irregularities that cause vibration producing noise known as rolling or traffic noise (Vahtera, 2011). This can be disturbing if noise levels in the vicinity is low. Noise is measured in decibels (dB) on a logarithmic scale. However, for the human ears to respond to the frequency range involved, it is measured using an A-weighted scale (dBA) (Transport Roads and Maritime Services, 2016).

Railway traffic noise has more sound energy at high frequencies and its reduction is essential for a higher quality of life. The noise can be combated by preventing noise generation at source through various technical solutions or by incorporating noise abatement measures such as noise barriers. Noise barriers can be developed using different approaches such as Portland cement concrete, (PCC), steel and aluminum etc. (Bendtsen, 2010). For railway tracks, low-height noise barrier (LHNB) is becoming popular. LHNB as shown in Fig. 1 are a type of noise barrier with a nominal height between 85 cm and 110 cm above the rail surface (Vahtera, 2011). LHNB are sited close to the rail track to dampen the impact of the rolling noise from the rail-wheel collision and their efficacy is determined by the insertion loss, which evaluates the sound pressure before and after incorporating the LHNB (Valdebenito and Dahmen, 2013). LHNB differ from regular noise barriers with regards to location, altitude, urban visibility, and construction costs. They do not obscure views from the train windows and have so far been built for testing purposes in Finland. LHNB are designed on a case-by-case basis due to changing track geometry and must meet at least the Finnish A3 category for sound absorption which is 8–11 dB (Liikennevirasto, 2017; Vahtera, 2011). Despite all these considerations in developing efficient LHNB, their environmental sustainability remains an open question.

While some studies have addressed the acoustic and non- acoustic aspects of LHNB and generally noise barriers (Bendtsen, 2010; Transport Roads and Maritime Services, 2016; Vanhooreweder et al., 2017), and fewer studies have focused on sustainable materials in development of noise barriers (Abbas et al., 2011; Arenas et al., 2017; Asdrubali, 2006;

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Louise Rose Joynt, 2005; Oltean-dumbrava and Richards, 2016), there has been very limited research on their life cycle assessment (LCA). A study on environmental assessment of noise barriers by Valdebenito and Dahmen (2013), documented environmental performance of a sound structure comparing a vegetative sound structure and PCC noise barrier. The environmental assessment performed was limited to the production phase and did not include the use and end-of-life phases. The assessment of potential environmental impacts of noise barriers cannot be based on the evaluation of any single phase of the technology, but from raw material extraction, via construction, service life of the final products as well as end-of-life.

LHNB and generally noise barriers are traditionally produced from PCC for their simple design and construction (Abbas et al., 2011). Environmental sustainability of PCC is highly dependent on cement, which is the key binding material with an estimated 4.1 billion tons of global production in 2016 (CEMBUREAU, 2017). Consequently, there have been variety of studies on improving environmental sustainability of PCC such as using recycled materials during production (Brennan et al., 2014; Marinković et al., 2017; Raut et al., 2011; Turk et al., 2015), substitution with geopolymer composite (Abdulkareem et al., 2019; Habert et al., 2011; Luukkonen et al., 2018; Weil et al., 2009), and employing additive manufacturing in construction (Nematollahi et al., 2017; Panda et al., 2017; Panda and Tan, 2018; Van Damme, 2018).

Geopolymers are generally used to depict low calcium alkali activated aluminosilicate binders and are produced by reacting solid aluminosilicate raw materials (precursor) with an alkali activator to form a hardened binder. These precursors can be in the form of natural raw materials such as metakaolin, or as industrial side-streams with a high Si/Al ratio such as coal fly ash (CFA) and granulated blast furnace slag (GBFS) (Davidovits, 1994; Provis, 2018). Integrating industrial by-products in the production of geopolymer composites by reusing and recycling waste materials as secondary raw materials, helps to avoid problems of waste disposal and associated environmental burdens.

Additionally, additive manufacturing is a technology for building three-dimensional (3D) elements from a 3D computer-aided design model. Advantages of 3D fabrications include more flexibility, increased innovations, faster construction, risk mitigation, high material resource efficiency, and cost effectiveness (Huang et al., 2017). 3D printing has an advantage of manufacturing customized products, while maintaining similar performance and functions. However, environmental performance of AM is still debated. While some consider AM as a sustainable solution due to the near zero waste achieved during building, other consider AM as not less wasteful, as it is reported to consume an estimated 100 times higher specific energy than traditional manufacturing (Liu et al., 2018; Výtisk et al., 2019).

In this paper, we investigate life cycle assessment (LCA) study of a pilot scale low-height noise barrier (LHNB) made from Portland cement concrete (PCC) and geopolymer composites. For piloting purposes of new materials and structures, these kinds of low-height structures are suitable due to lower material consumption and manufacturing effort when compared to high structures. Also, there is less manual work when the manufacturing has not been developed in full scale. The LHNB prototypes are predefined designs, and the objective is to analyze their environmental performance based on different mix designs, life cycle phases, and construction techniques using LCA methodology.

2. Materials and method

Life cycle assessment (LCA) methodology is a standardized and established to quantify environmental performance and potential impacts of a product or service throughout its life cycle from extraction of raw materials to its end-of-life phase (EN ISO, 14040, 2006; EN ISO 14044, 2006). A product interacts with the environment in several ways all through the different life cycle phases, with each phase demonstrating a different environmental strain. As a systematic approach, LCA consists of four major phases which are addressed in different sections of this article: goal and scope definition (section 2.1); inventory analysis (section 2.2); impact assessment (section 2.3); and interpretation phase (section 3) (see Fig. S1 in the supplementary material).

This LCA study analyses five different LHNB scenarios, a reference LHNB scenario using precast PCC and four alternative LHNB geopolymer composites scenarios using precast and additive manufacturing construction methods. The geopolymer composites LHNB scenarios are developed mainly from wastes materials and industrial by-products such as coal fly ash (CFA), granulated blast furnace slag, bottom ash, bio ash, crushed steel slag, fine and coarse tailings. These are described in detail in section 2.1.1. The principal function of the LHNB is to protect neighboring residents from excessive noise produced by railway traffic.

Fig. 1. Low-height noise barrier in Finland (Liikennevirasto, 2017).

The pilot LHNB analyzed in this study is 20m in length with a 10 dB absorption capacity. It is situated in the railway track of the city of Lappeenranta in Finland, where it will be in full operation. Acoustic and non-acoustic performances of a LHNB can depreciate over the duration of its working life due to exposure to different environmental conditions and other factors. Due to this, service life of the noise barrier can be defined as the duration it functions trouble-free with no visible change in insertion loss or appearance (Morgan et al., 2001).

Desirable service life for PCC noise barrier is averagely 40 years (Environmental Protection Department Highways Department, 2003; Parker, 2006). On the other hand, there is limited information on service life estimation for geopolymer composite noise barriers. Amorim Júnior et al. (2021) investigated durability and service life of metakaolin-based geopolymer with respect to chloride penetration. The service life of the geopolymer concrete based on Fick's second diffusion law and using the age influence coefficient 0.4 and 0.6 was estimated in the range 12–13 years and 39–45 years, respectively. However, the author stated the service life prediction is used prospectively due to lack of good accuracy. Due to differences in mix designs, the LHNB geopolymer composite scenarios may have different service lives and due to limited studies on the parameters needed to calculate service life of the geopolymer composites, 40 years of service life is assumed for all scenarios in this paper. However, sensitivity analysis for service life (10–40 years) of the geopolymer LHNB scenarios is conducted. When the LHNB depreciates and can no longer fulfill its function, the LHNB modules are demolished, crushed, and landfilled. Carbonation is also taken into consideration to determine potential CO_2 savings that can be achieved during the use and end-of-life phases.

2.1. Goal and scope definition

The goal of this study is to carry out an LCA of five different LHNB mix designs made from either PCC or geopolymer composite and to evaluate the impact of product system changes on their environmental performance. The reasons for carrying out this study is to support decision-making in the development of a LHNB. The functional unit is a 20 m LHNB with 10 dB absorption capacity. Although, the LHNB have the same function, differences in mix designs will influence their durability and service life which will further influence the effectiveness of their function over time. In this regard, the functional unit is adapted to include compressive strength and service life of the concretes to yield a more consistent interpretation and assessment of results (Marinković et al., 2021; Vieira et al., 2018). This is achieved by applying two indicators. The first indicator is defined as the ratio of environmental impact category to compressive strength (MPa) at 28 days of a 20 m long LHNB (Equation (1)). The second indicator is defined as the ratio of environmental impact category to compressive strength (MPa) at 28 days and service life (years) of a 20 m long LHNB (Equation (2)) (Müller et al., 2019; Vieira et al., 2018).

$$Indicator_1 = \frac{Environmental\ \ impact\ \ category}{MPa{\cdot}20m} \tag{1}$$

$$Indicator_2 = \frac{Environmental\ \ impact\ \ category}{MPa{\cdot}20m{\cdot}years} \tag{2}$$

System boundary as shown in Fig. 2 comprise all life cycle stages from cradle to grave. Processes include raw material extraction and secondary material production, construction, transportation, and utilities (energy). Precast and additive manufacturing construction methods are investigated in this study. Transport includes distribution of materials required for construction of the LHNB from suppliers to factory to place of erection. The use stage includes usage of LHNB. At the end-of-life, the LHNB is demolished and landfilled. Capital equipment are excluded unless they are already incorporated in the unit processes of the background system. The primary data of the product system is provided by developers of the LHNB. Where primary data could not be acquired, secondary data were sourced from literature. S0, S1, S2, S3, and S4 as shown in Fig. 2 are the different LHNB scenarios and are further discussed in the next section 2.1.1.

2.1.1. Scenario description

Different mix designs were developed for precast and additive manufactured (AM) LHNB as described in the five scenarios below.

- S0 – Precast PCC
- S1 – Precast geopolymer composite
- S2 – Precast geopolymer composite
- S3 – AM geopolymer composite
- S4 – AM geopolymer composite

S0 represents the reference scenario which all other scenarios are compared against. S1 and S2 describes two different precast geopolymer composite mix designs while S3 and S4 illustrates two different AM geopolymer composite mix designs as shown in Table 1. The materials

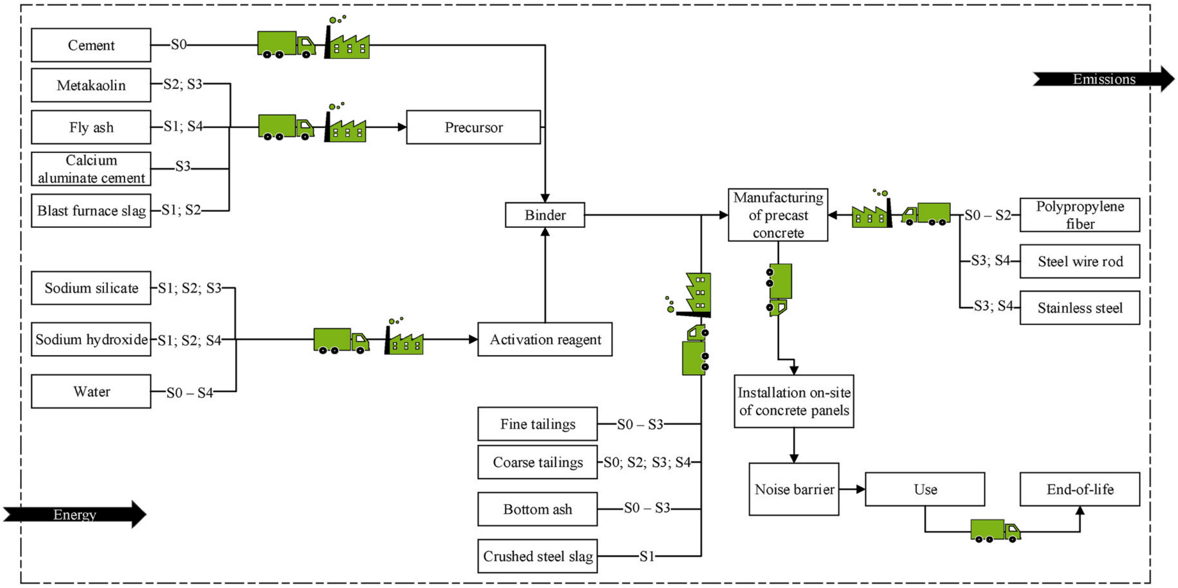

Fig. 2. System boundary depicting processes considered during the life cycle phase of the low-height noise barrier.

Table 1
Mix designs of the different scenarios (APILA Group, 2020).

Constituent	S0	S1	S2	S3	S4
Cement	27%				
Calcium aluminate cement				4%	
Activator		10%	15%	19%	0.3%
Waste precursor (CFA and GBFS)		25%	4%		37%
Metakaolin			9%	13%	
Fine aggregates	9%	13%	19%	13%	17%
Coarse aggregates	52%	45%	48%	43%	30%
Water	12%	6%	4%	6%	16%
Polypropylene fiber	0.14%	0.14%	0.14%		

CFA – coal fly ash; GBFS – granulated blast furnace slag.

needed for construction of S0 include cement, water, fine and coarse aggregates while materials required for construction of S1 – S4 are alkaline activator, precursors, water, fine and coarse aggregates as detailed in Table 1. The precursors used in S1 and S4 are mainly CFA and GBFS which have gone through beneficiation process while precursors for S2 combines GBFS and metakaolin, and precursor for S3 combines calcium aluminate cement and metakaolin. The fine aggregates are made up of fine tailings in all scenarios except S4 in which milled bio fly ash was used. Coarse tailings and bottom ash were used in S0, S2, and S3 respectively, as coarse aggregates while S1 contained bottom ash and crushed steel slag. Other materials include water and polypropylene fiber.

2.1.2. Preparation of pilot scale low-height noise barrier modules

In preparation of the pilot scale geopolymer composite LHNB, the activation reagent is prepared by weighing the solution reagents and then blending for a few minutes. The solution is left to dissolve completely and cooled. The geopolymer composite is prepared by weighing and mixing the dry ingredients. The activation reagent is poured into the dry mixture, stirred, and subsequently poured in molds or in a 3D printer with continuous mixing. The air bubbles are removed with a vibrator after casting. The products are cured at room temperature for 7 days shielded with a plastic film cover. The excess casting and other pieces are disposed with normal aggregate waste. This manufacturing applies to the geopolymer composite scenarios that are examined in this study (APILA Group, 2020).

According to preliminary product requirements, LHNB must be in two parts, a separate top of barrier and the foundation modules (Vahtera, 2011). For the precast LHNB, the modules are casted indoor and then transported to a construction site. The height of one module is 90 cm, a slab is placed 10 cm above ground surface making the total height of the LHNB to be 100 cm. The slab is not included in this study since it is same for all scenarios. The weight of one module as shown in Fig. 3 is 330 kg, and for a 20 m long LHNB 45 modules are used. The modules are attached to each other with stainless steel rebar welded to the caps screwed into the lifting anchors of the modules. The thickness of the LHNB is 150 mm which fits the Finnish standard concrete thickness (at least 100 mm) of a noise barrier (Liikennevirasto, 2017).

For the additive manufactured LHNB, the module is printed in factory and transported to the site for assembling. The weight and height of one module as shown in Fig. 4 is 57 kg and 45 cm, respectively. Two modules stacked on each other are needed to reach a 90 cm height and a slab is placed 10 cm above the ground making the total height of the barrier 100 cm. For a 20 m long LHNB, 90 modules are used. The module is hollow in shape and filled with 58.28 L of crushed aggregate per module. For 90 modules, 5245 L of crushed aggregate is utilized. The thickness of the concrete is 295 mm.

2.1.3. Carbonation (CO_2 uptake)

Carbonation "is a chemical reaction by which CO_2 penetrates concrete and reacts with hydration products, forming mainly calcium carbonate" (Andersson et al., 2019). When cement is produced, most of the CO_2 emitted is due to combustion of fuels required in production of cement and to some extent from calcination of limestone. The calcination reactions are reversible, thereby, CO_2 is absorbed into the concrete by a process referred to as carbonation. Carbonation is dependent on several factors such as the process lasting many years as it is a slow process. Other factors include CO_2 availability (as concrete must be exposed to CO_2 in air to carbonate), transport of CO_2 molecules into concrete (which can make carbonation rate faster when concrete is crushed), temperature, humidity, and porosity. Thus, considering carbonation in emission calculation of concrete is important (Stripple et al., 2018).

Carbonation reaction occurs in several steps but the main reaction is the reaction between the calcium and carbonate ions which takes place in water phase in the pore solution in the concrete, making water and moisture an important part of carbonation (Andersson et al., 2019). It is documented that half of the emissions that comes from raw materials required to produce concrete, can be reabsorbed during carbonation process of concrete during the use phase and partly in the end-of-life phase (Stripple et al., 2018). A report by Stripple et al. (2018) details carbonation reaction steps and has documented three different CO_2 uptake calculation methodologies based on complexity and accuracy. These different methods relate to an annual CO_2 uptake. In this study, the simplified methodology presented by Stripple et al. (2018) will be used to calculate the CO_2 uptake in the LHNB use and end-of-life phases.

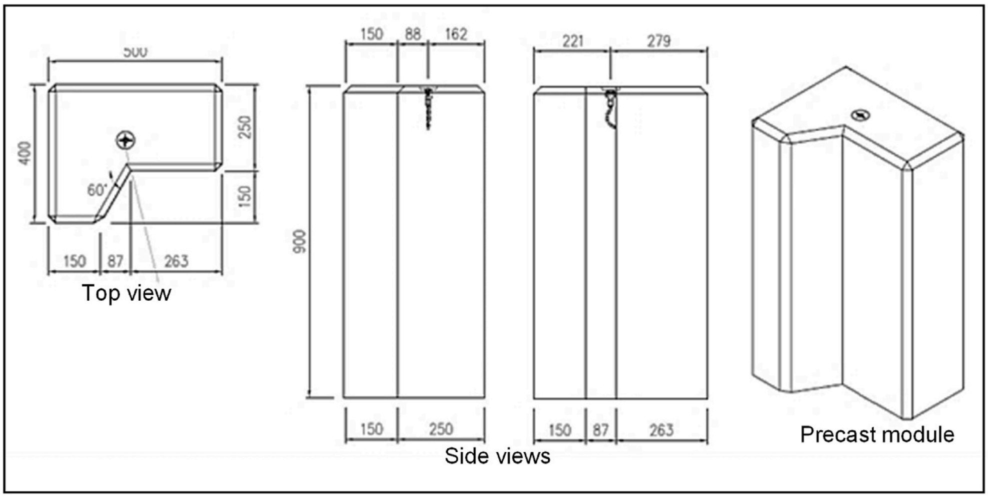

Fig. 3. Pilot precast LHNB module for the UIR project (Concept design by Design Reform ltd, 2020).

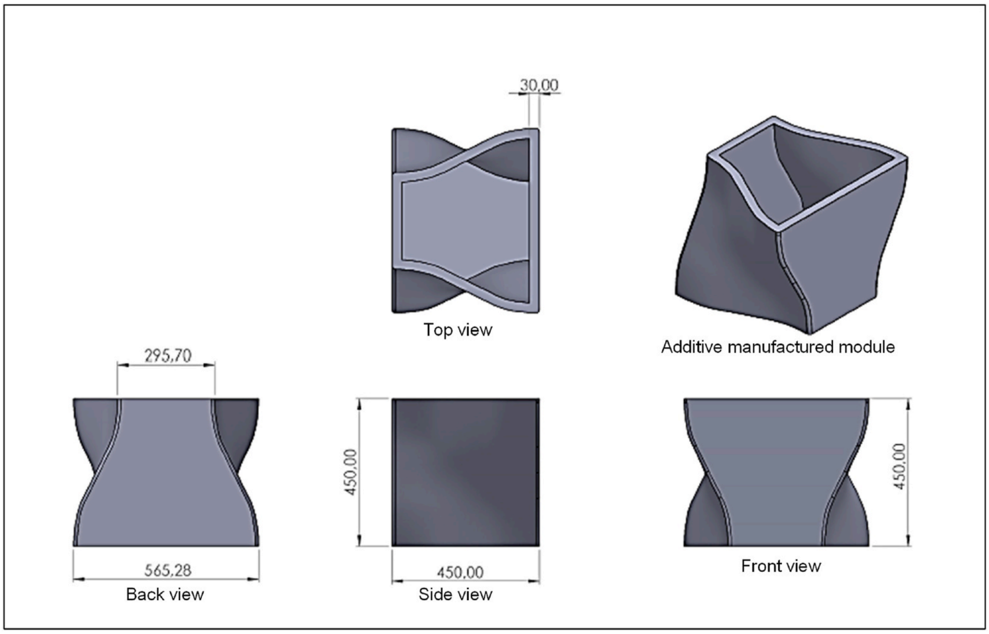

Fig. 4. Pilot additive manufactured LHNB element for the UIR project (Concept design by Design Reform ltd, 2020).

For the use stage, two alternative CO_2 uptake calculations are provided to handle uncertainty.

- Alternative A: annual CO_2 uptake for the use stage is estimated as “0.20 multiplied by the reported emission from calcination of consumed cement clinker”
- Alternative B: annual CO_2 uptake for the use stage is estimated as “0.15 multiplied by the reported emission from calcination of consumed cement clinker”

For the end-of-life phase (demolishing, crushing and storage).

- annual CO_2 uptake is estimated as “0.02 multiplied by the reported emission from calcination of consumed cement clinker”.

Alternatively, if both the amount of annual concrete recycling and annual crushed concrete used as secondary raw material is known, the CO_2 uptake in the end-of-life and secondary use phase can be individually calculated as 10 kg CO_2/m^3 concrete (Stripple et al., 2018).

2.2. Life cycle inventory (LCI)

LCI is where data is collected and compiled on elementary flows for all processes in the product system. LCI data for sodium hydroxide, polypropylene fiber, transportation, cement, electricity, and water were sourced from GaBi database. LCI for sodium silicate and calcium aluminate cement were respectively sourced from Ecoinvent database and environmental product declaration by Cimsa Cimento (CIMSA, 2015). Pedigree matrix is applied to assess the quality of data utilized in this study. More information of the data quality can be found in the supplementary material (see Table S1). The data source for the different processes is shown in Table 2 below.

Data quality indexes are evaluated based on five independent characteristics namely, reliability, completeness, temporal correlation, geographical correlation, and further technological correlation, respectively as shown in the brackets (x,x,x,x,x). Each independent characteristic is scored between 1 and 5 quality levels (1-excellent; 5-poor) (Weidema et al., 2013).

To produce metakaolin, kaolin is calcined at 2.5 MJ/kg of thermal energy from natural gas (Heath et al., 2014; NLK, 2002). LCI data for kaolin is reported in GaBi database. LCI data for beneficiating fly ash, tailings and crushed steel slag were sourced from local companies producing these materials. Energy consumption for processing tailings and crushed steel slag is 0.011 MJ/kg and 0.063 MJ/kg respectively while energy consumption for processing bio fly ash and CFA is 0.045 MJ/kg and 0.11 MJ/kg, respectively. GBFS goes through the processes of granulation, drying, crushing and grinding (Marceau et al., 2007). Thus,

Table 2
Data source and quality.

Type of data	Source	Data quality indexes Pedigree matrix
Sodium hydroxide	GaBi database 2019 – EU-28: Sodium hydroxide (caustic soda mix, 100%)	(3,3,2,2,2)
Sodium silicate solution	Ecoinvent database – EU-28: Sodium silicate production, hydrothermal liquor, product in 37% solution state	(2,2,5,1,1)
Portland cement	Cement (CEM I) [Minerals]	(3,3,4,4,5)
Metakaolin	Kaolin calcination (Heath et al., 2014; NLK, 2002)	(3,3,2,3,3)
Water	GaBi database 2019 – EU-28: tap water	(3,3,4,4,3)
Electricity	GaBi database 2019 – FI: electricity grid mix	(3,3,4,3,4)
GBFS	GBFS beneficiation (Marceau and VanGeem, 2003)	(2,3,5,4,1)
Coal fly ash	Locally sourced	(1,2,1,1,1)
Tailings	Locally sourced	(1,2,1,1,1)
Calcium aluminate cement	Cimsa Cemento (CIMSA, 2015)	(2,2,1,4,2)
Crushed steel slag	Locally sourced	(1,2,1,1,1)
Crushed stone	GaBi database 2019 – DE: crushed stone 16/32 ts	(3,3,2,3,2)
Transportation	GaBi database 2019 – Truck-trailer, Euro 5, 34–40 t gross weight/27 t payload capacity	(3,3,2,2,2)
Diesel	GaBi database 2019 – Diesel mix at filling station	(3,3,2,3,3)
Landfill	GaBi database 2019 – Inert matter (unspecific construction waste on landfill)	(3,3,2,2,3)
Polypropylene fiber	GaBi database 2019 – EU-28: Polypropylene fibers	(3,3,2,4,2)

materials and energy required to process GBFS were modelled according to data from Marceau and VanGeem (2003). Data on electricity requirements for dissolving alkaline activator is 0.0084 kWh/kg (Passuello et al., 2017) and mixing of constituents is locally estimated to be 0.0045 MJ/kg. Electricity requirements for 3D printing is locally estimated to be 7 MJ/t (Jäppinen, 2017) while data for precast is estimated to be 2.16 MJ/t (Tahvanainen, 2020). It is assumed that limited to no-maintenance and repair activities are required. The distance covered for the different materials used in the LHNB scenarios can be found in Table S2 of the supplementary material.

2.3. *Life cycle impact assessment (LCIA)*

The LCIA phase is where information from LCI is translated to environmental impact scores and categories. In this step, an overview of significant environmental impact categories for LHNB is conducted. The relevant environmental impact categories in assigning LCI results to environmental issues according to different literature studies (Estévez et al., 2006; Kawai et al., 2005; Kikuchi and Kuroda, 2011; Zhang et al., 2006) are global warming potential (GWP) (kg CO2 eq.), fossil depletion (ADP_FF) (kg oil eq.), photochemical ozone creation potential (POCP) (kg NO_x eq.), and acidification potential (AP) (kg SO_2 eq.). These environmental impact categories are selected as they are associated with environmental issues related to concrete production such as fossil and resource depletion, emissions to air, water, and land (Chen et al., 2010; Stajanca and Estokova, 2012). Environmental performance modelling was conducted using GaBi 9.2.0.58 software and selected method was ReCiPe 2016 v1.1 (midpoint hierarchist timeframe). ReCiPe indicators provide information on the environmental issues associated with inputs and outputs of the product system at both midpoint and endpoint level. It also provides characterization factors for a variety of elementary flows for different environmental impacts (Výtisk et al., 2019). It is a widely adopted method due to its robustness (Hischier et al., 2010).

2.4. *Sensitivity analysis*

Sensitivity analysis is applied to evaluate the influence of modelling assumptions and choices in a product system (EC-JRC, 2010). Service life of geopolymer composite was assumed to be 40 years same as PCC. However, due to material differences in the mix designs of the LHNB scenarios, sensitivity analysis was conducted for the geopolymer composite (S1 – S4) in range 10 years–40 years to determine the influence of changes in service life on the environmental performance of the geopolymer composite LHNB scenarios.

3. Results

The LCIA results generated are based on the environmental assessment of the different LHNB scenarios (see Table 1). These results illustrate the environmental impacts of the LHNB in their different life cycle phases.

In the production phase, with respect to GWP, S1, S2, S3 and S4 had 44%, 7%, 32% and 96% lower global warming effects respectively, when compared to S0. With respect to ADP_FF, S1, S2 and S3 have 33%, 123% and 36% increased oil extraction respectively while S4 has 87% decrease, respectively, when compared to S0. With respect to POCP, S1, S2, S3 and S4 had 41%, 17%, 47% and 94% lower formation of photochemical oxidants, when compared to S0. Finally, with respect to AP, S1, S2, and S3 have respectively, 10%, 62%, and 27% potential increase in atmospheric deposition of acidifying compounds while S4 has 96% decrease when compared to S0. Still in the production phase, regarding GWP, cement is the most significant contributing material in S0 (90%). In S1, alkali activator and transportation were the most significant contributor at 80% and 16% respectively. In S2, alkali activator and metakaolin were the significant contributors at 70% and 19% respectively. Regarding S3, sodium silicate, metakaolin and CAC contributed 59%, 19% and 13% respectively. While in S4, transportation, aggregates, and alkali activator were the most significant contributor at 39%, 38%, and 11%. With respect to ADP_FF, cement (70%) and transportation (21%) mostly contributed to S0. Alkali activator and transportation contributed 73% and 16% respectively, to S1. In S2 and S3, alkali activator contributed 61% each and metakaolin contributed 24% and 29% to the scenarios, respectively. In S4, transportation and aggregates contributed 33% each. With respect to POCP, cement and transportation contributed 84% and 15% respectively to S0. Alkali activator and transportation are the most significant contributors to S1 at 70% and 27% respectively, S2 at 71% and 17% respectively, and S3 at 69% and 14% respectively. In S4, transportation and aggregates had 93% and 19% contribution, respectively. Finally, with respect to AP, cement (91%) is also the most significant contributing material in S0. Alkali activator is the most significant contributing material in S1 (90%), S2 (91%), and S3 (75%). In S4, transportation and aggregates contributed 45% and 26%, respectively. Other materials had minimal contribution lower than 10%. Visual representation of contribution of the input materials and energy to the respective impact categories in the production phase can be found in the supplementary material (see section B: LCIA results – contribution analysis in the production phase).

In the use phase, carbonation as discussed in section 2.1.3 is taken into account, and alternative B is used to calculate the annual CO_2 uptake for more conservative results. Calcination emission from cement is estimated to be approximately 49% (Stripple et al., 2018). For the geopolymer scenarios which have no cement content, CO_2 uptake is not calculated. This is because of the limited data availability for the CO_2 uptake of CFA and GBFS. Although, CO_2 uptake for GBFS has been estimated to be 35 kg CO_2/ton, it is recommended to include these additions when advanced CO_2 uptake methodology is applied. Since, simplified CO_2 uptake methodology is applied in this study, CO_2 uptake for scenarios with cement content (S0 and S3) are the only ones considered. Also, since minimal to no-maintenance and repair activities are expected during the usage of LHNB, the emissions in the use phase are limited to activities leading to carbonation and CO_2 uptake. Thus, annual CO_2 uptake for S0 and S3 is estimated to be 270 and 27 kg CO_2 eq./20m, respectively.

In the end-of-life phase, LHNB are demolished and transported to landfill. Emissions from demolition, crushing, and landfill are comparable for all the scenarios since the weights of the LHNB are equivalent. Annual CO_2 uptake is also considered in the end-of-life phase and estimated to be 36 and 4 kg CO_2 eq./20m for S0 and S3, respectively.

Fig. 5 presents the LCA results of the LHNB scenarios and on the secondary axis is the respective compressive strength (MPa at 28 days) of the scenarios. For the overall LCA results, S2 has the highest GWP emissions, with 0.35% increase above S0, while S1, S3 and S4 have 37%, 26% and 89% lower GWP emissions compared to S0. With respect to ADP_FF, S1, S2, and S3 have 28%, 107% and 31% increased oil consumption respectively, while S1 has 76% decrease in oil consumption compared to S0. With respect to POCP, S1, S2, S3, and S4 have 36%, 15%, 41%, and 83% lower potential of formation of photochemical oxidants when compared to S0. With respect to AP, S1, S2, and S3 have 9%, 54%, 24%, respectively, potential increase in atmospheric deposition of acidifying compounds while S4 has 85% decrease, when compared to S0.

When comparing the total LCA results with compressive strength, the LHNB mix designs produced different compressive strengths, with S0 having the highest strength (32 MPa) and S4 with the lowest strength (13 MPa). For a more consistent interpretation and assessment of results, environmental performance results with respect to compressive strength and service life was conducted and is discussed further in the next section.

3.1. *Compressive strength related LCIA results*

The environmental performance of the LHNB scenarios is analyzed

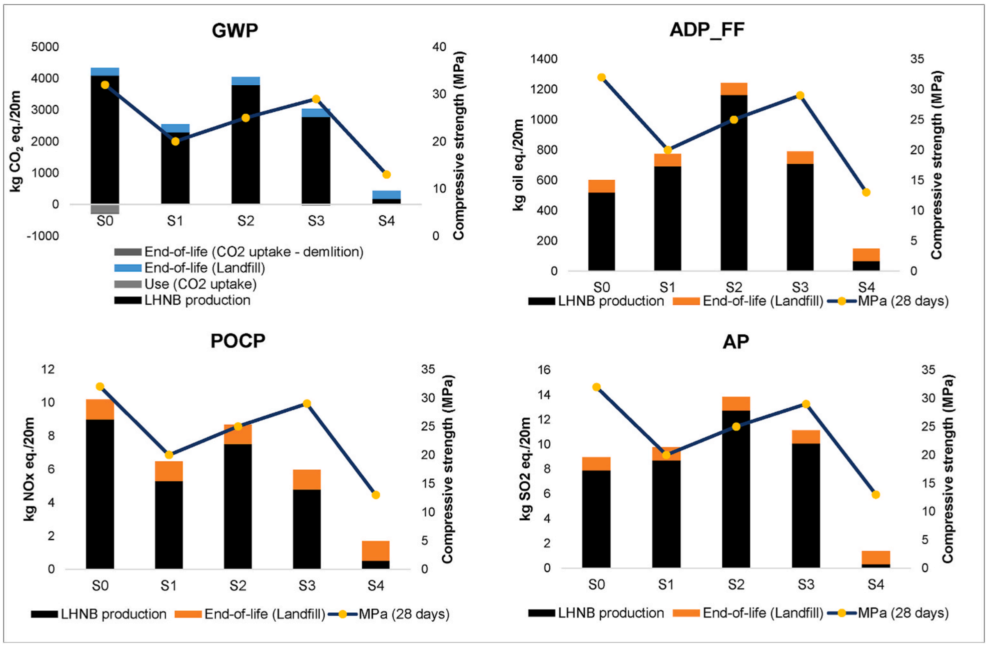

Fig. 5. Life cycle impact assessment results of the LHNB scenarios.

with respect to compressive strength using *Indicator*$_1$ (see Equation (1) in section 2.1). S2 has the highest emissions in the respective environmental impact categories, while S4 has the best environmental performance with this indicator as shown in Fig. 6.

3.2. Service life related LCIA results

For further consistent interpretation of results, the environmental performance of the LHNB scenarios is analyzed with respect to compressive strength and service life using *Indicator*$_2$ (see Equation (2) in section 2.1). As in the previous section, S2 is the worst scenario with this indicator while S4 has the best environmental performance as shown in Fig. 7. The limitation to this analysis is assumption of 40 years of service life for all the LHNB scenarios. As a result, a sensitivity analysis was conducted and is detailed in the next section.

3.2.1. Sensitivity analysis

The LHNB scenarios are made up of different mix designs with different materials which results in different compressive strength which can also influence the service life of the LHNB scenarios. Since PCC noise barrier has a desirable service life of averagely 40 years and an uncertainty on the service life of the geopolymer composites LHNB, a sensitivity analysis was conducted to determine how changes in the service life (10–40 years) of the geopolymer composite LHNB scenarios influence the LCA results. As shown in Fig. 8, the service life of S0 remains constant, thus, the environmental performance remains constant

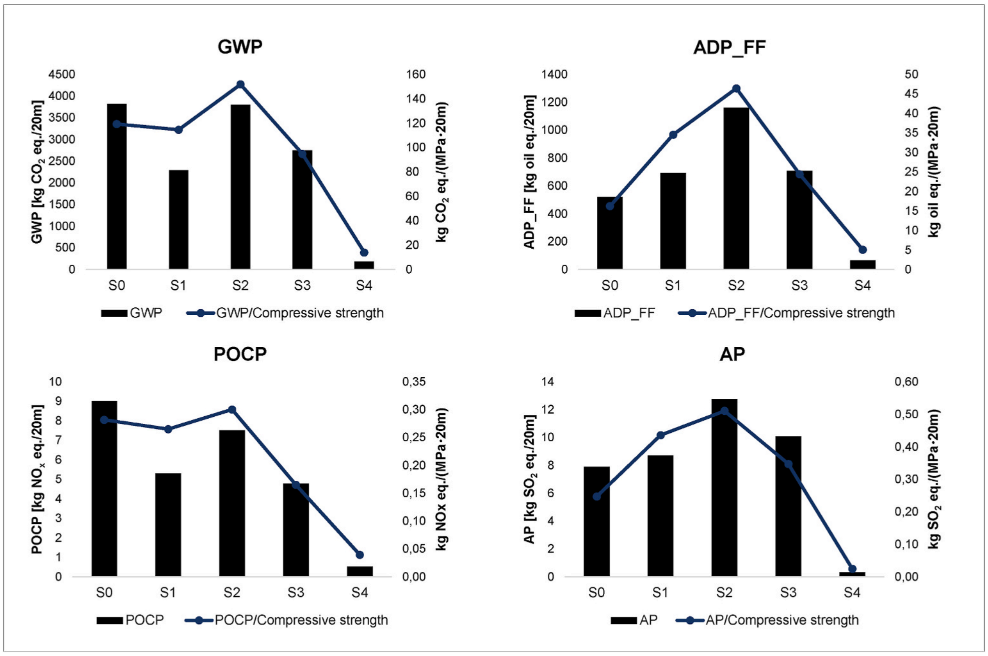

Fig. 6. Life cycle impact assessment results with respect to compressive strength of the LHNB scenarios.

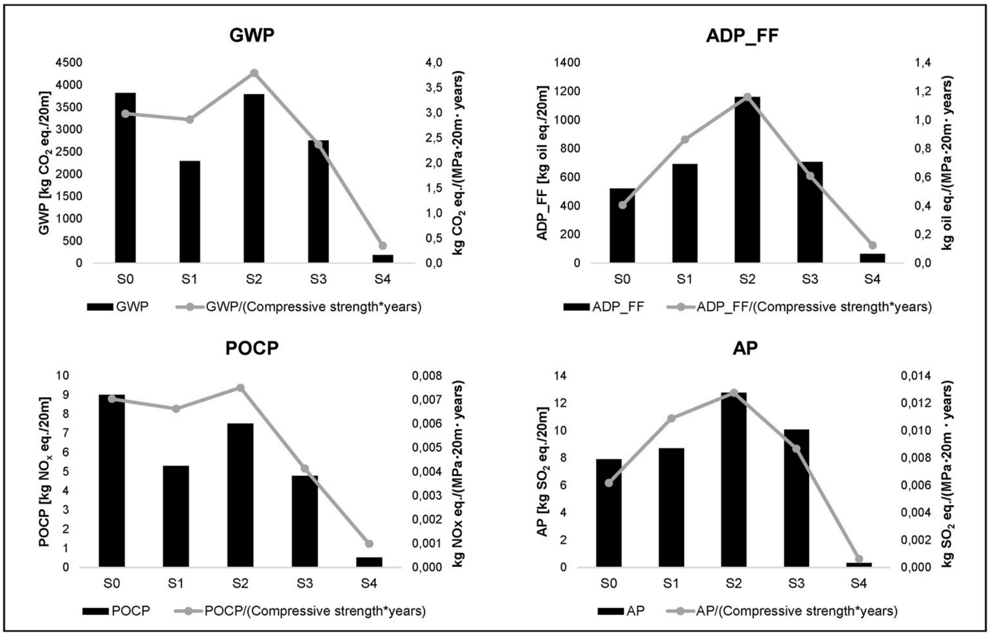

Fig. 7. Life cycle impact assessment results with respect to service life of the LHNB scenarios.

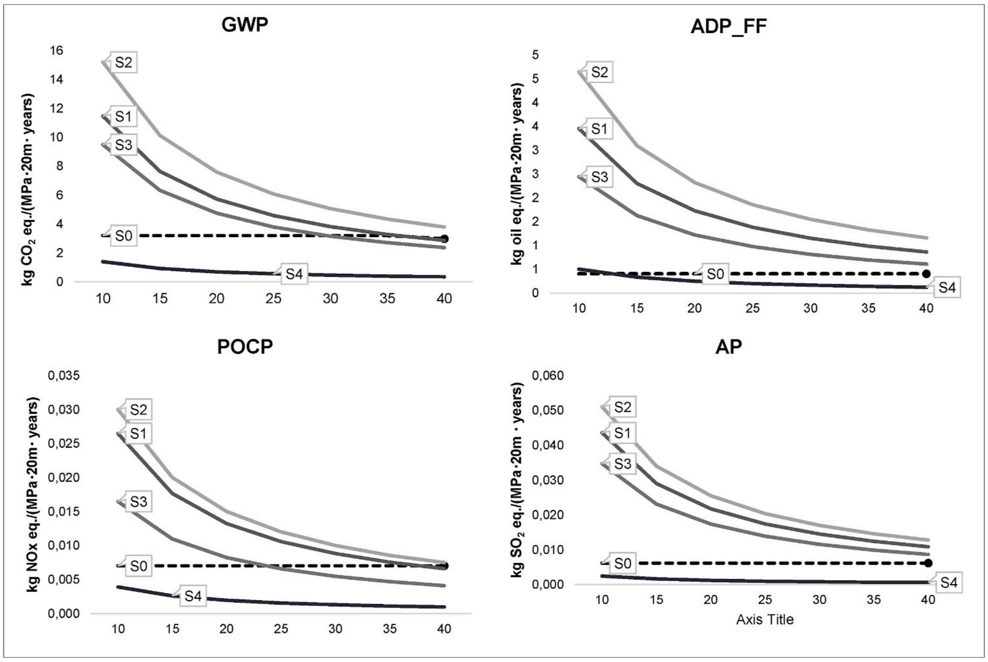

Fig. 8. Life cycle impact assessment results with respect to changing service life of the geopolymer composite LHNB scenarios.

whereas the environmental performance of the geopolymer composite scenarios is varied according to 10–40 years of service life duration.

With regards GWP, S4 has the best environmental performance with lower GWP emissions than S0 at the different years. The environmental impacts of S1, S2, and S3 is higher than S0. However, the environmental impacts of S1 and S3 becomes equal to S0 at 38 years and 32 years of service life respectively. With respect to ADP_FF and AP, only S4 has equivalent or better environmental performance than S0 whether it last 10 years or 40 years. With respect to POCP, S1, S2 and S3 have worse environmental performance when compared to S0. However, S1 and S3 become of equivalent environmental performance to S0 at 40 years and 25 years of service life while S4 remains environmentally favorable than S0 at the different years.

4. Discussion

It is essential to assess environmental impacts that will presumably occur during a product's life cycle and as such, it is possible to identify potential environmental problems and solutions. Resources and energy are much consumed in producing a LHNB. Thus, LCA of LHNB was achieved by analyzing different mix designs and proffering insight into details regarding their potential environmental impacts.

The assessment carried out shows that the production stage is the most significant life cycle phase. The major environmental problem associated with the reference scenario S0 (PCC LHNB) is due to cement production which has been known to be a major environmental pollutant (Andrew, 2018; Crossin and Carre, 2012). Most of the environmental impacts from the production phase of the geopolymer composites LHNB S1–S4, originated from alkali-activator. Studies have shown that there is a possibility to produce alkali activator from silica-rich chemically modified waste products such as rice husk ash and waste glass without compromising on their mechanical properties (Tong et al., 2018; Vinai and Soutsos, 2019). Environmental assessment study by Abdulkareem et al. (2021), further demonstrated that environmental improvements are achieved from this substitute (Abdulkareem et al., 2021). Furthermore, transportation emissions were significant during production of S4. Transportation emissions is of importance due to environmental burden from long distance transportation of materials. Thus, most of the materials are transported only within regional scale (averagely 200 km).

When the environmental impact categories were initially assessed without considering compressive strength and service life (Fig. 5), S0 (PCC LHNB) had the worst environmental performance in GWP and POCP, while S2 had the worst environmental performance in ADP_FF and AP. When the environmental impacts were assessed with respect to compressive strength (Fig. 6), S2 had the worst environmental performance in all assessed impact categories followed by S1. Finally, when the environmental performance of the LHNB mix designs were assessed with respect to a fixed 40 years' service life (Fig. 7), S2 also had the worst environmental performance followed by S1. One of the limitations of this study is not calculating the specific service life of the different scenarios for a more consistent result, however, sensitivity analysis was conducted to determine effect of differences in service life on the overall results. When the service life of the geopolymer composites (S1–S4) were varied from 10 to 40 years due to uncertainty in the service life of geopolymer composites (Fig. 8), only S4 showed equivalent to better environmental performance than S0. Overall, S4 had the best environmental performance. These differences in results shows the significance of including compressive strength and service life for a more consistent interpretation of results.

Furthermore, Arenas et al. (2017) investigated noise properties of fly ash-based geopolymers and found the sound absorption of fly ash-based geopolymers is similar to commercial products. The study highlighted that sound absorption coefficient is dependent on ratio of aggregates to binder and not on the type of binder, activating solution ratio, and/or aggregates so far, the size distribution of the aggregates is alike. The study further highlights that sound absorption of a material depends on the thickness of a specimen, and a 120 mm thickness of material is appropriate as road traffic noise barriers which corresponds with the Finnish standard thickness for concrete noise barrier which is at least 100 mm (Liikennevirasto, 2017). Together, the standard thickness corroborates with the thickness of the precast LHNB (S0–S2) which is 150 mm and the thickness of the AM LHNB (S3 and S4) which is 295 mm (see section 2.1.2). Also, the specific mass of the LHNB scenarios is comparable with a safety marginal inclusive in the design.

S4 illustrates improvement potential in developing LHNB from 83% industrial waste materials and maximizing the efficient use of resources using AM construction method. The integration of AM in geopolymer makes it a superior and sustainable alternative to precast PCC (Yao et al., 2020) due to increased flexibility. This is also highlighted in this study comparing S2 and S3. Although, both mix designs are comparable, S2 had worse environmental performance than S3, as the later was constructed through additive manufacturing, with a unique hollow shape resulting in flexible LHNB development and lesser material consumption. Whereas S2 was produced in the traditional construction method resulting in more material consumption. Although, the environmental desirability of AM from carbon and energy viewpoint varies depending on how the printing is executed (Saade et al., 2020), other uniqueness include complexity-achievement and reduced hazardous exposure of workers etc. (Saade et al., 2020). Conversely, the shift to AM can lead to loss of jobs due to less manpower needed. There is still an open question on AM revolutionizing traditional construction, however, it can be said that AM will transform construction to highly sophisticated structures with improved environmental performance.

5. Conclusion

This study explores the environmental performance of five mix designs of low-height noise barriers (LHNB) from Portland cement concrete and geopolymer composite recipes, using LCA methodology. With compressive strength and service life (40 years) as indicators in assessing the environmental performance of the LHNB, S4 had the best environmental performance due to lower amounts of chemicals, virgin materials, and using additive manufacturing construction method whereas S2 had the worst environmental performance of the LHNB. When compared to S0, a potential decrease in emission between 40% and 73% is achieved in S4 in all assessed environmental impact categories. When compared to S1, a potential decrease in emission between 60% and 78% is achieved in S4. When compared to S2, a potential decrease in emission between 63% and 81% is achieved in S4. Finally, when compared to S3, a potential decrease between 37% and 72% is achieved in S4 in all the assessed environmental impact categories. Due to possibly different service lives of the geopolymer composites LHNB, sensitivity analysis carried out by varying the service lives of the LHNB geopolymer composites from 10 to 40 years and the result shows that only S4 has equivalent or better environmental performance compared to S0 at the different years.

The environmental hotspot of S0 is cement while alkali activator is the hotspot for S1, S2, and S3. Transportation emissions is the hotspot of S4. Based on the simplified methodology in calculating CO_2 uptake (Stripple et al., 2018), 270 and 27 kg CO_2 eq./20m can be absorbed during the use phase in S0 and S3, respectively, while in the end-of-life phase, 36 and 4 kg CO_2 eq./20m can be absorbed in S0 and S3, respectively.

S4 depicts solutions and concepts that result in environmental improvement potentials for a low-height noise barrier. This study highlights that although, geopolymer composites may be considered a low carbon alternative to Portland cement, this conclusion highly depends on the quantity of alkali activators in the mix design, its durability and service life. The results from this study supported decision-making and guided in local development of LHNB from geopolymer composites, by minimizing the use of alkali activators and natural precursors (metakaolin) in a mix design. These results show the possibility of developing a geopolymer composite LHNB from 83% industrial wastes and by-products and 0.3% alkali activator.

CRediT authorship contribution statement

Mariam Abdulkareem: Conceptualization, Formal analysis, Investigation, Data curation, Methodology, Software, Visualization, Roles. **Jouni Havukainen:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Jutta Nuortila-Jokinen:** Conceptualization, Funding acquisition, Project administration, Resources, Visualization, Writing – review & editing. **Mika Horttanainen:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

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

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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.2021.129169.

References

Abbas, A.R., Liang, R.Y., Frankhouser, A., Cardina, J., Cubick, K.L., 2011. Green Noise Wall Construction and Evaluation.

Abdulkareem, M., Havukainen, J., Horttanainen, M., 2019. How environmentally sustainable are fibre reinforced alkali-activated concretes? J. Clean. Prod. 236 https://doi.org/10.1016/j.jclepro.2019.07.076.

Abdulkareem, M., Havukainen, J., Nuortila-Jokinen, J., Horttanainen, M., 2021. Environmental and economic perspective of waste-derived activators on alkali-activated mortars. J. Clean. Prod. 280, 124651 https://doi.org/10.1016/j.jclepro.2020.124651.

Amorim Júnior, N.S., Andrade Neto, J.S., Santana, H.A., Cilla, M.S., Ribeiro, D.V., 2021. Durability and service life analysis of metakaolin-based geopolymer concretes with respect to chloride penetration using chloride migration test and corrosion potential. Construct. Build. Mater. 287, 122970 https://doi.org/10.1016/J.CONBUILDMAT.2021.122970.

Andersson, R., Stripple, H., Gustafsson, T., Ljungkrantz, C., 2019. Carbonation as a method to improve climate performance for cement based material. Cement Concr. Res. 124, 105819 https://doi.org/10.1016/j.cemconres.2019.105819.

Andrew, R.M., 2018. Global CO 2 emissions from cement production. Earth Syst. Sci. Data 105194, 195–21710.

APILA Group, 2020. Apila Group [WWW Document]. URL. https://www.apilagroup.fi/en/. accessed 11.10.20.

Arenas, C., Luna-Galiano, Y., Leiva, C., Vilches, L.F., Arroyo, F., Villegas, R., Fernández-Pereira, C., 2017. Development of a fly ash-based geopolymeric concrete with construction and demolition wastes as aggregates in acoustic barriers. Construct. Build. Mater. 134, 433–442. https://doi.org/10.1016/j.conbuildmat.2016.12.119.

Asdrubali, F., 2006. Survey on the acoustical properties of new sustainable materials for noise control. In: Euronoise 2006. Tampere, Finland., pp. 1–10

Bendtsen, H., 2010. Noise Barrier Design: Danish and Some European Examples.

Brennan, J., Ding, G., Wonschik, C.-R., Vessalas, K., 2014. A closed-loop system of construction and demolition waste recycling. In: Isarc.

Cembureau, 2017. CEMBUREAU Activity Report 2017.

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., 2010. Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. J. Clean. Prod. 18, 478–485. https://doi.org/10.1016/j.jclepro.2009.12.014.

CIMSA, 2015. Environmental Product Declaration - Çimsa Çimento San. Ve Tic. A.Ş.

Crossin, E., Carre, A., 2012. Comparative Life Cycle Assessment of Concrete Blends.

Davidovits, J., 1994. Properties of Geopolymer Cements, Alkaline Cements and Concretes.

EC-JRC, 2010. International reference life cycle data system (ILCD) handbook - General guide for life cycle assessment - detailed guidance, International reference life cycle data system (ILCD) Handbook. In: General Guide for Life Cycle Assessment – Detailed Guidance. https://doi.org/10.2788/38479. Luxembourg.

EN ISO 14044, 2006. ISO 14044 – Environmental Management — Life Cycle Assessment — Requirements and Guidelines. https://doi.org/10.1007/s11367-011-0297-3. ISO 14044.

EN ISO 14040, 2006. SFS-EN ISO 14040 ENVIRONMENTAL MANAGEMENT. LIFE CYCLE ASSESSMENT . PRINCIPLES AND FRAME- WORK (ISO 14040 : 2006).

Environmental Protection Department Highways Department, 2003. Guidelines on Design of Noise Barriers.

Estévez, B., Aguado, A., Josa, A., 2006. Environmenta impact assessment of concrete recycling, coming from construction and demolition waste (C&DW). Deconstruction Mater. Reuse 250, 165–175.

Habert, G., D'Espinose De Lacaillerie, J.B., Roussel, N., 2011. An environmental evaluation of geopolymer based concrete production: Reviewing current research trends. J. Clean. Prod. 19, 1229–1238. https://doi.org/10.1016/j.jclepro.2011.03.012.

Heath, A., Paine, K., McManus, M., 2014. Minimising the global warming potential of clay based geopolymers. J. Clean. Prod. 78, 75–83. https://doi.org/10.1016/j.jclepro.2014.04.046.

Hischier, R., Weidema, B.P., Althaus, H., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. In: Implementation of Life Cycle Impact Assessment Methods. Ecoinvent report.

Huang, R., Riddle, M.E., Graziano, D., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2017. Environmental and economic Implications of distributed additive manufacturing: the case of Injection mold tooling. J. Ind. Ecol. 21, S130–S143. https://doi.org/10.1111/jiec.12641.

Jäppinen, P., 2017. Electricity Consumption for 3D Printing.

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, 435–456. https://doi.org/10.3151/jact.3.435.

Kikuchi, T., Kuroda, Y., 2011. Carbon dioxide uptake in demolished and crushed concrete. J. Adv. Concr. Technol. 9, 115–124. https://doi.org/10.3151/jact.9.115.

Liikennevirasto, 2017. Radan Matalan Meluesteen Tuotevaatimukset. Liikennevirasto in Finnish.

Liu, Z., Jiang, Q., Cong, W., Li, T., Zhang, H.-C., 2018. Comparative study for environmental performances of traditional manufacturing and directed energy deposition processes. Int. J. Environ. Sci. Technol. 15, 2273–2282. https://doi.org/10.1007/s13762-017-1622-6.

Louise Rose Joynt, J., 2005. A Sustainable Approach to Environmental Noise Barrier Design. University of Sheffield.

Luukkonen, T., Abdollahnejad, Z., Yliniemi, J., Kinnunen, P., Illikainen, M., 2018. One-part alkali-activated materials: a review. Cement Concr. Res. 103, 21–34. https://doi.org/10.1016/j.cemconres.2017.10.001.

Marceau, M., VanGeem, M.G., 2003. Life Cycle Inventory of Slag Cement Manufacturing Process CTL Project No, 312012.

Marceau, M.L., Nisbet, M.A., Vangeem, M.G., 2007. Life Cycle Inventory of Portland Cement Concrete.

Marinković, S., Dragaš, J., Ignjatović, I., Tošić, N., 2017. Environmental assessment of green concretes for structural use. J. Clean. Prod. 154, 633–649. https://doi.org/10.1016/j.jclepro.2017.04.015.

Marinković, S., Carević, V., Dragaš, J., 2021. The role of service life in Life Cycle Assessment of concrete structures. J. Clean. Prod. 290, 125610 https://doi.org/10.1016/J.JCLEPRO.2020.125610.

Morgan, S.M., Kay, D.H., Bodapati, S.N., 2001. Study of noise barrier life-cycle costing. J. Transport. Eng. 127, 230–236. https://doi.org/10.1061/(ASCE)0733-947X(2001)127:3(230).

Müller, H.S., Moffatt, J.S., Haist, M., Vogel, M., 2019. A new generation of sustainable structural concretes – design approach and material properties. IOP Conf. Ser. Earth Environ. Sci. 290, 012002 https://doi.org/10.1088/1755-1315/290/1/012002.

Nematollahi, B., Xia, M., Sanjayan, J., 2017. Current Progress of 3D Concrete Printing Technologies.

NLK, 2002. Ecosmart Concrete Project: Metakaolin Pre-feasibility Study. British Columbia, Vancouver. Report EA2860.

Oltean-dumbrava, C., Richards, M., 2016. Assessing the Relative Sustainability of Long Parallel Noise Barriers and Related Noise Reducing Devices for a Motorway in Italy, pp. 4253–4260. Hamburg.

Panda, B., Tan, M.J., 2018. Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing. Ceram. Int. 44, 10258–10265. https://doi.org/10.1016/J.CERAMINT.2018.03.031.

Panda, B., Paul, S.C., Hui, L.J., Tay, Y.W.D., Tan, M.J., 2017. Additive manufacturing of geopolymer for sustainable built environment. J. Clean. Prod. 167, 281–288. https://doi.org/10.1016/J.JCLEPRO.2017.08.165.

Parker, G., 2006. Effective noise barrier design and specification. In: 1st Australas. Acoust. Soc. Conf. 2006, Acoust. 2006 Noise Prog, pp. 349–353.

Passuello, A., Rodríguez, E.D., Hirt, E., Longhi, M., Bernal, S.A., Provis, J.L., Kirchheim, A.P., 2017. Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators. J. Clean. Prod. 166, 680–689. https://doi.org/10.1016/j.jclepro.2017.08.007.

Provis, J.L., 2018. Alkali-activated materials. Cement Concr. Res. 114, 40–48. https://doi.org/10.1016/j.cemconres.2017.02.009.

Raut, S.P., Ralegaonkar, R.V., Mandavgane, S.A., 2011. Development of sustainable construction material using industrial and agricultural solid waste: a review of waste-create bricks. Construct. Build. Mater. 25, 4037–4042. https://doi.org/10.1016/j.conbuildmat.2011.04.038.

Roads, Transport, Maritime Services, 2016. Noise Wall Design Guideline to Improve the Appearance of Noise Walls in NSW.

Saade, M.R.M., Yahia, A., Amor, B., 2020. How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. J. Clean. Prod. 244, 118803 https://doi.org/10.1016/j.jclepro.2019.118803.

Stajanca, M., Estokova, A., 2012. Environmental impacts of cement production. Tech. Univ. Kosice, Civ. Eng. Fac. Inst. Archit. Eng. 296–302.

Stripple, H., Ljungkrantz, C., Gustafsson, T., Andersson, R., 2018. CO 2 Uptake in Cement-Containing Products Background and Calculation Models for IPCC Implementation Commissioned by Cementa AB and IVL Research Foundation.

Tahvanainen, T., 2020. Electricity Consumption of Casting.

Tong, K.T., Vinai, R., Soutsos, M.N., 2018. Use of Vietnamese rice husk ash for the production of sodium silicate as the activator for alkali-activated binders. J. Clean. Prod. 201, 272–286. https://doi.org/10.1016/J.JCLEPRO.2018.08.025.

Turk, J., Cotič, Z., Mladenovič, A., Šajna, A., Cotič, Z., Mladenovič, A., Šajna, A., 2015. Environmental evaluation of green concretes versus conventional concrete by means of LCA. Waste Manag. 45, 194–205. https://doi.org/10.1016/j.wasman.2015.06.035.

Vahtera, E., 2011. Raidemelun Vaimennuskyky Matalien Meluesteiden Tuotevaatimuksena (in Finnish).

Valdebenito, M.J., Dahmen, J., 2013. Life Cycle Assessment Screening: Environmental Impacts of a Novel Vegetative Sound Structure Authors.

Van Damme, H., 2018. Concrete material science: Past, present, and future innovations. Cement Concr. Res. 112, 5–24. https://doi.org/10.1016/J.CEMCONRES.2018.05.002.

Vanhooreweder, B., Marcocci, S., Alberto, D., 2017. Technical Report 2017-02. State of the Art in Managing Road Traffic Noise: Noise Barriers. Conference of European Directors of Roads.

Vieira, D.R., Calmon, J.L., Zulcão, R., Coelho, F.Z., 2018. Consideration of strength and service life in cradle-to-gate life cycle assessment of self-compacting concrete in a maritime area: a study in the Brazilian context. Environ. Dev. Sustain. 20, 1849–1871. https://doi.org/10.1007/s10668-017-9970-4.

Vinai, R., Soutsos, M., 2019. Production of sodium silicate powder from waste glass cullet for alkali activation of alternative binders. Cement Concr. Res. 116, 45–56. https://doi.org/10.1016/j.cemconres.2018.11.008.

Výtisk, J., Kočí, V., Honus, S., Vrtek, M., 2019. Current options in the life cycle assessment of additive manufacturing products. Open Eng. 9, 674–682. https://doi.org/10.1515/eng-2019-0073.

Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., Wernet, G., 2013. Overview and Methodology. Data Quality Guideline for the Ecoinvent Database Version 3.

Weil, M., Dombrowski, K., Buchwald, A., 2009. Life-cycle analysis of geopolymers. Geopolymers: Structures, Processing, Properties and Industrial Applications. Elsevier, pp. 194–210. https://doi.org/10.1533/9781845696382.2.194.

Yao, Y., Hu, M., Di Maio, F., Cucurachi, S., 2020. Life cycle assessment of 3D printing geo-polymer concrete: an ex-ante study. J. Ind. Ecol. 24, 116–127. https://doi.org/10.1111/jiec.12930.

Zhang, Z., Wu, X., Yang, X., Zhu, Y., 2006. BEPAS - A life cycle building environmental performance assessment model. Build. Environ. 41, 669–675. https://doi.org/10.1016/j.buildenv.2005.02.028.