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ENVIRONMENTAL ASSESSMENT OF ALKALI-ACTIVATED MORTARS USING DIFFERENT ACTIVATORS

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ABSTRACT: This study sheds light on the environmental performance of three alkali-activated mortars (AAMs) using sodium hydroxide, sodium silicate powder and 2-part aqueous alkali solutions respectively, as activators. A comparative environmental assessment study of the different AAM mix-designs and Ordinary Portland Cement (OPC) mortar was carried out using Life cycle assessment (LCA) methodology. Results showed a significant difference in the environmental performance of the different AAMs. The mix-designs activated using sodium hydroxide and 2-part aqueous alkali solution respectively, were more environmentally sustainable than OPC. Based on the contribution analysis conducted, the alkali-activators were the significant contributors especially sodium silicate powder activator, which is produced consuming thrice the amount of energy needed to produce sodium silicate aqueous solution. This study indicates that depending on the type and quantity of activators, AAMs can be more or less environmentally sustainable than OPC mortar. Hence, development of AAMs with lower amounts of alkali activators without compromising on their mechanical properties shows great potential in reducing their environmental burdens.

Keywords: alkali activators, life cycle assessment, contribution analysis, alkali-activated mortars, environmental sustainability

1. INTRODUCTION

The need to intensify sustainability in the concrete industry has seen to increasingly research in cementless binders. Cementless binders are alternative inorganic binders that can be substituted for cement for the main purpose of reducing greenhouse gas (GHG) emissions emanated during cement production (Yang et al., 2008). As a result, cementless binders such as alkali-activated binders, have been investigated and developed to be used in mortar or concrete production. Ordinary Portland Cement (OPC) mortar is a mixture of water, cement and sand while OPC concrete is a mixture of these materials in addition to gravel and coarse aggregates, to make it more durable.

Alkali-activated binders are synthesized from the reaction of an alkali source and solid aluminosilicate raw material such as coal fly ash (CFA), ground granulated blast furnace slag (GGBFS) and calcined clay (Provis, 2016; Singh et al., 2015). They are known to be produced using two main pathways namely; one-part and two-part mixtures (Luukkonen et al., 2018). One-part mix is formed by dry mixture of alkali powder, solid aluminosilicate raw material and water (Duxson and Provis, 2008; Luukkonen et al., 2018) and two-part mix is formed by a reaction between aqueous alkali solution, solid aluminosilicate raw material and water (Duxson et al., 2007; Luukkonen et al., 2018). Two-part mixtures have some impracticalities such as difficulty in handling and transportation of large amounts of viscous and corrosive alkali solutions. However, they have been included in several full-scale applications when compared to one-part mixtures (Luukkonen et al., 2018).

There have been several studies carried out using different types of activators to develop alkali-activated binders (Abdulkareem et al., 2014; Gholampour et al., 2019; Hasnaoui et al., 2019; Luga and Atis, 2018; Ma et al., 2018; Ng et al., 2018; Panda and Tan, 2018; Yang et al., 2010; Zhao et al., 2007). Furthermore, a considerable amount of research has been carried out on the environmental performance of alkali activated mortars and concretes using 2-part mixtures of sodium silicate solution and sodium hydroxide as activators (Davidovits, 2015; Habert et al., 2011; McLellan et al., 2011; Ouellet-Plamondon and Habert, 2015; Passuello et al., 2017; Van Den Heede and De Belie, 2012; Yang et al., 2013). However, less attention has been paid to comparative environmental assessment of alkali-activated mortars or concretes when different activators are employed.

Thus, the objective of this study is to perform a comparative environmental assessment study of different mortars activated using different alkali activators. The study is to estimate and compare the impacts of the different alkali-activated mortars (AAMs) while also identifying the materials significantly contributing to their environmental burdens that could be taken into account in their future development.

2. MATERIAL AND METHODS

Life cycle assessment (LCA) methodology was employed in this study as it addresses environmental aspects and potential environmental impacts through a product life cycle (EN ISO 14040, 2006). This study is carried out using Centrum voor Milieukunde Leiden (CML) indicators according to ISO 14040/44 standards (EN ISO 14040, 2006) along with ILCD handbook guidelines (JRC, 2010). 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.

2.1 Goal and scope definition

The goal of this study is to assess and compare the environmental performance of different alkali-activated mortars (AAMs), and to observe how these mortars with different types of alkali activators compare in terms of environmental performance. The functional unit of this study is defined as the environmental impact generated due to the activities involved in the production of $1m^3$ of mortar with equivalent compressive strength of 45MPa at 28 days.

2.2 System boundary

The system boundary of the product system studied is represented in Figure *1*. Heat Curing was included in the mortar production phase for some of the AAMs and is taken into consideration during analysis. It is assumed that comparable and similar impacts are expected from transportation, use and end-of-life phases. Thus, they are omitted from this study. Since this study is primarily focussed on mortar production, the focus of study will mainly be from cradle-to-gate (raw material stage to production stage) as shown in Figure *1*.

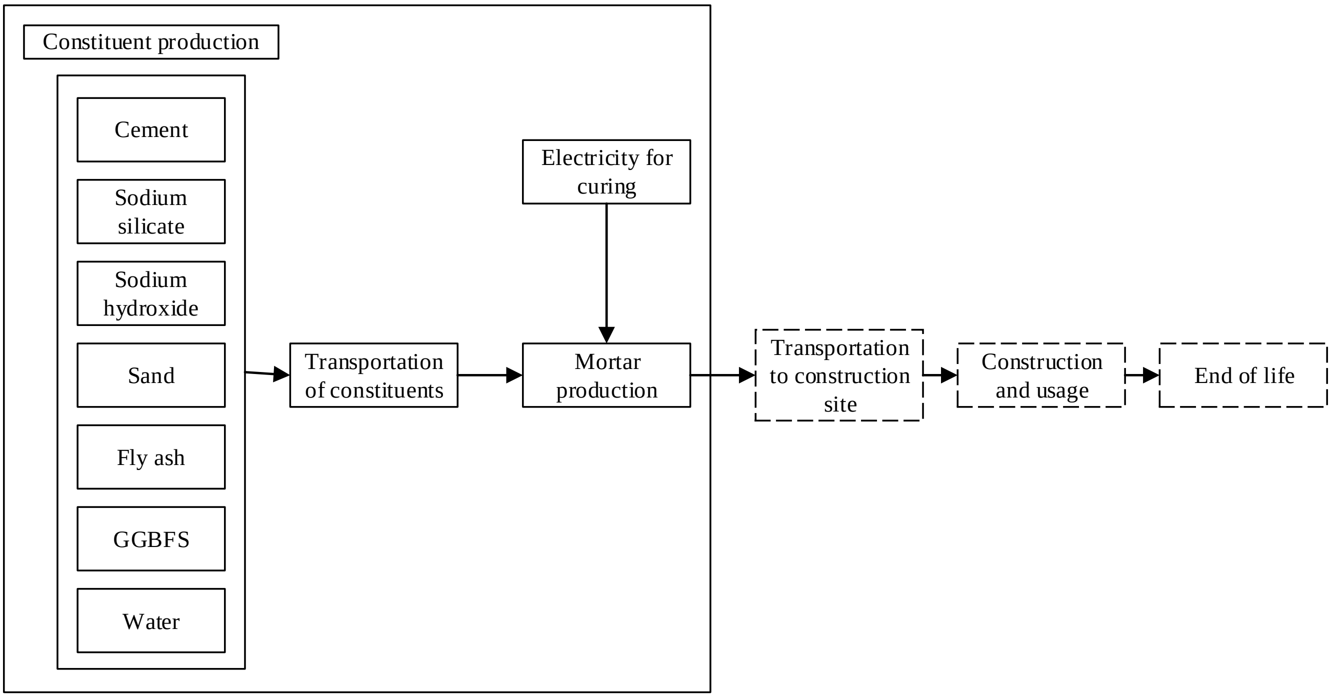

Figure 1. LCA system boundary illustrating production of 1m3 of mortar

2.3 Scenarios description

Three alternative scenarios for the AAMs were included in this study along with the baseline scenario which is ordinary Portland cement (OPC) mortar. The mix-designs of these scenarios were collected as directly reported from literature and as shown in Table 1 below.

- S_0 Baseline Scenario: OPC mortar
- S_1 Scenario 1: sodium silicate powder alkali-activated mortar
- S_2 Scenario 2: Sodium hydroxide alkali-activated mortar
- S_3 Scenario 3: Sodium silicate solution and sodium hydroxide alkali-activated mortar

Table 1. Mix-designs representing the different scenarios analysed in this study

Scenarios	S_0 [1]	S_1 [2]	S_2 [3]	S_3 [4]
Cement (kg)	500			
Fly ash (kg)				342
GGBFS (kg)		383	450	
NaOH pellets (kg)			109	48
Na_2SiO_3 (kg)		83 [a]		101 [b]
Sand (kg)	1501	1398	1350	823
Water (kg)	250	250	180	65
Compressive strength MPa	45	46	44	47

[1] Yang et al., 2008 [2] Yang et al., 2010 [3] Luga and Atis, 2018 [4] Abdulkareem et al., 2014

GGBFS – Ground granulated blast furnace slag, NaOH – Sodium hydroxide, Na_2SiO_3 – sodium silicate

[a] sodium silicate powder; [b] sodium silicate solution

For meaningful comparisons during analysis, it is necessary these scenarios are based on having equivalent mechanical strength (Habert et al., 2011). S_0 represent a mortar mix-design with a strength of 45 MPa with OPC as binder (Yang et al., 2008). S_1 is a mix-design using ground granulated blast furnace slag (GGBFS) as aluminosilicate source material and sodium silicate powder as alkaline activator. The compressive strength developed was 46 MPa (Yang et al., 2010). S_2 employed fly ash as aluminosilicate source material and sodium hydroxide as alkaline activator with a compressive strength of 44 MPa (Luga and Atis, 2018). Lastly, S_3 was developed using fly ash as source material with sodium hydroxide and sodium silicate solution as activator, to actualise a compressive strength of 47 MPa (Abdulkareem et al., 2014).

2.4 Life cycle inventory

Life cycle inventory (LCI) is the phase where all unit processes included in the system boundary are quantified. All mix-designs representing the different scenarios analysed in this study were sourced from literature studies and the LCA modelling was conducted using GaBi 8.6.0.20 software system LCA tool. LCI data for processes such as OPC, sodium hydroxide, sand and water were sourced from GaBi database. The unit process of sodium silicate solution was modelled following the approach and LCI data from Fawer et al., (1999). This solution is produced by hydrothermally dissolving silica sand in sodium hydroxide solution (Fawer et al., 1999) . The unit process of sodium silicate powder was also modelled following the approach and LCI data from Fawer et al., (1999). Sodium silicate powder is produced by drying sodium silicate solution (Fawer et al., 1999). For GGBFS, it is assumed that it comes into the system boundary with no environmental burdens. However, for GGBFS to be used as a supplementary cementitious material (SCM), it goes through the processes of granulation, drying, crushing and grinding (Marceau et al., 2007). Thus, materials and energy required to process GGBFS were modelled according to data from Marceau and VanGeem, (2003). Fly ash is considered to have a very small environmental footprint because it mostly does not require beneficiation. (Lemay, 2017; Marceau et al., 2007). Thus, only transportation impacts will be attributed to fly ash. Oven Curing is required for mortar production in S_2 and S_3. Oven curing is essential for initiating chemical reaction of AAMs at first instance and consumes 86.4 MJ of electricity at 85℃ for 24 hours (Bai et al., 2014).

The LCI database 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 GaBi 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
Sodium hydroxide	GaBi database 2018 (sodium hydroxide, 100% caustic soda)
Sodium silicate solution	Fawer et al., 1999; (sodium silicate 2.0, hydrothermal liquor, 48% solid)
Sodium silicate powder	Fawer et al., 1999; (sodium silicate 2.0, spray powder)
Cement	GaBi database 2018 (Portland cement CEM I)
Sand	GaBi database 2018 (sand 0/2)
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)
Diesel	GaBi database 2018 (diesel mix at refinery)

2.5 Life cycle impact assessment

The impact assessment categories employed in this study in assigning LCI results to specific environmental issues, are namely; global warming potential excluding biogenic carbon (GWP 100 years), ozone layer depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), abiotic depletion potential (ADP of metals and minerals), abiotic depletion potential (ADP of fossil fuels), 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 (Deviatkin et al., 2016).

The normalisation principle employed in this study is based on CML 2015. 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). The normalisation reference values employed in this study are based on European equivalents. 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).

3. RESULTS AND DISCUSSIONS

The normalized results of the scenarios are presented in *Figure 2* and it shows how different impact categories compare to each other. The normalised results cannot be summed up because they are shares 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.

The results clearly indicated that AAMs activated with just sodium hydroxide (S_2) had the best environmental performance of all the scenarios. Although, S_1 had the lowest amount of activator (83 kg/m^3 of sodium silicate powder) compared to the other alternative alkali-activated scenarios, it had the worst environmental performance, slightly worse than baseline scenario (OPC mortar S_0). As discussed in section 2.4, sodium silicate powder is produced from drying sodium silicate solution, requiring thrice the amount of energy needed to produce sodium silicate solution (Fawer et al., 1999). The high impact of S_1 is mainly due to the high energy consumption needed for sodium silicate powder production. Although, sodium silicate powder is considered a more convenient activator since it is in solid form and can be used similarly to OPC as opposed to aqueous alkali solution which can be difficult to handle (Luukkonen et al., 2018), its environmental performance however makes it a less desirable option. Overall, S_ 1 had 6% increased emissions when compared to the baseline scenario S_0, while S_2 and S_3 had decreased emissions of 52% and 42% respectively.

From the normalized results, the impact categories which had the highest emission contribution are AP, GWP, ADP (fossil) and MAETP as seen in Figure 2, making them the most relevant impact categories.

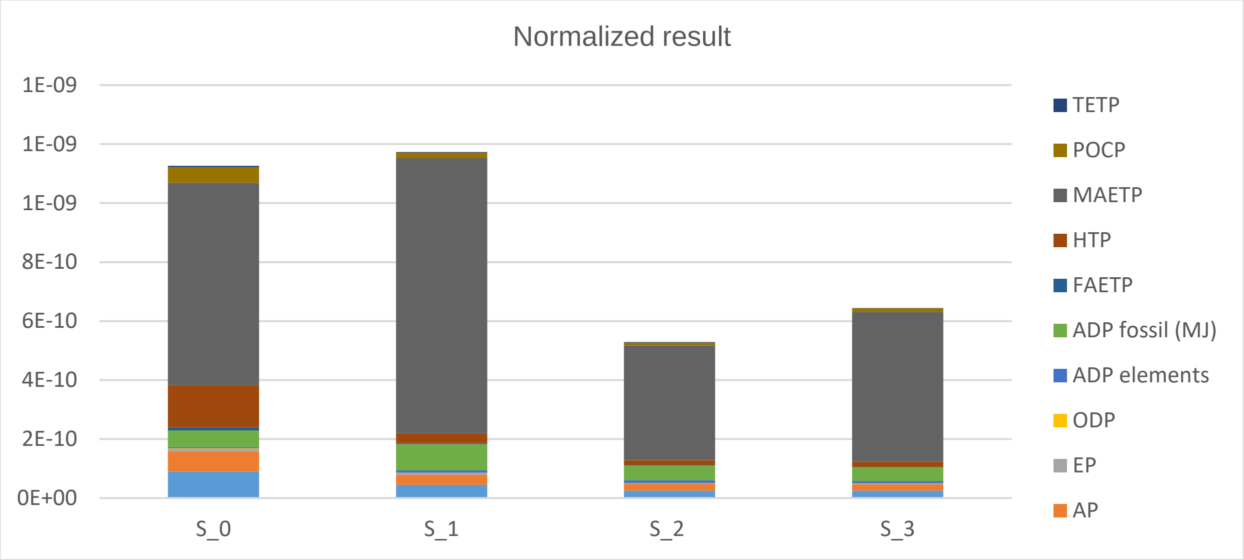

Figure 2. Normalized results of the studies scenarios

Contribution analysis was carried out on the most relevant impact categories (AP, GWP, ADP_fossil and MAETP), to find out constituents with significant contributions. As shown in Figure 3, sodium silicate powder, sodium hydroxide and sodium silicate solution were the most significant contributors for all the alternative scenarios.

In AP impact category, sodium silicate powder had 88% contribution in S_1. In S_2, sodium hydroxide had a 77% contribution while in S_3, sodium silicate solution and sodium hydroxide had 54% and 35% contribution respectively. Other processes in these scenarios had minimal contribution of less than 10% respectively. Overall, S_1, S_2 and S_3 had 50%, 68%, and 69% respectively, less emissions than S_0.

In the GWP impact category, sodium silicate powder had 90% contribution in S_1. In S_2, sodium hydroxide had a 78% contribution while in S_3, sodium silicate solution and sodium hydroxide had 56% and 34% contribution respectively. Other processes in these scenarios had minimal contribution of less than 10% respectively. Overall, S_1, S_2 and S_3 had 50%, 72%, and 71% respectively, less emissions than S_0.

In the ADP fossil impact category, sodium silicate powder had 86% contribution in S_1. In S_2, sodium hydroxide and GGBFS had 71% and 16% contributions respectively, and in S_3, sodium silicate solution and sodium hydroxide had same contribution as in GWP. Other processes in these scenarios had minimal contribution of less than 10% respectively. Overall S_2 and S_3 had 9%, and 16% respectively, less energy consumption than S_0 while S_1 had 60% more enegy consumption than S_0. This is due to the high energy consumed during sodium silicate powder production.

In the MAETP impact category, sodium silicate powder had 89% contribution in S_1. In S_2, sodium hydroxide, GGBFS and electricity for curing contributed 52%, 28% and 16% respectively. In S_3, sodium silicate solution, sodium hydroxide and electricity for curing contributed 70%, 18% and 11% respectively. Other processes in these scenarios had minimal contribution of less than 10% respectively. Overall S_2 and S_3 had 44%, and 26% respectively, less emissions than S_0 while S_1 had 37% more emissions than S_0. *Figure 3* below illustrates the contribution analysis.

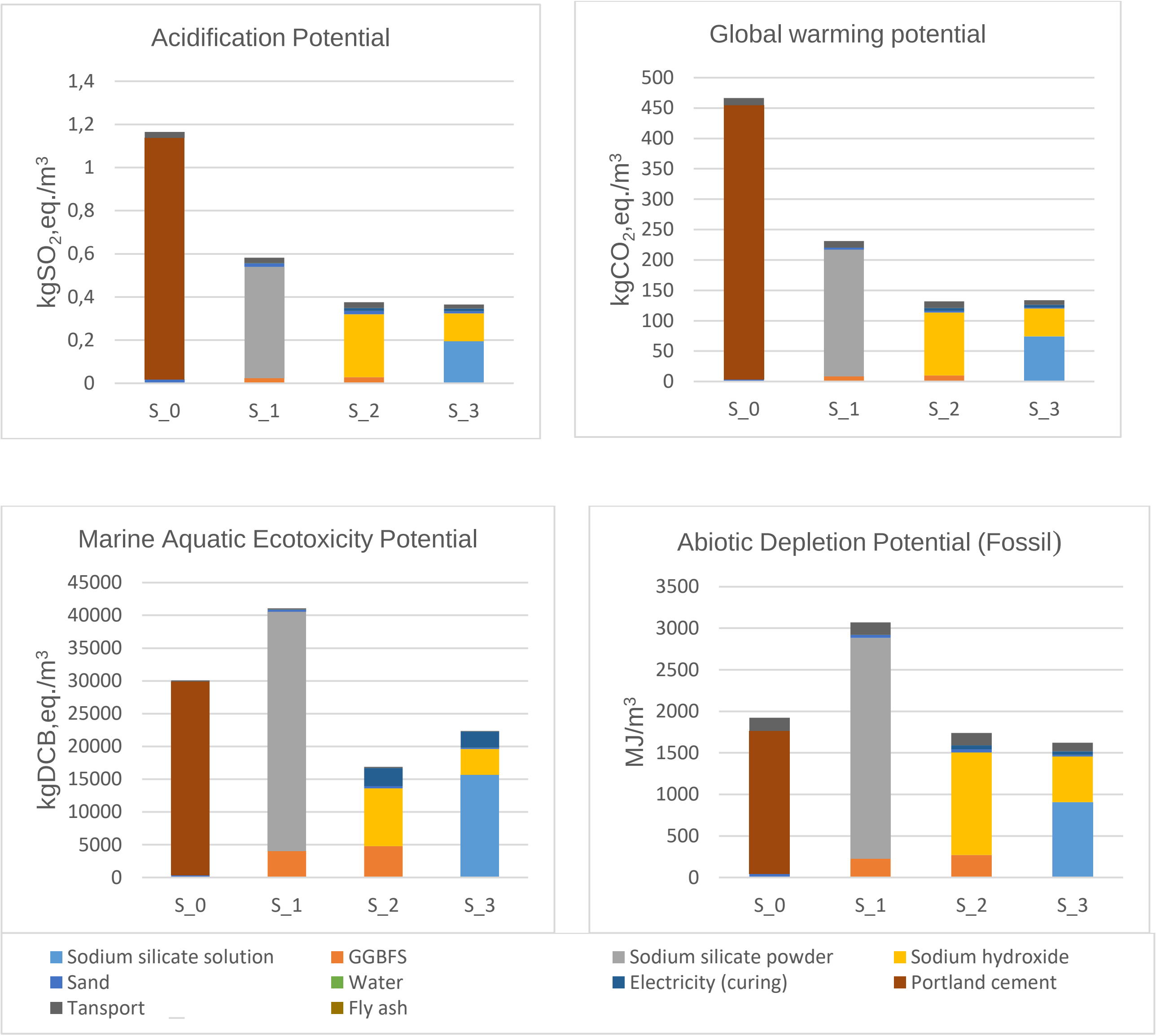

Figure 3. Contribution of the different processes to AP, GWP, ADP and MAETP for the studied scenarios

The reason the alkali activators are the most significant contributors are due to the amount of energy needed for production especially in the cases of sodium silicate solution and sodium silicate powder (Fawer et al., 1999). (Abdulkareem et al. (2019) carried out a study on fibre reinforced alkali-activated concretes and conducted a sensitivity analysis to observe how using renewable energy to substitute fossil energy in sodium silicate solution production, influenced the LCIA results. The results of the study showed improvement in the environmental impact results when renewable energy was used. The study also went on to analyse how using different LCI data sources of sodium silicate influenced the overall LCIA results. It was observed that the results could have a better or worse environmental performance depending on the type of LCI data used (Abdulkareem et al., 2019). As such, careful considerations should be taken with respect to LCI data sources when conducting LCA.

4. CONCLUSIONS

This paper presents an envioronmental assessment of different alkali-activated mortars (AAMs), and how they compare in terms of environmental performance. The results of the study showed that for similar strength of mortar, AAM activated using just sodium hydroxide (S_2) and 2-part aqueous alkali solution (S_3), had less environmental burdens when compared to the baseline OPC mortar scenario (S_0) while AAM activated using sodium silicate powder (S_1) had higher environmental burdens. This is primarily due to the high energy consumed in the production of sodium silicate powder. For future development of AAMs, it is recommended that lower amounts of high impact activators such as sodium silicate powder should either be used or substituted with a more environmental friendly activator while not compromising on the mechanical properties of the mortar or concrete.

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