LIFE CYCLE ENVIRONMENTAL IMPACT OF TRADITIONAL AND ALTERNATIVE SUSTAINABLE MATERIALS IN STRUCTURAL MEMBERS: A COMMERCIAL BUILDING CASE STUDY IN BANGLADESH

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ABSTRACT

During the building design and construction process, the issue of material sourcing, usage, and their environmental impact is often neglected despite holding significant potential in assessing the sustainability of the building project. Thus, utilization of the life cycle assessment (LCA) method, where the environmental impact of material extraction, processing, and end-use is assessed, holds significant potential. This study focuses on the LCA of a commercial building with 2278 m² of gross floor area, considering an operational life of no more than 50 years, located in Bangladesh. Materials used in load-bearing structural members and energy-consuming utilities during the construction phase were considered while conducting the LCA analysis of selected stages using One-Click LCA. The study follows a process of designing the building model in Autodesk Revit and exporting it for LCA analysis of the materials and construction parameters in One-Click LCA, a cloud-based LCA analysis system. Two designs of the building were done and analyzed following this process. Design 1 used only traditional materials while Design 2 utilized ready-mix concrete having 40% and 10% ground granulated blast furnace slag in the construction of slab and column structures respectively, and 10% fly ash in the ready-mix concrete used for foundation construction. The results of the two designs were then compared. The objective of the study is to explore different materials and segments of the building structure with their corresponding carbon emission, and how alternative materials can mitigate impacts on carbon emissions of the commercial building. The study outcome helps to quantify the leverage of material selection in vertical and horizontal structural members and substructures in reducing the environmental footprint of a commercial building while considering construction parameters like machine hours, site electricity and fuel consumption, and transportation for the different designs. The analysis suggests that integrating the considered sustainable materials in the stated specifications reduces emissions by 132.68 tons of CO2 in the life-cycle stages, which translates to a 6.72% mitigation. This can provide insights to policymakers and designers regarding the life-cycle environmental impact of integrating alternative sustainable materials in the building design and construction process.

Keywords: *Sustainable material selection, life cycle assessment, carbon emission, GWP*

1. INTRODUCTION

The value of using LCA for the construction industry in transitioning to sustainable material selection and stable economic growth without compromising global ecosystem functionality can be understood by noticing the environmental impact of the construction materials in building construction on their life cycle scale in terms of carbon emission and global warming potential (GWP). The built environment induces 40% of greenhouse gas (GHG) emissions (World Green Building Council, 2019), 40% of energy consumption (Comstock et al., 2012), and building materials manufacturing alone claims 5-10% of GHG emission (Habert et al., 2012) on the global scale.

LCA, being a standardized method (International Organization for Standardization, 2006), makes actionable and measurable data regards to environmental impacts of a building design accessible if provided with specifically defined parameters of boundary and can be extremely helpful for comparing sets of alternative scenarios, referring to their individual impacts on the environment (Hellweg & Milà i Canals, 2014). The data may include environmental impacts on the scale of tropospheric ozone, land/water acidification, eutrophication, ozone depletion, and global warming (Council, 2013).

The leverage of LCA in reducing Whole-life Embodied Impacts (WEI) of buildings by helping to select materials of low impact has substantial potential (Pomponi & Moncaster, 2016). A study focusing on the simplifications in LCA building components found typical simplifications of life cycle stages, and life cycle inventory can have a significant context to LCA results corresponding to component type (Kellenberger & Althaus, 2009). So, in evaluating embodied carbon emissions, with regard to handling early-stage uncertainty, a structured route to design process classification can be more relevant (Resch et al., 2020).

However, by breaking down the design processes into groups of a structured set of specifications, corresponding components, and elements of the building have been used to assess alternatives and their environmental effects (Basbagill et al., 2014; Duprez et al., 2019; Resch et al., 2020; Zhang & Zheng, 2020), as early design decision-making has proven to be responsible for leveraging substantial levels of environmental footprint (Häkkinen et al., 2015; Shi & Yang, 2013). Though analyzing a design alternative of the case study building may not always be appropriate due to the individuality of the structure. and the sheer variations of factors affecting the embodied carbon emissions (Griffin et al., 2013), this encourages researchers to focus more on precise datasets from the building, and the Environmental Product Declaration (EPD) of the materials that are being used in construction to minimize unwarranted noise in output results for a more accurate assessment regards to Initial Embodied Impacts (IEI) i.e. A1-A5 stages of the LCA assessment (EN, 2011) which, by including all impacts required to acquire, manufacture, transport, and construct the construction materials on-site, considers the net embodied impacts to the point of the complete construction of the building structure (World Green Building Council, 2019).

This can help designers, and researchers in making more sustainable early-stage choices using pre-assessed alternatives which have proven to be quite significant in sustainable decision-making (Morini et al., 2019). Pre-assessed environmental impacts can be immensely useful in the process of material selection in the design phase (Meex et al., 2018).

Table 1: Building Life Cycle Stages in EN 15978 standards (EN, 2011)

Product Stage	**Raw material supply**	**A1**
	Transport	A2
	Manufacturing	A3
Construction Process Stage	Transport to Building Site	A4
	Installation into Building	A5
Use Stage	Use/application	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End-of-Life Stage	Deconstruction	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4
Benefits and loads beyond the system boundary	Reuse	D
	Recovery	
	Recycling	

A study in the context of Bangladesh, in accordance with EPD data of locally available materials used in the building construction only focused on the product life cycle stage (A1-A3) of a residential building (Islam & Chowdhury, 2021).

However, since then, more relevant EPD data has become accessible, causing this study to focus not only on the product stage (A1-A3) but additionally, on the construction process stage of the case study buildings' LCA (A4-A5). This analysis also focuses on quantifying the changes in the environmental impact by comparing a design using traditional materials (designated as "Design 1") to a design that substitutes traditional design materials of ready-mix concrete with 40% and 10% Ground Granulated Blast Furnace Slag (GGBS) integration in the Ready-mix Concrete (RMC) used for slabs and columns respectively, and 10% Fly-ash (FA) integration in the RMC used in foundation construction (designated as "Design 2"). The study aims to demonstrate preliminary results of most contributing components in the environmental impact scale in terms of carbon emission to the atmosphere from the material production stage to the construction stage including transportation and on-site construction activities to provide sharp insight on how to reduce carbon emissions in the context of commercial building construction by using sustainable alternatives from an LCA perspective. Thus addressing a crucial gap in the literature focusing on LCA-centric building construction and design research in Bangladesh.

2. METHODOLOGY

The commercial building chosen for this study consists of six stories, located in Gazipur, Bangladesh. The case study has been chosen because commercial building construction has seen exceptional growth in recent years due to the development of the service industry of the country. The construction material data of the main load-bearing structural elements were gathered from the designers and regulatory authorities, then the two building designs were modeled in Autodesk Revit, and the LCA was conducted with One Click LCA, a cloud-based software that's fully in compliance with the standards of EN 15978. In calculating a building LCA, EN 15978 is very specific by outlining the processes for object assessment (building scenario, functional equivalent, scope, etc.), environmental data selection (e.g. EPD), building inventory quantification, environmental indicator calculations, and reporting of the results with verifications by dividing the building life-cycle into five stages (EN, 2011), of which the first two- product stage and construction process stage will be fully assessed. Moreover, data on transportation of construction materials to the building site, construction processes, and the following construction site parameters: machine hours, construction site electricity, and water usage (not for ready mix concrete mixing, which is accounted for in the EPD, but for curing and miscellaneous activities), construction waste, and fuel consumption were also taken into account. These data are represented in Figure 3 and Table 2.

One Click LCA processes these datasets and corresponds to their EPD and usage, then generates a report on emissions by building components and material types, with emissions of the building life-cycle product and construction process stage taken into consideration. The initial design using traditional materials (design 1) and potentially more sustainable design (design 2) datasets were fed in for processing along with the data of on-site activities and then compared by categorizing the results into three parameters.

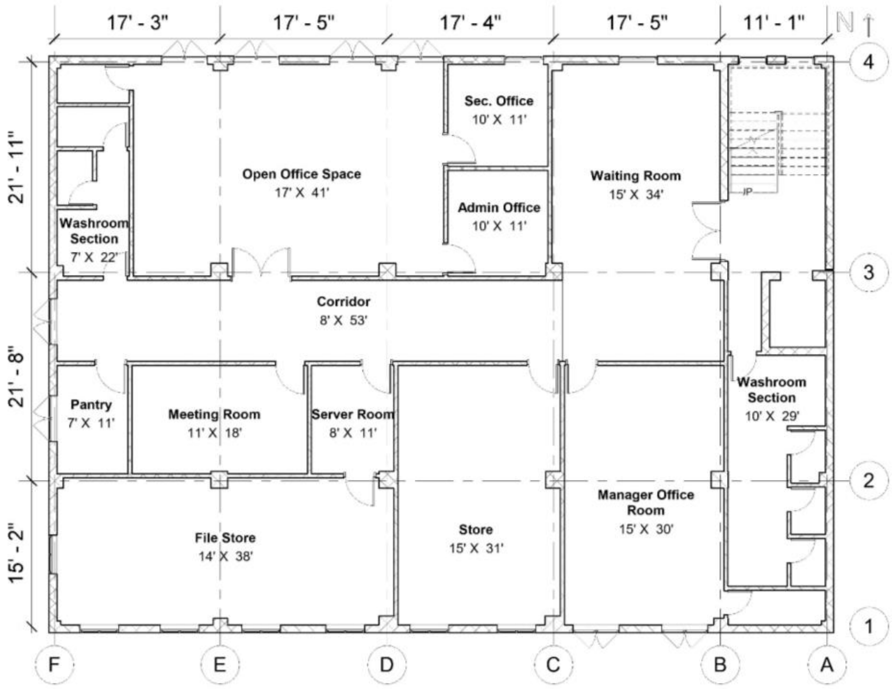

Figure 1: Typical floor (sixth) plan of the building structure

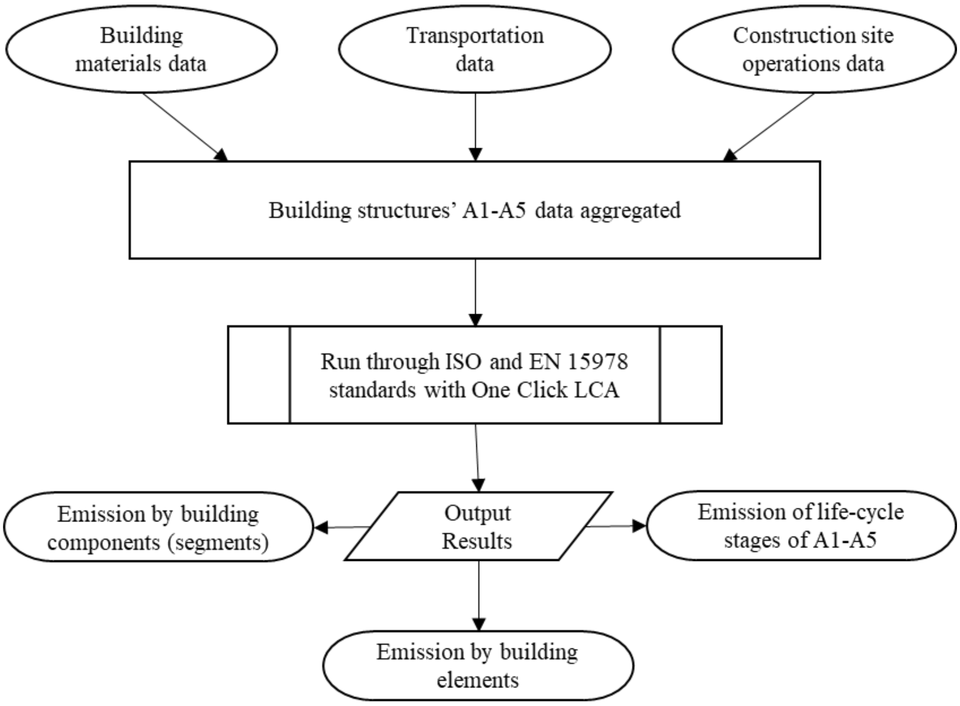

Figure 2: Methodology flowchart illustrating the study approach

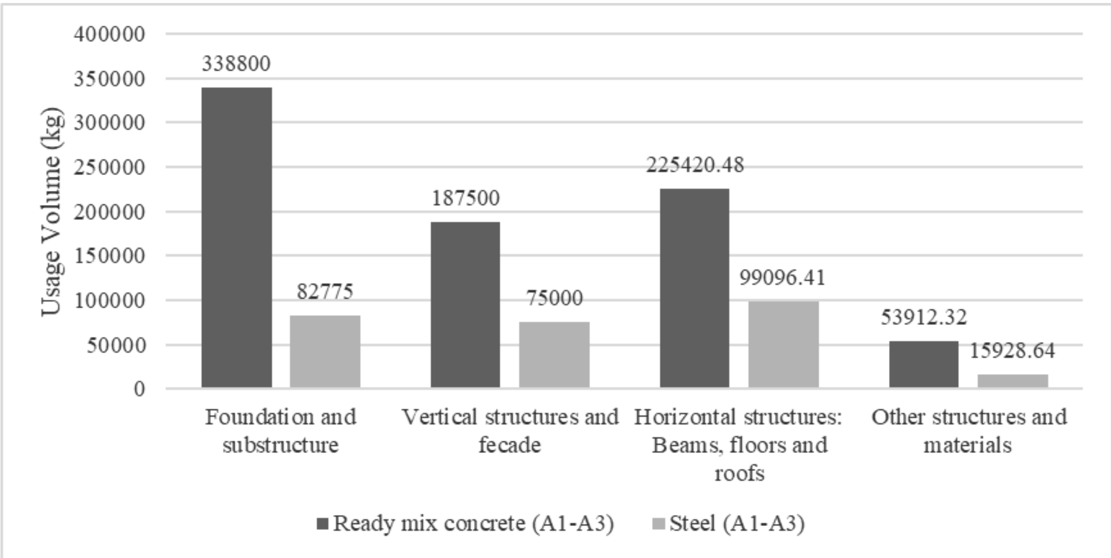

Figure 3: Material usage mass by building components collected from project approval models and documents

Table 2: On-site activities and their metrics (e.g. machine hours, electricity and water usage, etc.) aggregated from site engineers and project scheduling and costing documents

Items	Usage
Excavator, wheeled, diesel-driven, operation per hour, average power: 88kW, loading factor: 32%	240 Hours
Generator, diesel-driven, operation per hour, average power: 35kW, loading factor: 50%	14976 Hours
Compactors, diesel-driven, operation per hour, average power: 45kW, loading factor: 30%	200 Hours
Electricity	4800 KWh

Site Fuel (Diesel)	15000 Liters
Water	178,800 kg
Soil Waste Management and Transfer	234832.7 kg

3. RESULTS AND DISCUSSIONS

3.1 Emission by building component types:

Building components were compartmentalized into four distinguished portions and their individual tCO2e (tonnes of carbon dioxide equivalent) were determined as shown in Figure 4.

From correlating Figure 3 to Figure 5, the issue with horizontal members having difficulty in carbon emission reduction relative to vertical members despite having 30% more GGBS integration in its RMC can be credited to its relatively high steel usage as steel is responsible for no less than 40% of emission in both of the designs (from figure 12 and 13) despite relatively low usage by mass, seen in figure 3. To gain more insight, in figures 6 and 7 the emissions of components in both designs were broken down by percentage in order to check any disproportional changes among them. Noticeably, a somewhat proportional reduction of emission by all of the building components despite integrating 40% GGBS in slabs, 10% GGBS in columns, and 10% FA in foundation RMC may be attributed to steel usage per RMC being different in each of the building component types that have been indicated in figure 3.

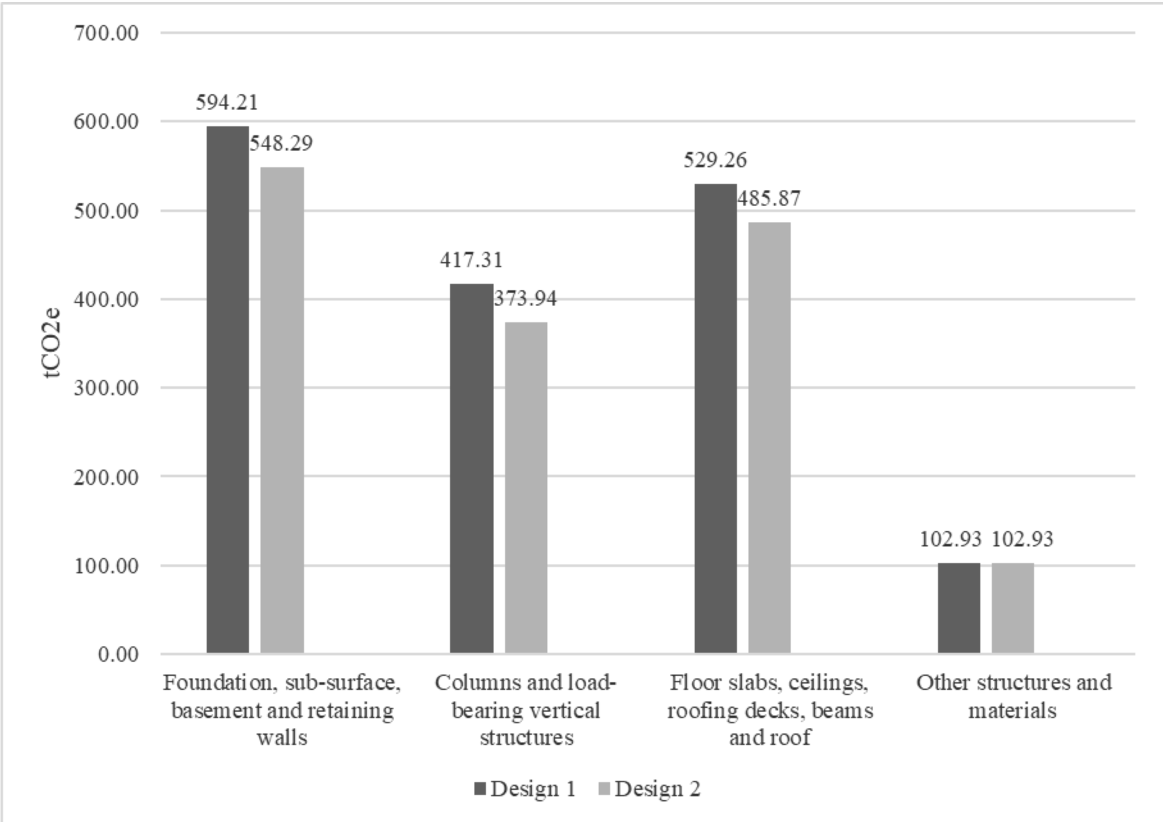

Figure 4: Emissions by building component types

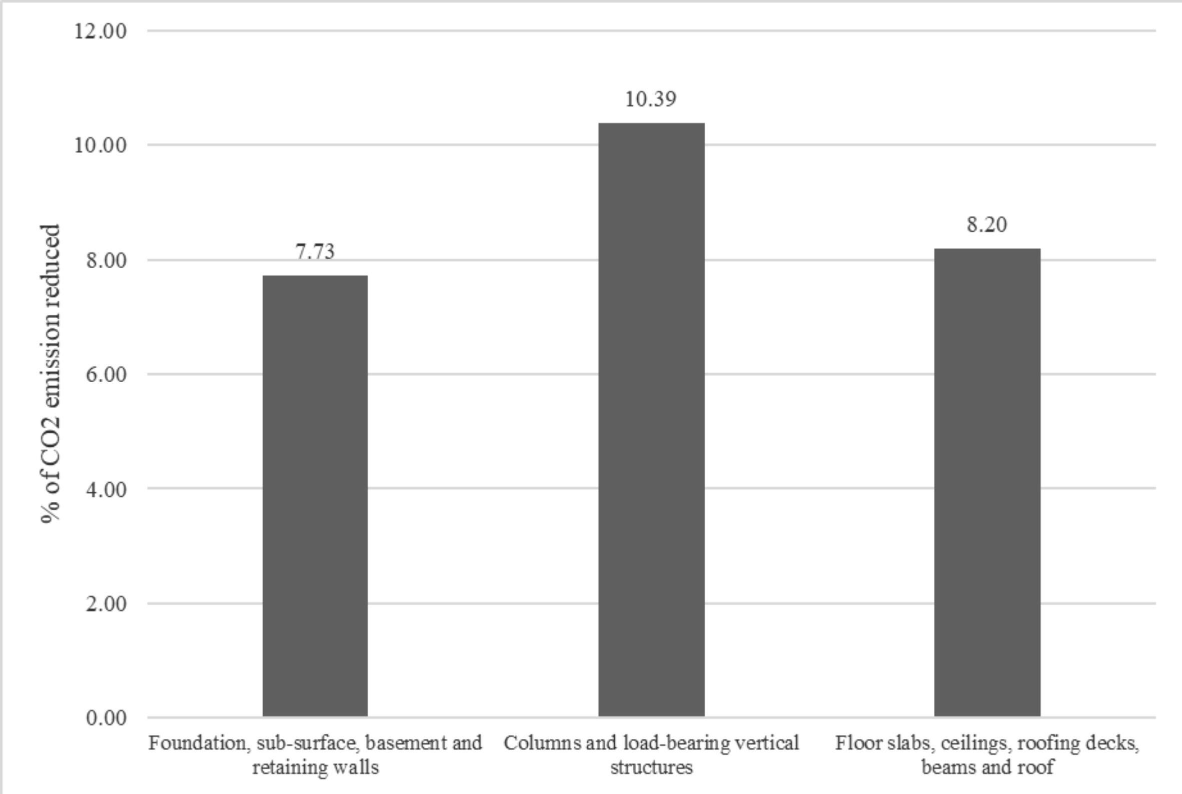

Figure 5: Emission percentage reduced in design 2 by building component types

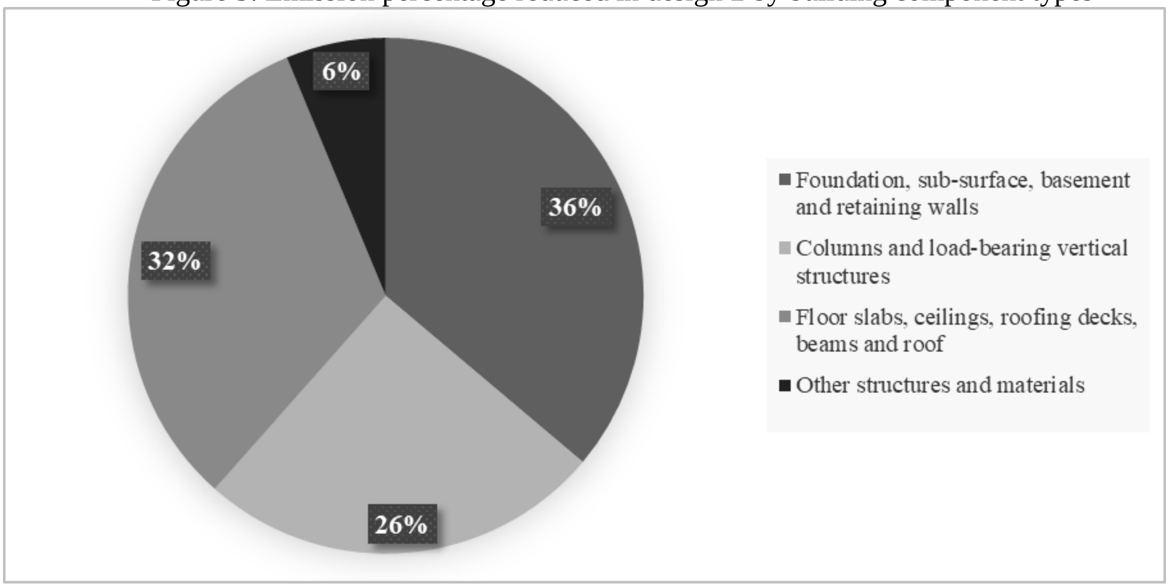

Figure 6: Emission percentage by building component types in design 1

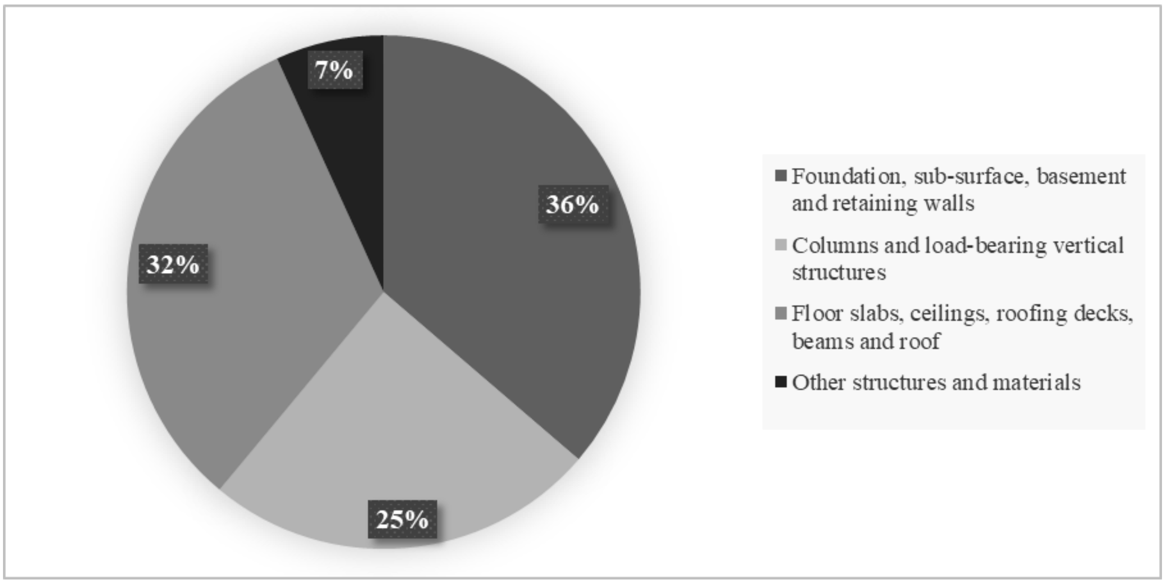

Figure 7: Emission percentage by building component types in design 2

3.2 Emission by on-site construction activities

The usage of sustainable materials has insignificant effects on the reduction of emissions from construction site activities as machine hours and site fuel consumption are related to construction site personnel behavior, preference, and work schedules, being independent of the types of sustainable materials used in this case study as illustrated in figure 8.

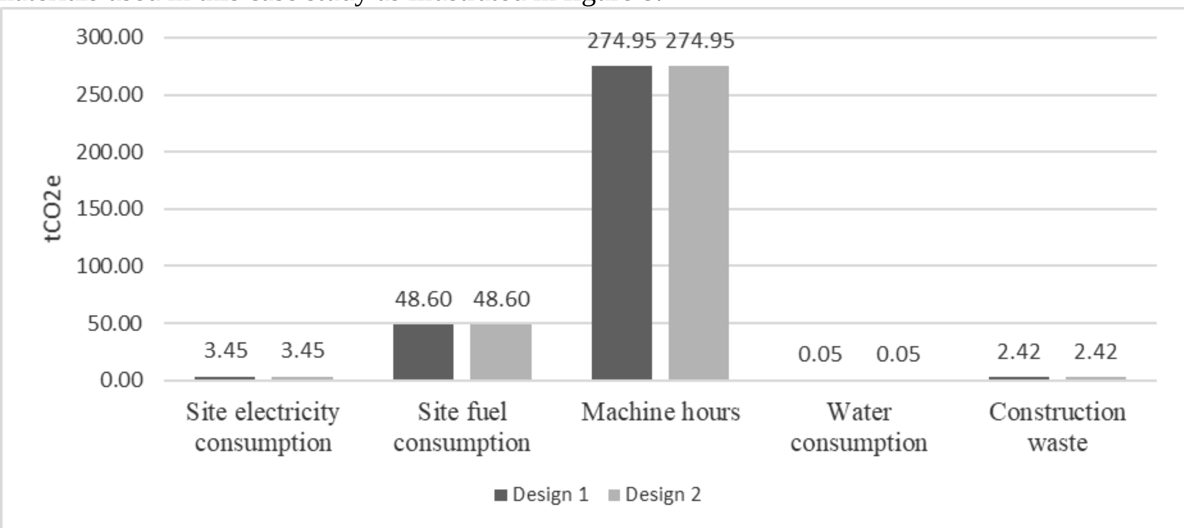

Figure 8: Emissions by construction site operations

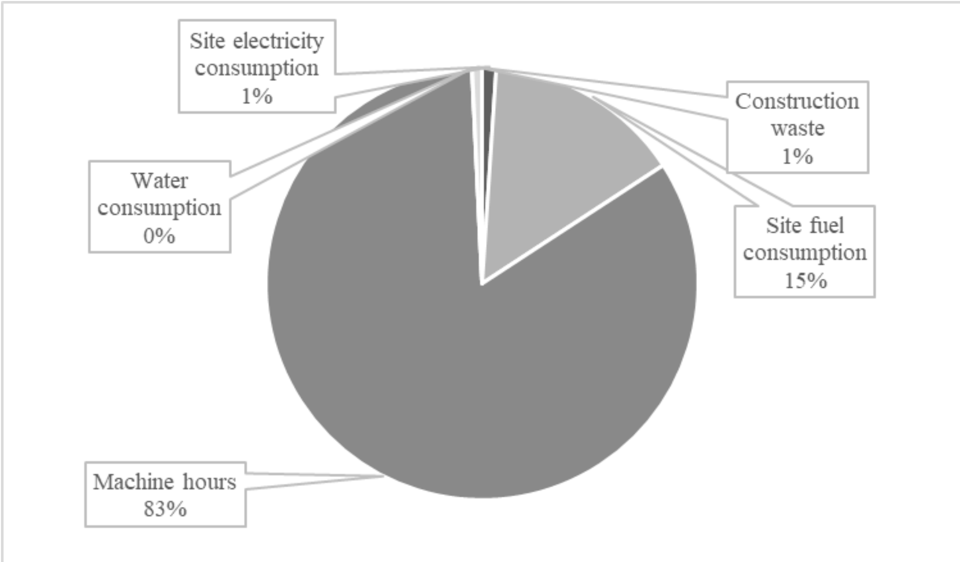

Figure 9: Emission percentage by construction site operations

While it can be perceived as beneficial to focus on construction waste in a new construction process to reduce emissions; figure 9 indicates that, compared to other construction activities and their emissions; it's evident that machine hours and site fuel consumption management can hold more potential while emissions from water consumption have proven to be insignificant.

3.3 Emission by building elements and life-cycle stages of A1-A5

Figure 10 on the other hand, indicates, that the material transportation emission in this study despite being relatively low compared to A1-A3 and A5 life-cycle stages emissions; is actually very critical as it appears to be unchangeable despite using sustainable construction materials since this issue is related to material transportation technique.

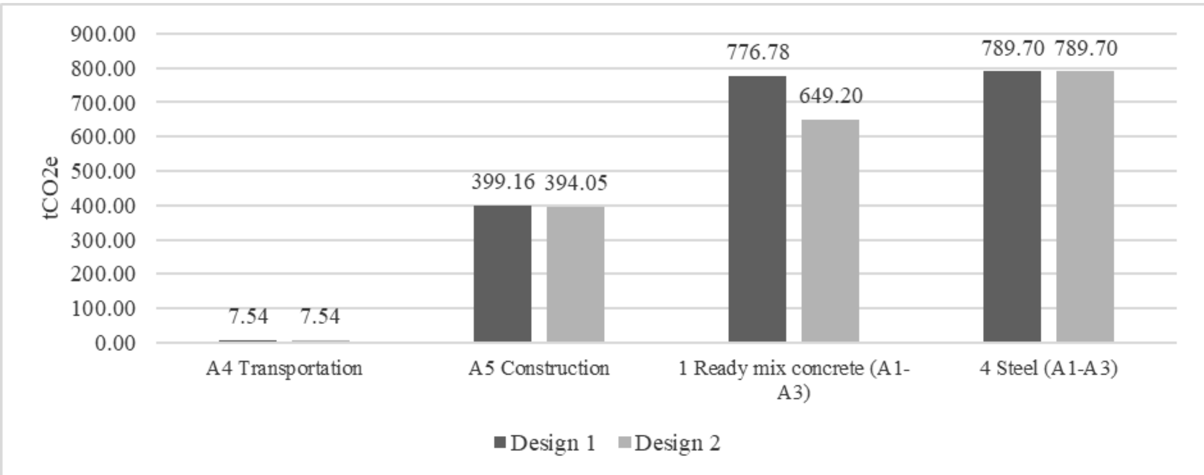

Figure 10: Emissions by elements and life-cycle stages

From comparing the two designs' emission results, the alternative design (design 2) has proven to have a lower emission footprint than the design using traditional ready-mix concrete. From Figure 10, it is clear that the leverage gained in design 2 is essentially due to the more sustainable materials it used in ready-mix concrete that has significantly low carbon emissions in its product stage (A1-A3) which has also been noticed in Figure 11. The relatively low emission reduction in the construction process of design 2 (i.e. A5) noticed in Figures 10 and 11 may be relatively small in volume but still considerable.

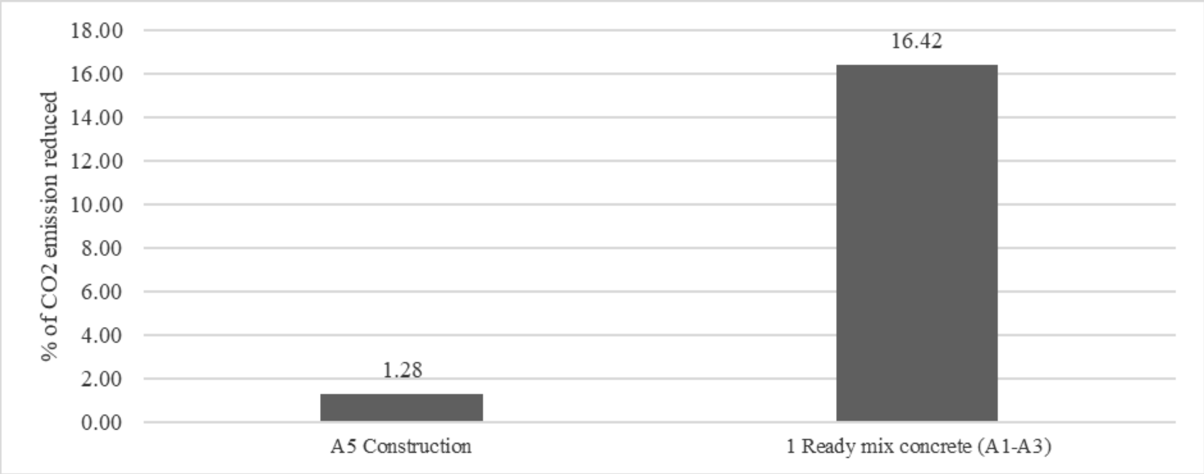

Figure 11: Emission percentage reduced in Design 2 by elements in life-cycle stages

Figure 11 indicates that the integration of given sustainable materials in RMC results in significantly more emission reduction in the A1-A3 phase than in the A5 phase of the building life-cycle while no significant changes in emission reduction relating to steel usage.
For further assessment, the share of emissions of elements in the two different designs was individually derived in Figures 12 and 13.

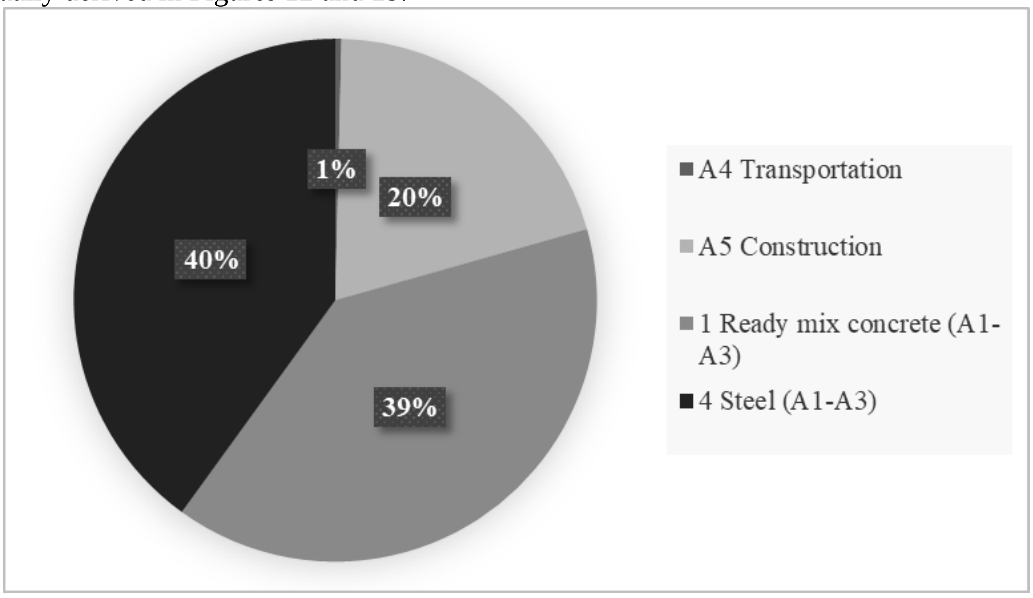

Figure 12: Emissions by elements and life-cycle stages percentage for design 1

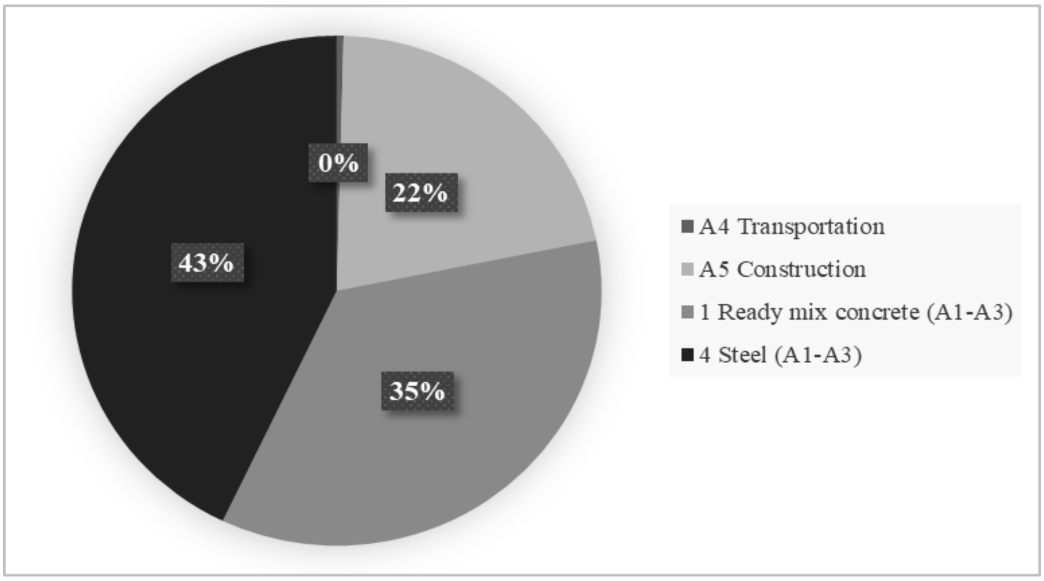

Figure 13: Emission by elements and life-cycle stages percentage for design 2

Comparing design 1 to design 2 with figures 12 and 13, we see steel being 3% more responsible in its total share of emission due to design 2 using a set of more sustainable materials integrated into RMC, causing the emissions in RMS elements to reduce by 4%.

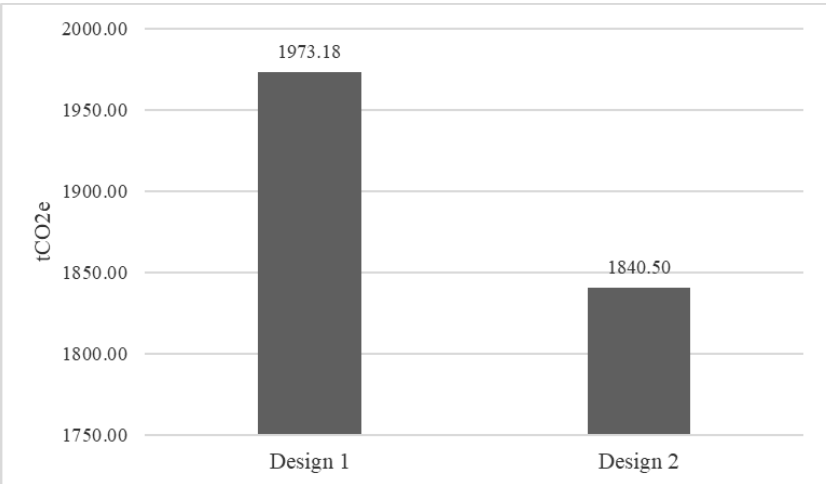

Figure 14: Total emissions (A1-A5) comparison

In terms of assessing the net total reduction of emission, figure 14 indicates that 132.68 tCO2e can be avoided by implementing design 2 over design 1, for this type of commercial building using the given set of alternative sustainable materials in their corresponding percentage of integration.

4. CONCLUSION

In the case study building, the alternative design has the potential to reduce the net tCO2e by 6.72% considering LCA phases from A1-A5, due to the alternative materials integrated and their corresponding assembly processes having lower CO2 emissions. Thus indicating a positive environmental impact from using the given alternative materials. Conclusion regarding horizontal members holding potentially untapped leverage in emissions reduction because of their additional steel usage in this type of building design encourages inquiry into feasibility studies for recycled reinforcements to be used in those component types of the building structure for lowering emissions.

While the study focuses on the output of integrating GGBS and FA in RMC, one of the most promising ways to lower the demand for resources and reduce the embodied carbon of building structures is to emphasize the environmental analysis of recycled material usage in building construction. Studies focusing on alternative transportation systems for materials and their emission profile comparisons can also be performed to measure the net reduction of the life-cycle environmental impact of building projects, especially for rural projects.

This study focuses on the A1-A5 stages of the building life cycle. These stages are impossible to change after the construction process has taken place, so it is essential to conduct LCA on these phases during the design process in order to integrate the findings in the design decision-making system with stakeholders and relevant regulatory bodies. This analysis will be helpful for designers and regulatory authorities in considering more sustainable decision-making approaches and developing regulatory policies on material selection. Additionally, if more EPD data on locally available traditional and sustainable alternative materials become accessible, a diverse range of design alternatives can be explored.

The impact of alternative materials in the whole life-cycle assessment of the building, emphasizing thermal demands and energy consumption in the operational phase is another potentially significant option for further studies.

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