Environmental Impact Assessment of Residential Building – A Case Study

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Abstract. Concrete is the material widely used in the construction industry, satisfying physical and mechanical properties apart from the functional requirements of the building. The negative environmental aspects were not considered during its life cycle. A major stumbling block in achieving a sustainable world is to produce sustainable concrete. To achieve this, alterations in conventional concrete were instigated. Most of the studies suggested replacing, reusing, and recycling materials to reduce the negative impacts. The present study investigates to quantify and compare the possible environmental effects produced by replacing Fly ash and GGBS with cement in varying proportions in conventional concrete. The study aims to assess the performance of concrete towards sustainability by adopting the Life Cycle Assessment (LCA) tools. The environmental performance of these concretes has been accessed using Revit and Tally applications. Further, a comparative analysis was made on seven variants of cement concrete mixes from cradle-to-grave considering some boundary conditions. From the findings, it is evident that GGBS based concrete mixes are more sustainable than Fly ash-based concretes.

Keywords: Environmental aspects · Sustainable · Replacement · Fly ash · GGBS · LCA

1 Introduction

As the Construction industry is a massive industry that impacts every other industry, it accounts for 6% of world GDP. It accounts for one-third of all waste, which ends up in the landfill (Mastrucci et al. 2017). Sustainable environment and surroundings have become a pivotal issue for purchasers and realty developers (Arukala et al. 2020). From the product phase to the demolition phase, buildings have a serious impact on the environment. Globally, buildings utilize 30 to 40% of primary energy in their entire life cycle and account for 40% of global warming emissions (Bansal 2007). In India, the demand for primary energy accounted for 24%, and electrical energy was 30%. India is the sixth largest generator and consumer of power world, accounts for 4% of electricity generation globally. In India, the building sector emits about 22% of CO_2 emissions of the economy, of which 80% are from the product/industry processes of cement, steel, lime and bricks. There is an alarming need to transform construction practices to reduce

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the resulting environmental impacts (Spence et al. 1995). True advancement towards a sustainable developed environment necessitates a life cycle thinking approach, i.e., a comprehensive assessment of all building life cycle stages (Horvath 2004). Extraction of minerals of their natural ores continues to be a labor activity that requires power, produces scrap, and adds to environmental contamination, including adverse consequences such as resource exhaustion, biological losses, and other consequences such as Smog Formation Potential (SFP) global warming emissions, and acid rain.

Modifying the traditional cement concrete has become mandatory to minimize construction's environmental impacts and move nearly to sustainable advancement in the community. Structures are one of the spaces in the metropolitan progression that should be evaluated regarding their environmental repercussions. They give fundamental infrastructure for productive activities and satisfy basic human needs. However, due to this advantage controlled by the structures, stakeholders sometimes do not acknowledge the developing countries' environmental impact. Life Cycle Assessment is a beneficial tool in this regard as it contributes an account of materials and energy required in a product or system and estimates the associated environmental effects (ISO 14040). With the detailed analysis, LCA facilities the necessary data to systemically reduce the impacts and develop a sustainable environment. The present research aims to evaluate and estimate the environmental impacts of a residential house with a service life of 60 years, considering various concrete variants. Many previous case studies have carried out an analysis on Life Cycle Energy (LCE) and suggested methods to reduce LCE usage. The present study focuses on knowing how different pozzolanic materials with varying percentages in cement replacement can alter the impacts of the overall life cycle and its performance towards overall sustainability.

1.1 Autodesk Revit (BIM)

It is a leading BIM (Building Information Modelling) software program for architects, engineers, contractors, and designers. Building Information Modelling is an industry-wide technological development in the Architecture, Engineering, and Construction (AEC) industries. With BIM innovation, a realistic visual representation of a structure can be created, which is referred to as the Building Information Model. Ultimately, it will facilitate planning, design, construction, and operation. When it has been completed, the BIM model will provide accurate geometry and correlated data to support research, acquisition, fabrication, and construction activities, thereby leading to the successful completion of the project.

1.2 Tally

Tally is a plug-in for Autodesk Revit software, which allows the user to perform LCA of building and calculates the environmental impacts of the BIM models assigned with materials. LCA of the BIM model will be carried out when the construction materials in Tally's database are assigned to BIM elements. It is easy to operate and does not require any special modeling skills. It provides design option comparison, allowing the user to compare two or more design options. It evaluates six impact categories: Eutrophication Potential (EP), Acidification Potential (AP), Global Warming Potential (GWP), Smog Formation Potential (SFP), Ozone Depletion Potential (ODP), and Primary Energy Demand (PED).

1.3 Life Cycle Assessment

The Life Cycle Assessment (LCA) method is one of the systems for estimating the environmental imprints of products, processes, and activities by analyzing the life cycle of raw materials, production, and disposal, as well as the product itself. According to ISO 14040 (1997) defines as “LCA is a technique for assessing the potential environmental aspects associated with a product (or service) by compiling an inventory of relevant inputs and output”. It evaluates the potential environmental impacts associated with these inputs and outputs, and interprets the results of the inventory and impact phases. LCA is carried out in four steps: Planning, Inventory analysis, Impact assessment, and Improvement analysis.

- Planning: A framework for LCA planning, with its goals, objectives, boundary, breadth, and scope identifies how the study will proceed.
- Inventory analysis: An analysis of the inputs and outputs of the system is based on the measurement of energy, raw materials, air pollutants, waterborne effluent, and solid waste.
- Impact assessment: The environment effect of the product is assessed through the use of qualitative and quantitative procedures that analyze the use of raw materials, energy production, water consumption, air emissions, and solid waste production.
- Improvement analysis: In improvement analysis, changes are made to reduce environmental burdens associated with a product or system by taking an accurate view of the entire life cycle and analyzing the impact the changes will have on the environment.

2 Literature Review

Authors evaluated a number of residential buildings (one-, two-, and multi-storey) for their energy efficiency. Thermal Insulation (TI) on walls and roofs as well as Double Pane Glass for Windows (DPGW) were tested in almost ten houses. In general, the LCE of the building varies from 240 to 380 kWh/m^2 per year, depending on the building and climate. Further examination was done on one of the buildings to assess LCE performance with on-site power generation. It is observed that about 5–30% of LCE was saved with TI on the wall and roof together with DPGW (Ramesh et al. 2012). In one of the studies, the LCE of a building consists of various energies such as Constructional Energy (CE), Operational Energy (OE), and Demolition Energy (DE), represents a case study on LCE analysis of residential progress consisting of 96 indistinguishable apartment-type homes sited in Southern India and found that CE is an essential component of LCE of residential buildings with partial or no air-conditioning. As a result of reduced building service life periods and increased energy efficiency in the operations phase, the CE becomes imperative as the OE (Devi et al. 2014). It is also precise that the highest contributor in GHG emissions is RCC framework and steel and observed that 59% of the total energy is consumed only in their operation phase (Sharma et al. 2011). The embodied energy in residential buildings during their life cycle and it ranges from 1.5 to 30% (Dascalaki et al. 2021). It is evident that fiber is highest carbon emission, next to it is ceramics, then the metals, elastomers, and polymers (Ansari 2017).

With the usage of BIM platform's, a more sustainable environment can be built by integrating the BSA methods in BIM (Carvalho et al. 2021). Building information models (BIM) are used to facilitate the construction procurement process by providing innovative ways to employ e-procurement in construction (Costa et al. 2015). BIM as a tool that enables storage space and reuses the information and acquaintance all through the project's lifecycle. The concept of BIM is clearly stated in this paper (Yadav et al. 2018). The comparison of practical tools application that is noticeably significant to understand the current potentials and the remaining limitations of the BIM-based LCA tools under development (Bueno et al. 2018).

2.1 BIM Integration with LCA

Three major aspects were found in the literature study about the integration of BIM with LCA. Firstly, identifying the information about LCA tools and their necessity to integrate with BIM. Secondly, discover the data that could be included in the BIM model, and lastly examining two diverse structures for energy and environmental performance in order to understand the implications of the designer's choices on the building's performance. The primary source for LCA tools databases is the Environmental Product Declaration (EPD), Enacted and harmonized with EN 15942:2011. This facilitates the product's environmental performance for business-to-business (Standards 2011). In the present study, Tally is chosen to perform the LCA since it is one of the rare tools that directly operate as a plug-in Autodesk Revit and can work with, also it combines the two most crucial entities in the recognized areas, Autodesk Revit, as a BIM software, and Tally as LCA software and GaBi database (Li et al. 2020; Santos et al. 2016; Zotkin et al. 2016).

3 Methodology

The present study employs quantitative research to quantify a residential building's environmental impact assessment and compare it with the varying concrete mixes. It includes unit processes from the "cradle-to-grave", including all the phases starting from raw mineral extraction, processing, manufacturing, transportation, construction, installation, and demolition phase. The scope of the study is limited to compare the environmental impact of a residential building with varying concrete mixes. Seven variations in the concrete mixes were considered, varying the percentage of fly ash and GGBS. A building is modeled in Revit with a built-up area of 650 sqft and exported to Tally to carry out the impact assessment, the impact evaluation method used is TRACI 2.1. The present research considered a case study of a building made of fly ash and GGBS based concrete with varying percentages and analyze the impact categories in each life cycle phase of the building.

The study considered six major environmental impact categories namely AP, EP, GWP, ODP, SFP and PED (Fig. 1 and Table 1).

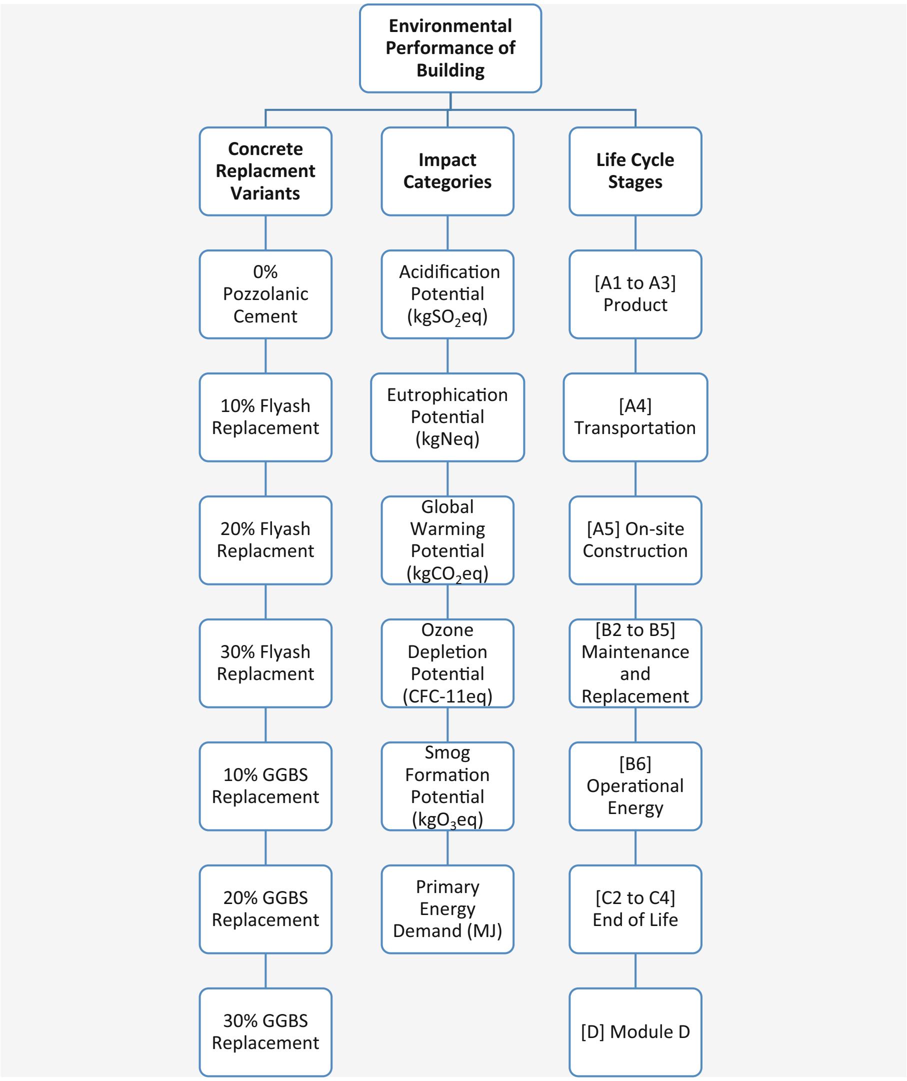


Fig. 1. Methodological framework.

4 Case Study

Table 1. Residential building components.

Building element	Description of buildings system
Internal and External walls	External walls: Brick (190 × 190 × 10) with mortar. Edge brick sealed with cement. exterior acrylic latex Internal walls: 10 mm finish Gypsum board on stud, acrylic paint exterior finish
Foundation	Reinforced concrete isolated footing of 450 mm thickness
Floors	Ceramic tiles (8 mm) unglazed with cement grout and cement mortar
Column	RCC column of size 450 × 300 mm
Roof	RCC slab of 100 mm thickness
Doors	External doors: Timber frame, double door with dead bolt with gloss finish. Internal doors and laundry: Timber frame, Single door with gloss finish
Windows	Timber frame with Curtain wall system (Glazing)

4.1 System Boundaries

The system boundaries include all the four stages of building Product/Manufacturing stage, on-site construction stage, operational stage and demolition stage. Impacts of transportation are also considered and the transport distance of the material was chosen from the nearest vendor. On-site construction and water usage was included in the system boundaries. Indoor air quality assessment was excluded from the assessment. The service life of building is considered as 60 years.

4.2 Functional Unit

According to ISO, ISO 14040, functional unit is defined as unit of reference that is used to compute the systematic variable performance in LCA technology. The functional unit chosen for this assessment is “m^2”.

4.3 Life Cycle Inventory

A custom LCA database has been developed by Tally that consolidates information on material properties, structural details, and construction details along with environmental impact data generated from a collaboration between Kieran Timberlake and thinks step. The LCA modeling was completed in GaBI 8.5, using GaBI 2018 databases, and following the databases and modeling principles of GaBI.

5 Results and Discussion

LCA impacts for the residential building are presented in this section. The four stages of the life cycles i.e., Manufacturing/product stage, construction stage, operational stage, and demolition stage were assessed. From the findings it is evident that operational stage has represented 90% of impacts in all impact categories dominating the other life cycle modules (Table 2).

Table 2. Life cycle impacts of RCC without addition of pozzolanic material.

Row labels	Acidification potential total ($kgSO_2eq$)	Eutrophication potential total (kgNeq)	Ozone depletion potential total (CFC-11eq)	Global warming potential total ($kgCO_2eq$)	Smog formation potential total (kgO_3eq)	Primary energy demand total (MJ)
[A1−A3] Product	135	6.21	43687	−1.82E−05	2034	502254
[A4] Transportation	1.96	0.16	423	1.45E−11	64.89	6162
[A5] On-site Construction	2.57	4.42	879	1.39E−09	22.73	15551
[B2−B5] Maintenance and Replacement	9.61	0.23	694	3.47E−06	54.53	14903
[B6] Operational Energy	5490	318	2340000	3.96E−06	58500	44100000
[C2−C4] End of Life	14.71	0.78	4935	1.28E−08	290	53834
[D] Module D	−7.88	−0.21	−2912	1.70E−05	−64.15	−29,446
Grand Total	5646	330	2387708	6.28E−06	60903	44663259

Note: Negative values found in GWP in module A1 to A3 are credits for allocation of co-products. According to EN15804, credit allocation is not done in Module D (Gervasio and Dimova 2018).

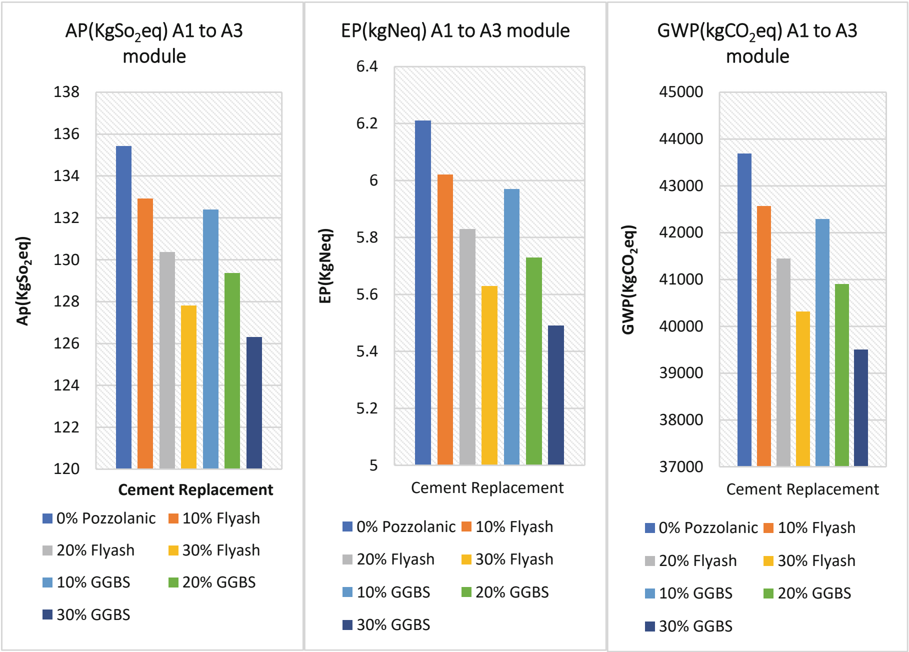
Table 2, indicate that the product/manufacturing stage (A1 to A3) will emerge as a critical module with 70 to 90% of life cycle impacts when the Operational phase (B6) is ignored, thus making it an essential and evident category for the usage of resources.

Table 3, shows the life cycle impacts of the different concrete mixes used in the research. As mentioned above, B6 (Operational stage) has been the dominant impact creator in the scenario. But, when replaced with pozzolanic materials, Cement has shown significant improvements in A1 to A3 (Product stage) Module. Other modules got affected by the addition of pozzolanic materials are A4 (Transportation), which partially involved C2 to C4 (End life stage), whereas the remaining modules like A5 (On-site

Table 3. Life cycle impacts of pozzolanic variants.

S. No.	Environmental impact indicators	0% Pozzolanic	10% Flyash	20% Flyash	30% Flyash	10% GGBS	20% GGBS	30% GGBS
1.	AP (KgSO$_2$eq)	5646.41	5,643.91	5,641.40	5,638.85	5643.42	5640.41	5637.42
2.	EP (KgN-eq)	330.19	330.01	329.82	329.62	329.96	329.72	329.42
3.	GWP (KgCO$_2$eq)	2387708	2386596	2385483	2384345	2386323	2384434	2383548
4.	ODP (CFC-11-eq)	6.28E−06	6.28E−06	6.28E−06	6.28E−06	6.28E−06	6.28E−06	6.28E−06
5.	SFP (KgO$_3$-eq)	60903.32	60,848.26	60,793.20	60,737.17	60840.89	60776.51	60713.28
6.	PED (MJ)	44663259	44656635	44650012	44643129	44653861	44644423	44635017

construction) and B6 (Operational) modules were unaffected by the pozzolanic materials as the impacts of these modules are calculated by consumption units irrespective of the material used in the building.

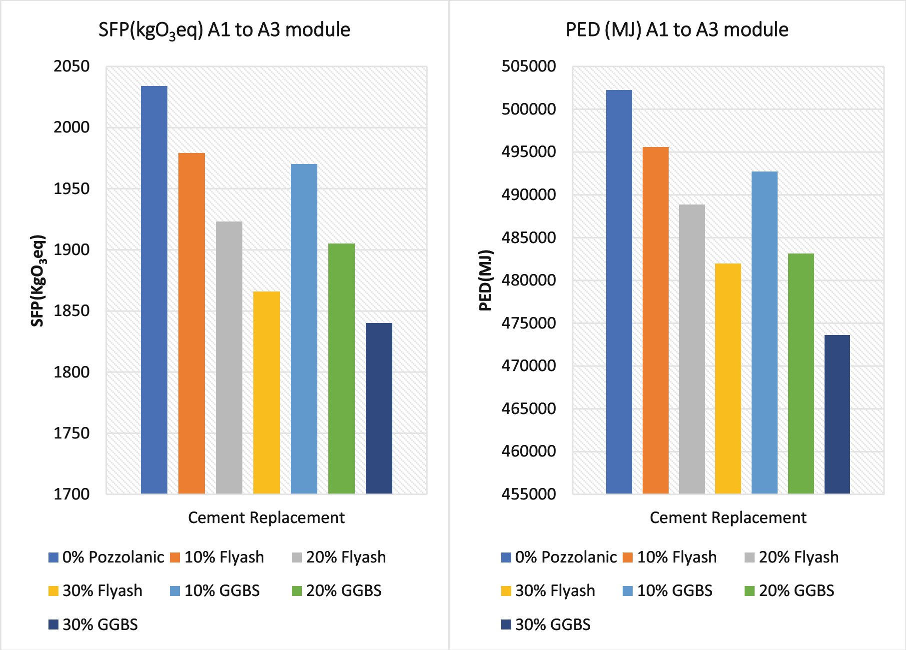


(a) AP comparison. (b) EP comparison. (c) GWP comparison.

Fig. 2. Module comparison for various cement replacements: (a) A1, (b) A2, (c) A3.

Figure 2(a) shows the acidification potential impacts of product stage/manufacturing stage (A1 to A3) of various cement replacement percentages. Cement, when replaced with 10% fly ash, brought down the impacts by 1.8%. This trend continued with replacements of 20%, 30% as 3.72% and 5.62% respectively.

Impacts of GGBS were found to be lower than fly ash, which led to further reduction of impacts compared to that of fly ash. GGBS when replaced with 10% of cement the impacts are found to be 2.24% and further addition (20%, 30%) impacts were found to be 4.48%, and 6.73% respectively. From Fig. 2(b) a similar linear variation is observed. The impacts were reduced with incremental replacement of fly ash as 3.05%, 6.11% and 9.33% for 10%, 20% and 30% respectively while that of GGBS were 3.8%, 7.7% and 11.5% respectively. Cement is the major impact producing material for eutrophication potential, with 32% of total emissions (excluding the operational stage) lead to further drop-down of the impacts compared to acidification potential. From Fig. 2(c) we can infer that the global warming potential of fly ash variants reduced by 2.5%, 5.11% and 7.72%, and GGBS variants by 3.12%, 6.3% and 9.58% respectively. Though cement being the major impact-producing material of global warming potential with 29%, masonry bricks were the second highest impact producer with 23% of impacts. This variation in the impact contribution material is leading to the variation of the reduction in impacts produced by the cement.



(a) SFP comparison.

(b) PED comparison.

Fig. 3. Module SFP and PED comparison for various cement replacements: (a) A1, (b) A2, (c) A3.

Figure 3(a) shows the impacts of smog formation potential, and the fly ash replacement impacts are as follows 2.7%, 5.4% and 8.26%. respectively whereas the GGBS replacement impacts are 3.1%, 6.3% and 9.55% respectively. Cement was the major impact-producing material of the smog formation potential with 28% of total impacts. Figure 3(b) Shows the demand for primary energy demand, while with 10% replacement of fly ash the primary energy demand was reduced by 1.33%(6700 MJ) and for 20%, 30% it was reduced by 2.66% and 4.04% respectively. For GGBS variants the reduction of impacts is found to be 1.9%, 3.8% and 5.7% respectively. From the analyzes it is also found that primary energy required for masonry brick is 33%, major consumer, similarly 17% for steel and 16% for cement consumption.

Table 4. A4 transportation module impacts.

Row labels	Acidification potential ($kgSO_2eq$)	Eutrophication potential (kgNeq)	Global warming potential ($kgCO_2eq$)	Ozone depletion potential (CFC-11eq)	Smog formation potential (kgO_3eq)	Primary energy demand (MJ)
0% Pozzolanic	1.96	0.16	423.79	1.45E−11	64.89	6,162.78
10% Flyash	1.99	0.16	428.99	1.47E−11	65.68	6,238.45
20% Flyash	2.01	0.16	434.20	1.49E−11	66.48	6,314.13
30% Flyash	2.03	0.17	438.97	1.50E−11	67.21	6,383.54
10% GGBS	2.01	0.16	433.89	1.49E−11	66.44	6,309.74
20% GGBS	2.05	0.17	443.33	1.52E−11	67.88	6,446.92
30% GGBS	2.10	0.17	453.30	1.55E−11	69.41	6,591.98

Table 4 shows the impacts of the A4 transportation module. From the results, it is clear that transportation of pozzolana's from long distances has an increased impact on the environment. The fly ash procurement distance was assigned as 70 kms from a thermal plant, and the GGBS procurement distance was assigned as 550 kms.

6 Conclusions

This research presents an overview of the life cycle impacts of a residential structure with all life cycle phases. BIM was carried out in Autodesk Revit, and LCA was carried out using the Plug-in Tally. The analysis leads to the following conclusions that:

- Fly-ash and GBBS reduce the Life cycle impacts and the impact categories are varying linearly concerning the replacement of cement.
- The impacts of cement have reduced by 5–8% with every 10% replacement of cement.
- 30% Replacement variants of Fly ash and GGBS are more sustainable when compared to other variants in the research
- EP was the most reducing impact category, while A1-A3 module was most sustainable module.

These results provide a basis to say that GGBS is more sustainable pozzolana than fly ash though the procurement distance of GGBS was seven times greater than the fly ash. Though the variation in percentage was less than 5% in many cases, In India, where 1.6 million new houses are built every year, these numbers can be significant game-changers and can address many issues in the long run towards the environment's overall sustainability.

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