Lifecycle assessment of alkali activated cement concrete

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Abstract. Climate change is one of the most important environmental problems that our planet Earth is facing. This is due to the increased emission of greenhouse gases such as carbon dioxide. Concrete, the most consumed material in the construction industry is reported to be responsible for about 8% of worldwide carbon dioxide emissions. The manufacturing of ordinary Portland cement is both resource and energy-intensive and is accountable for 1.35 billion tons of carbon dioxide emitted annually. Hence potential alternative to Portland cement widely recognized is the adoption of alkali-activated cement. Alkali-activated cement commonly utilizes industrial by-products such as fly ash, GGBS, etc. along with alkali activators such as sodium silicate and sodium hydroxide. The literature review indicates that the environmental impact due to the usage of Portland cement can be reduced by the adoption of alkali-activated cement. However, the manufacture of alkali activators is likely to contribute to the emission to the environment. In addition, the heat curing commonly adopted during the production of concrete to activate the alkalis might also have a bearing. Hence a comparative study using the lifecycle assessment (LCA) method is carried out to assess the impact due to the production of alkali-activated cement concrete using supplementary cementitious materials (SCM) fly ash and GGBS with varying proportions of alkali activators (sodium silicate and sodium hydroxide). Data is extracted from the published literature corresponding to two different compressive strength ranges of OPC concrete and alkali-activated cement concretes that have utilized four varying proportions of alkali activator ratios. It is then analyzed by the 'cradle to gate' approach using LCA software SimaPro. The impact assessment is done using the ReCiPe 2016 method. A comparison of results and their interpretation is done based on its compressive strength ranges, the alkali activator ratios, and the effect due to change in the SCMs utilized.

1. Introduction
The infrastructure sector is a fast-growing industry and by 2022 India would become the third-largest construction market globally [1]. The infrastructure industry is one of the key factors that drive the Indian economy. The Indian construction sector mainly utilizes ordinary Portland cement (OPC) for its construction activities. This forms the major reason for carbon dioxide emission and thereby contributing towards global warming. Globally, the production of cement contributes at least 5-7% of CO2 emissions [2]. The manufacturing of OPC is both resource and energy-intensive, hence the adoption of industrial wastes such as flyash and GGBS as binders for construction will be beneficial [3]. It is high time that new technology and new materials have to be used in the Indian construction sector. Though research attempts are made, adoption is less due to a lack of standards/protocols for systematic usage. Alkali-activated cement (AAC) is a promising alternative to ordinary Portland cement [4].
primarily used materials for the production of alkali-activated cement are the by-products from industry such as GGBS, fly ash, etc. These by-products are aluminosilicates which are activated using alkali sources and thus alkali-activated cement is produced. Literature review indicates this as an environment-friendly option, which can also give good compressive strength and durability when adopted in concrete [5,6]. An earlier study by Matheu et.al. [8], indicates that the energy required for the production of AAC is lower than that needed for the production of OPC. The greenhouse gas emission was reported [2] as 44% lesser than OPC. The environmental impact during the production of AAC might be caused mainly during the manufacturing of the alkali activator source. Also, the energy required for the heat curing of AAC concrete could be another contributing factor. Thus, the reduction in the environmental emissions depends on the type, dosage of the alkali activator used [9].

1.1. Alkali activated cement concrete
Alkali activated cement concrete is obtained by substituting the ordinary Portland cement with industrial by-products such as GGBS, FlyAsh, etc. The binders are then activated using alkali hydroxides or silicates. Alkali activators play an important role in the design of alkali-activated cement. The industrial byproducts are binders that contain aluminosilicates. Alkali activators thus help to effectively react with aluminosilicates. The usage of dual activators ie the sodium silicate and sodium hydroxide are reported to be effective with aluminosilicates having high as well as low calcium [10]. The increase in the amount of alkalis enhances the bond formation between alkali aluminosilicates which in turn increases the compressive strength [11]. Another influential factor contributing to strength during alkali activation is the ratio between silica and alumina [12]. Heat curing of AACs is beneficial to reduce the drying shrinkage as well as to accelerate the strength development [5,7,13].

1.2. Lifecycle assessment
Life cycle analysis (LCA) is the method to compute environmental impacts based on material input during the production process. The lifecycle assessment is carried out in mainly 4 steps. These 4 steps are specified in ISO 14040-14044 [14]. SimaPro is one of the most popular and commonly used software programs over the last 15 years [13], as it helps in easy modeling and analysis of complex life cycles systematically and transparently. It also helps to measure the environmental impact of any products and services of all life cycle stages. The ReCiPe 2016 is used for the impact assessment. The analysis is carried out in two levels. Results of midpoint analysis show global warming potential to water footprint. Endpoint analysis provides quantitative results of general environmental impact assessment [12].

1.3. Scope of the present study
The objective of the present study is to identify the environmental impacts caused during the production of alkali-activated cement concrete. The analysis of environmental impact is done using lifecycle assessment (LCA). The study is carried out in different compressive strength ranges of alkali-activated cement concrete with varying proportions of alkali activators along with a comparison with OPC concrete of similar strength. The analysis focuses on the variation of the alkali activator ratio and the effect of elevated curing temperature.

2. Methodology
Lifecycle assessment is carried out based on the guidelines and recommendations of the International Standard Organization (ISO) for environmental management (ISO 14040- ISO 14044). There are mainly four phases in the life cycle assessment as shown in Figure 1.
2.1 Goal and scope definition
The first and foremost step in LCA is to define its aim. A clear and well-picturized framework leads to the ideal completion of work. In this study, the aim is to understand the environmental impact during the production of AAC concrete. The effect due to the usage of different ratios of alkali activators and the effect due to heat curing is proposed to be studied.

2.1.1 Functional unit. It defines the aim of the study in a relative manner. It helps in defining the performance of the product's system and is used as a reference unit [14]. It is a reference unit on which the whole study evolves. In this study, the functional unit is defined as the environmental impact due to the activities involved during the production of 1 m$^3$ of Alkali activated concrete of compressive strength ranges 30-35 MPa and 45-50 MPa.

2.1.2 System boundary. It is the total boundary in which the whole lifecycle assessment is done. The system boundary is a set of criteria that specifies the stages of the product’s lifecycle that is considered in the assessment. The different system boundaries are cradle to cradle, cradle to gate, and cradle to grave, based on the processes involved in the product lifecycle. In the study of AAC concretes, the process involved is from the extraction of raw material to the production of AAC concrete, therefore the system boundary is cradle to gate.

2.2 Lifecycle Inventory
In the second stage of LCA, the required data is collected and analysed. Based on the defined functional unit, the data associated with the production of 1 m$^3$ concrete of compressive strength ranges 30-35 MPa and 45-50 MPa is compiled from various published literature. The mix proportioning details were collected from various literature in which different AAC properties were investigated. The most reliable and consistent data are required for accurate LCA. For the study, the necessary data included the mix proportions of AAC concrete from different compressive strength ranges. The details of the activities and energy required during various processes involved in the production of AACs (such as extraction of raw materials, production of alkali activators, etc.) were gathered. The data of raw materials utilized were obtained from the database Eco-invent v3. The energy required for alkali activator production and the production of AAC were based on literature survey [17,42,43].

2.3 Lifecycle impact assessment
The third stage is impact assessment, the stage in LCA where the intensity and importance of the environmental impacts for a product are understood. This phase brings a relationship between the inventory analysis results and the environmental impacts. There are various methods by which impact assessment is carried out. ReCiPe 2016 is the most recent, improved impact assessment method. In the ReCiPe method, the lengthy inventory results are cut short to various environmental impact indicator...
scores. This indicator scores thus gives a comparative analysis result on how severe it is on the environment. The results are grouped into different impact categories, based on which the interpretation is done. The impacts are categorised as midpoints and endpoints (Fig.2).

In the ReCiPe 2016 method there are two different levels viz., midpoint impact categories and endpoint impact categories. There are 18 midpoint impact categories which are integrated into three endpoints. The midpoint indicator focuses on individual environmental impact problems whereas the endpoint focuses on specific areas of damage. Figure 2 depicts the 18 midpoints and the 3 endpoint impact categories of ReCiPe 2016 which indicates the environmental impact.

3. Analysis and Discussion
The analysis was done in two stages viz., to study the environmental impact due to usage of alkali activators in various proportions and also to study the environmental impact due to elevated heat curing. The mix designs enlisted in Table 1, Table 2 and Table 3 for the study were extracted through literature review [13-36]. This study was carried for OPC concrete and AAC concrete utilizing three types of binders ie., flyash(FA), GGBS, as well as FA and GGBS blend. The concrete mix details were sorted based on the compressive strength range and alkali activator (AA) ratio for the first part of the study. The alkali activators were sodium hydroxide (NaOH) and sodium silicate (Na$_2$SiO$_3$). The alkali activator ratio accounts for the ratio of Na$_2$SiO$_3$: NaOH in the liquid state. Four different alkali activator ratios were chosen i.e., 1, 1.5, 2 and 2.5. Mix details corresponding to these ratios under two compressive strength ranges 30-35MPa and 45-50MPa (Table 1) along with OPC concrete mixes (Table 2) were compared. For the second part of the study, mix details of both ambient-cured and heat cured concrete for similar alkali activator ratios were considered (Table 3).

Table 1: Mix details of different strength ranges for varying alkali activator ratios.

| Concrete Type | Alkali activator ratio | Alkali Activator (Liquid) | Mix Design |
|---------------|------------------------|---------------------------|------------|
|               |                        | NaOH | Na$_2$SiO$_3$ | GGBS | Flyash | NaOH (DRY) | Na$_2$SiO$_3$ (DRY) | Sand | Gravel | Water |
| **Compressive Strength Range 30-35 MPa** |
| A11           | 1                      | 118  | 118          | -    | 428   | 47.20      | 47.59             | 487  | 1191   | 143.79 |
| A12           | 1                      | 76   | 76           | 400   | -     | 38.00      | 34.88             | 844  | 844    | 223.12 |
| A13           | 1                      | 108  | 108          | 88    | 293   | 17.20      | 41.93             | 760  | 1005   | 155.88 |
Table 2. Mix Details of OPC Concrete.

| Concrete Type | Raw Material | Strength (MPa) |
|---------------|--------------|----------------|
|               | Cement       | Sand | Gravel | Water | Total |
| NC1           | 413.33       | 800.52 | 991.99 | 185.99 | 2391.8 |
| NC2           | 450          | 767.25 | 994.25 | 180   | 2391.5 |

Table 3. Mix design corresponding to different strength ranges for heat-cured AAC concrete.

| Concrete Type | Raw Materials | Curing Regime |
|---------------|---------------|---------------|
|               | GGBS | Flyash | NaOH | Na₂SiO₃ | Sand | Gravel | Water |
| Compressive Strength Range 30-35 MPa |
| 1 ACF         | -   | 444   | 45   | 111 | 540 | 1260 | 551 | 1514 | 121.97 |
| 1 ECF         | -   | 400   | 46   | 114 | 400 | 29.44 | 4731 | 860 | 860 | 124.55 |
| 1 ACG         | 500 | -     | 444  | 183 | 565 | 1050 | 565 | 1050 | 232.50 |
| 1 ECG         | 560 | 58    | 82   | 668 | 1148 | 71.36 |
| 1 ACFG        | 1772 | 273  | 5.14 | 125.36 | 775.44 | 1057.56 | 116.79 |
| 1 ECFG        | 135 | 315  | 70.71 | 176.79 | 760 | 972.00 | 162.30 |

Compressive Strength Range 45-50 MPa

| 2 ACF         | -   | 500   | 110  | 165 | 427 | 1081 | 162.47 |
| 2 ECF         | -   | 530   | 80   | 120 | 514 | 1117 | 109.172 |
| 2 ACG         | 356.36 | -   | 64.14 | 96.22 | 467.12 | 1284.29 | 106.37 |
| 2 ECG         | 400 | -     | 65.45 | 114.55 | 876 | 876.00 | 134.23 |
| 2 ACFG        | 195 | 195   | 61.29 | 153.21 | 775.43 | 1057.56 | 140.66 |
The energy required for the production of AAC concrete is the major factor that contributes to the environmental impact. The energy requirement is mainly for three aspects: 1) the production of the alkalinity source (i.e., NaOH and Na$_2$SiO$_3$), 2) preparation of alkali activator and 3) for elevated temperature curing.

For the production of NaOH, the energy required is 20.5 MJ/Kg [17] and for the production of Na$_2$SiO$_3$, the energy required is 5.37 MJ/Kg [43]. During Alkali activator preparation, the energy required to maintain the alkali activator at 75° C for 24hrs is 5.8 MJ [17]. The energy required for elevated curing was calculated by the equation, $Q = mC\Delta T$ (where $m$ is the density of the mix, $C$ is the specific heat of AAC concrete, and $\Delta T$ change in temp to raise the temperature from 21°C to higher curing temperature). In order to maintain the curing temperature, 0.19MJ/m$^2$/hr is required.

Therefore, for 1m$^3$ of concrete, for an oven size with 13.5m$^2$ as surface area, the required energy for maintaining the temperature would be 0.194×13.5=2.619 MJ/hr (based on the duration of curing this will get modified) [42].

Energy calculation is carried for all the mixes according to the above-discussed stages for the Alkali activated cement concrete mixes. The mix details along with the calculated energy requirement for each mix are fed into the SimaPro software. As per the ISO 14044 guidelines, each step in LCA was carried out using the software. It takes up other relevant data from the inbuilt dataset Eco-invent and Impact assessment is carried out using the ReCiPe2016 method to obtain the LCA results.

3.1 Effect of alkali activator ratio

In the ReCiPe method of impact assessment, the environmental impact is divided into the midpoint categories and endpoint categories. At the midpoint 8 impact categories affect human health, 13 impact categories affect the ecosystem, and 2 categories affect resource availability. The analysis results corresponding to mixes of strength range 30-35 MPa (i.e., A group mixes), and strength range 40-45 MPa (i.e. D group mixes), are shown respectively in Figure 3 and Figure 4.

![Figure 3 (a): Environmental impact on Human health (Strength 30-35 MPa)](image)

For A group mixes, the impact categories that affect human health mainly are fine particulate formation (FMP), global warming (Figure 3 (a)). These impacts are found to be more in mix A11 where the alkali activator ratio is 1, with a count of $1.99 \times 10^{-3}$ DALY and $1.16 \times 10^{-3}$ DALY respectively. DALY (Disability Adjusted to Life Years) is the unit used for human health impact, ie the no of years the life lost or no of years lived as disabled. The least impact is shown by the mixes A41 and A43, which are mix with an alkali activator ratio of 2.5. A comparison with normal OPC concrete mix is also carried...
out whose impact $3.43 \times 10^{-3}$ DALY for fine particulate matter emission and $2.080 \times 10^{-3}$ DALY for global warming, which is comparatively much more than the other AACC mixes.

As shown in Figure 3 (b), global warming and land use cause damage to the ecosystem the most during the production of A group mixes, with the highest impact of $3.51 \times 10^{-6}$ species.yr and $2.70 \times 10^{-6}$ species.yr by A11. The least in the group is shown by A41 and A43, with $1.6 \times 10^{-6}$ to $1.7 \times 10^{-6}$ species.yr due to global warming and $1.25 \times 10^{-6}$ species.yr due to land use. The normal mix of OPC concrete has the highest impact on the ecosystem when compared with the AACC mixes, $6.27 \times 10^{-6}$ for global warming and $4.83 \times 10^{-6}$ due to land use. Species.yr is the unit that indicates the loss of species over a certain area over a certain time.

Mineral resource scarcity and fossil resource scarcity are the two problems that cause damage to resources (Figure 3 (c)). Among A group mixes, A11 has a major impact of $35.11$ USD 2013 for fossil scarcity among the AACC mixes. The unit USD represents the extra cost for mineral and fossil resources extraction in the future. Fossil scarcity is comparatively lower for A41 and A43 with just $17.41$ USD 2013 and $17.16$ USD 2013. The normal concrete costs about $59.31$ USD2013 of fossil resource scarcity.

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Figure 3 (d) gives the total environmental impact on the three endpoints and human health is having a major impact when compared with the ecosystem and resource scarcity. In group A mixes, A11 has a total impact of $65.86$ Pt, which comprises of human health damage of $61.13$ Pt, impact on the ecosystem as $4.47$ Pt, and impact on resource availability as $0.26$ Pt. The least is for A43 with a total of $30.57$ Pt, with $28.37$ Pt contribution towards human health, $2.07$ Pt towards the ecosystem, and $0.13$ Pt towards
resources. Pt is a dimensionless impact assessment unit; 1 Pt meaning one-thousandth of the yearly environmental load of one average European inhabitant. The normal OPC concrete mix NC1 has a total impact of 113.85Pt, which contributes 105.54 Pt towards human health, 7.89 Pt to Ecosystem, and 0.42Pt towards resources.

In D group mixes, the impact categories that cause damage to human health are fine particulate matter formation, global warming, human carcinogenic, human non-carcinogenic toxicity, and water consumption (Figure 4 a). The normal OPC concrete NC4 has the highest damage contribution towards human health. Among the AACC, D11 has the highest impact and D41 has the least impact. The impact categories that cause damage to the ecosystem (Figure 4 b) are land use, terrestrial acidification, freshwater eutrophication ozone formation, and water consumption. Land use has the highest impact. The OPC concrete NC4 has the highest impact on land use and terrestrial acidification. Among the AACC mixes, D11 with an AA ratio of 1 has the highest impact, and D41 with an AA ratio of 2.5 has the lowest impact on the ecosystem.

In the Resource availability aspect (Figure. 4 c) major impact is due to fossil resource scarcity. NC4 mix has the highest impact on the resources when compared with the AACC mixes. D11 has the highest impact of 59 USD2013 and D41 has the lowest impact of 19 USD2013.

Figure 4 (a). Environmental impact on Human Health (Strength 45-50 MPa)

Figure 4 (b). Environmental impact on Ecosystem (Strength 45-50 MPa)
The total environmental impact (Figure 4 d) due to D11 is the highest among AACC mixes with a total of 59.07 Pt which contributes 54.82 Pt on human health, 4.01Pt to the ecosystem, and 0.24 Pt to resources. The impact is lowest for D41 with a total of 32.79 Pt, which comprises of the impact on human health 30.43Pt, towards ecosystem is 2.22 Pt and that on resources being 0.14 Pt.

3.2 Effect of curing type
To understand the effect due to heat curing on AAC concrete production, 6 mixes each for two different compressive strength range (i.e., 30-35 MPa and 45-50 MPa) but a similar AA ratio of 2.5 were analysed. The impact categories that affect human health mainly are FPM formation and global warming. The impact categories that damage the ecosystem mainly are land use, global warming, and terrestrial acidification. The mixes which are cured at elevated temperature have a higher environmental impact when compared with ambiently cured mixes. A major impact is shown by fossil resource scarcity in both cases.
Figure 5 gives the total environmental impact on the three endpoints. The total impact is higher for elevated cured concrete mixes when compared with ambiently cured mixes. Referring to Figure 5 (a), the total environmental impact due to 1 ACF is 34.09 Pt and that of 1 ECF is 38.64 Pt. The total environmental impact due to elevated GGBS-based AACC, 1 ECG is 62.97 Pt whereas that of ambiently cured GGBS based AACC, 1 ACG is 40.09 Pt. The total environmental impact due to 1 ECFG is 55.12 Pt and that due to 1 ECF is 37.48 Pt. For a normal concrete mix of a similar strength range, the total environmental impact is much more than that of AACC mixes cured at elevated temperatures.

For mixes with compressive strength ranges of 45-50 MPa concrete also the total environmental impact (Figure 5 b) is higher for elevated cured fly ash-based AAC concrete when compared with the ambiently cured fly ash-based concrete. A similar trend is observed in GGBS based concrete as well as GGBS-flyash based concrete.

3.3 Observations
From the analysis, it was observed that the impact due to the production of OPC concrete is nearly twice greater than the impact due to AAC concrete. Almost 93% of the impact is caused on human health, 6% impact on the ecosystem, and less than 1% impact on the resource. The environmental impacts on human health are mainly caused due to fine particulate matter formation (FPM) and global warming. The FPM formation causes respiratory diseases in humans whereas global warming is responsible for malnutrition and causes other diseases in the human body. The impact categories that mainly cause damage to the ecosystem are land use, global warming, and terrestrial acidification. These factors cause damage to the terrestrial species in the ecosystem. Fossil resource scarcity is the impact category that damages resources.

In AACC mixes, the environmental impact was higher for mixes with AA ratio 1, and the lower impact was seen in mixes with AA ratio 2 and 2.5. A similar trend was observed in both the strength ranges. No significant variations in environmental impact were observed across the different strength ranges. The energy required for the production of alkali NaOH was nearly four times higher than that of Na$_2$SiO$_3$. Hence as the AA ratio increased from 1 to 2.5, there was a reduction in the environmental impact. But slight variations were observed due to the differences in the proportions of various ingredients.

When AACC mixes are compared with OPC concrete mix within the same strength range, the environmental impact due to AACC is much less than that of OPC concrete mix. The impact due to AACC is nearly 50% less than the normal OPC concrete mix. This reiterates that AACC is a potential alternative to OPC concrete in terms of environmental impact.

4. Conclusion
The following conclusion is drawn based on the analysis of AAC concrete and applies to the range of parameters considered.

The environmental impact is mainly due to global warming, fine particulate matter formation, land use and fossil resource scarcity. These impact categories damage human health the most. Around 93% of the total impact is on human health, 7% on Ecosystem and resources is affected by less than 1%. Mixes with Alkali activator ratio 1 had the highest impact among AAC concrete and mixes with ratio 2.5 had the least. The total impact for the high strength range is slightly larger than that for the lower strength range. But the impact trend in terms of AA ratio is similar for all groups. The total impact due to OPC concrete production is 50% higher than ambiently cured AACC and is 35% higher than the heat-cured AACC.
Acknowledgements

The authors are grateful to express their gratitude and indebtedness to all who, directly or in directly had an impact on the execution of work.

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