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ASSESSING THE ENVIRONMENTAL IMPACT OF BUILDING MATERIALS: A LIFE CYCLE APPROACH TO SUSTAINABLE BUILDING SOLUTIONS

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Abstract- Climate change, driven by carbon emissions and greenhouse gases, is a major global challenge. In Pakistan, rapid urbanization and growing construction activities are key contributors to these emissions, further intensifying global warming. Cement production is one of the most emission-intensive processes, making the need for sustainable construction practices critical. This research explores the Life Cycle Assessment (LCA) of building materials used in affordable housing in Pakistan, focusing on identifying eco-friendly alternatives to reduce carbon footprints. Using a single-story residential unit in Peshawar as a case study, this research quantifies the embodied carbon emissions associated with traditional construction materials. Results demonstrate that alternative materials like rammed earth bricks, fly ash, and blast furnace slag significantly reduce carbon emissions compared to conventional materials. Scenario-based analysis shows that up to 70% reductions in carbon emissions are possible by integrating these sustainable materials into construction practices, highlighting the potential for low-carbon affordable housing in Pakistan. This study contributes to the Sustainable Development Goals (SDGs) by providing practical solutions for reducing carbon emissions in the construction industry.

Keywords- Life Cycle Assessment (LCA), Sustainable Construction, Climate Change, Carbon Emissions

1. Introduction

Global climate change, largely driven by carbon emissions and greenhouse gases, has emerged as a pressing challenge worldwide. These emissions, increased by rapid urbanization and the pursuit of higher living standards, have far-reaching consequences such as global warming, glacial melting, ocean acidification, and severe health risks [1]. Carbon emissions, including chlorofluorocarbons (CFCs), also contribute to ozone layer depletion, allowing harmful ultraviolet (UV) rays to reach the Earth, exacerbating environmental and health problems [2].

Building industry is one of the main contributors to the increase in carbon emissions and is a key source of contributing to the degradation of the environment. The growth in human activities for diverse goals has raised the pace of carbon emissions leading to an increase in global warming and increase in the risks of ocean acidification, eutrophication, health difficulties, lower agricultural development [3]. The construction sector is a major contributor to carbon emissions, with cement production being a particularly high-emission process. Cement manufacturing ranks as the third largest industrial source of pollution, releasing over 500,000 tons of sulfur dioxide, nitrogen oxides, and carbon monoxide annually [4].
LCA is a methodology that evaluates the environmental impact of a product or process from raw material extraction through manufacturing, use, and disposal. It provides insights into reducing carbon footprints and enhancing sustainability. The application of LCA in construction can reveal opportunities to minimize the environmental impacts of materials, as demonstrated in studies such as those by Hurt, Franklin, and Bulle [5] [6].

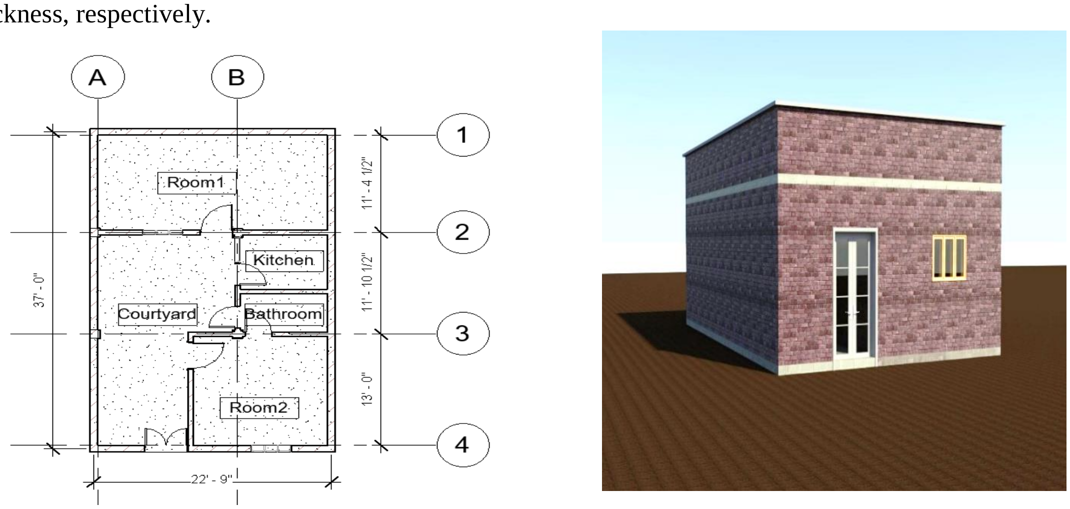
GHG emissions, covering carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), play a vital role in estimating the impact of climate change [7]. LCA provides for the assessment and quantification of these emissions throughout different stages of the product's life cycle. By quantifying these emissions in carbon dioxide equivalents (CO_2e), which accounts for their varying global warming potentials, LCA provides a full evaluation of the carbon footprint and global warming potential of the system under consideration. This enables decision-makers to identify and mitigate the climate change impact associated with the assessed system, supporting the creation of policies to minimize GHG emissions and promote sustainability [8].

Despite its limitations, LCA is a valuable tool for sustainable construction. It enables comparisons of environmental impacts among different materials, promoting sustainable design and innovation. The approach helps reduce carbon emissions, as demonstrated by case studies across Europe and the work of researchers like Brooks, Cho, Na, and Liu, which show significant reductions in emissions through the use of low-carbon materials and construction techniques [9]. To enable an efficient and cost-effective solution, new construction techniques were investigated by various researchers in last decade [10]. Structures consisted of mortar-free interlocking blocks. Mortar-free blocks used in structure played an important role during strong ground motion. These blocks dissipated more energy during seismic event, because of the relative movement at the block interfaces [11].

2. Research Methodology

2.1 Case Study

This research focuses on an Isolated single-story residential building that typifies most residential units in the Peshawar Saddar area, consisting of two bedrooms, one bathroom, a kitchen, and a courtyard, as depicted in Figure 1 . The structure encompasses a total gross area of 68.25 square meters, with exterior and interior walls measuring 0.22 meters and 0.15 meters in thickness, respectively.



a) b)

Figure 1 Residential Building Model Selected a) Plan view b) Three-Dimensional view

The study involves quantifying the amounts of bricks, concrete, mortar, and steel reinforcement used in the structure. These quantities are crucial for evaluating the carbon intensity of the building, thereby facilitating an accurate assessment of its environmental impact and enabling measures to mitigate its carbon footprint. Table 1 presents the estimated volumes of bricks, mortar, concrete, and the total weight of steel used in the building.

Table 1 Quantities of Building Materials Used in the Single-Story Residential Structure

Category	Volume (m^3)	Wet Volume (m^3)	Dry Volume (m^3)
Bricks	46.38	46.38	46.38
Mortar	19.87	19.87	30.61
Concrete	34.14	34.14	52.57
Steel Quantity in Kilograms	2012.1 kg		

2.2 Work Procedure

This research intends to decarbonize the building by introducing alternative low carbon building materials. The approach of the research work contains a series of assessments on different building materials and examines their impact on the environment till the construction phase of the structure. To investigate the materials based on their carbon emissions, ISO (International Organization for standardization) standards belonging to ISO 14000 family of environmental management standards are followed. A systematic and transparent study is provided by ISO 14044's well-defined life cycle assessment (LCA) procedure, which contains several phases: aim and scope, inventory analysis, impact assessment, and interpretation. GHG quantification accuracy is improved by IPCC techniques. The findings are given context and legitimacy when constraints like data uncertainty and boundary settings are acknowledged. [12].

2.3 Data Analysis

To effectively quantify the carbon footprints of materials, it is vital to monitor the energy use throughout the various stages of the material life cycle. The following stages are involved in the calculation of Embodied Carbon from building construction.

2.4 Production Stage(A1-A3)

Carbon emissions during production stage are given in Equation 1. Database for this stage is provided by ICE (Inventory of Carbon and Energy) its version V3.0 – 10Nov, 2019 [13].

$$\text{Total Carbon emissions } (kgCO_2e) = \text{Quantity (kg)} \times \text{Carbon factor } (kgCO_2/kg) \quad (1)$$

2.5 Transportation Stage(A4)

Transportation stage includes carbon emissions from the transportation of building materials from batching plant to the construction site. Carbon emissions during transportation stage are calculated in Equation 2

$$\text{ECF (A4), i} = \sum_{mode}(TD \times Li \times TEF) \qquad (2)$$

Here. TD = Transport Distance, Li = Liters consume per kilometers, TEF = Emission Factors provided by ISO 14064
Table 2 shows carbon intensity factors for transportation Stage and distances of different materials categories from their batching plant to the construction site taken as Peshawar Saddar. The carbon factors for the transportation stage are calculated using the RICS guidelines.

Table 2 Transportation Intensity Factors and Distances for Different Building Materials

Material Category	Distances (km)	A4 ($kgCO_2/kg$)
Bricks	10	0.001
Mortar and Concrete	12	0.0012
Steel Reinforcement	6	0.0006
Distance From Construction site to Disposal Site	12	0.0012

2.6 Construction Stage(A5)

This stage involves carbon emissions from the construction activity of the building. It mainly includes the emissions generated from construction machinery.

2.7 Materials Wastage on site (A5w)

This stage refers to those carbon emissions from the materials that are brought to site but are not used in building construction. Materials wastage on site are calculated in equation 3.

$$\text{ECF (A5w), i} = \text{Wfi (ECF (A1-3i) + ECF (A4i) + ECF (C2i) + ECF (C3-4i))} \qquad (3)$$

Here: Wfi = Waste factor for materials are calculated in equation 4.

$$\text{Which is, WFi} = \frac{1}{1-\text{WRi(waste rate in \%)}} - 1 \qquad (4)$$

Where.

ECF = Embodied Carbon Footprints for

1 Production (A1-3i)
2 Transportation to site (A4i)
3 Transportation away from site (C2i)
4 Waste processing disposal (C3-4i) (According to RICS guide, it is suggested that in the absence of better data, emissions for processing and disposal of the waste material is 0.013 $kgCO_2/kg$ [14])

2.8 Data Analysis

Table 3 provides the carbon emission values for each type of material when multiplied by the specific quantity utilized in a single-story building. The materials used in the research work are readily available from the selected site. They are selected for their applicability and cost-effective substitutes of conventional materials in residential buildings.

Table 3 Data Analysis on Building Materials

No.	Material	Material Quantity (kg)	Total Carbon Factor from A1-A5 ($kgCO_2/kg$)	Total Carbon Emissions (kg)	Total Carbon Emissions (tons)	Percent Reduction (%)
Bricks and Block Masonry Units						
1	Engineering Bricks	69106.2	0.271	18731.24	18.73	--
2	Concrete Blocks	92760	0.121	11228.6	11.23	40.05
3	Rammed Earth Bricks	83484	0.037	3113.953	3.11	83.38
Cement Used in Mortar						
1	General	6294.86	0.878	5525.63	5.52	--
2	Portland Cement	6294.86	0.962	6055.72	6.05	--
3	Blast furnace Cement (88%)	6294.86	0.156	986.70	0.98	82.1
4	Pozzolanic Cement (46%)	6294.86	0.529	3332.36	3.33	39.7
Concrete						
1	General	126181.4	0.111	14067.23	14.06	--
2	Portland Concrete	126181.4	0.121	15262.64	15.26	--
3	30% Replacement by Fly Ash	126181.4	0.098	12340.54	12.34	12.3
4	75% Replacement by Blast Furnace	126181.4	0.054	6894.819	6.89	51
Steel Reinforcement						
1	Steel Rebar	1907.615	2.096	4000	4.00	--
2	Recycled Rebar	1907.615	1.264	2413	2.41	40

3. Results and Discussion

3.1 Bricks and Block Masonry Units

Various types of bricks were compared with traditional engineering bricks. The results of this comparison are illustrated in Table 3. The results highlight that the CO_2 emissions of building materials are directly linked to the energy required for their production and transportation. The more energy-intensive a material is to produce and transport, the higher its carbon footprint [15].

3.2 Mortar and Concrete

Cement contributes significantly more to carbon emissions compared to sand and aggregates used in mortar and concrete [16]. To address this, the results examine the replacement of cement with alternative cementitious materials, such as natural pozzolana, Fly Ash and blast furnace slag as shown in Table 3. Ordinary Portland Cement (OPC) and normal concrete are used as benchmarks, with their CO_2 emissions set at 100% for comparison purposes. Table 3 illustrates that as the proportion of cement replacement increases, carbon emissions decrease, aligning with the findings of Maddalena et al [17].

3.3 Steel Reinforcement

Table 3 illustrates that the use of recycled steel can reduce carbon emissions by approximately 40% compared to virgin steel bars. According to Shaymsteel's research, recycling steel saves up to 74% of the energy required for primary steel production, significantly lowering carbon emissions [18].

3.4 Embodied Carbon Emissions in a Single-Story Unit: Different Scenarios

Three scenarios were developed to assess the embodied carbon emissions of a single-story unit using various building materials, as outlined in Table 4. Each scenario compares the carbon emissions of alternative materials with those of traditional ones.

Scenario 1: Conventional materials such as Portland concrete, Portland cement, steel bars, and engineering bricks are used, resulting in total carbon emissions of 44.05 tons.
Scenario 2: In this case, 30% of the cement used in concrete is replaced with fly ash, 46% of cement used in mortar is replaced with pozzolana, while steel bars and concrete blocks are also used. This reduces the total carbon emissions to 30.90 tons, a 29.85% decrease compared to Scenario 1.
Scenario 3: This scenario employs alternative materials with the highest potential for carbon reduction, including a 75% replacement of cement with blast furnace slag in concrete, an 88% replacement in mortar, recycled steel bars, and rammed earth bricks. Total carbon emissions in this scenario are 13.4 tons, representing a 69.56% reduction compared to Scenario 1.

As shown in Table 4, Scenario 3, which uses the lowest-carbon materials from Table 3, achieves a 70% reduction in embodied carbon compared to conventional materials. These findings are consistent with the research of moghayedi et al., where a similar scenario resulted in a 75% reduction in carbon emissions [19].

Table 4 Embodied Carbon Emissions Comparison from Cradle to Practical Completion Stage

Scenarios	Concrete	Cement used in Mortar	Steel	Bricks	Total Emissions(tons)	Percent Reduction
Conventional Materials	Portland Concrete	Portland Cement	Steel bars	Engineering Bricks	44.05	--
Alternative Materials case II	30% replacement of cementitious materials with Fly Ash	46% Cement Replacement by Pozzolana	Steel bars	Concrete Block	30.90	29.85
Alternative Materials Case III	75% Replacement of cement by blast furnace slag	88% Replacement of Cement by Blast Furnace	Recycled Steel bars	Rammed Earth Bricks	13.4	69.56

4. Conclusions

The findings of this study underscore the critical role that material selection plays in reducing carbon emissions in the construction sector, particularly for affordable housing in Pakistan. By applying the Life Cycle Assessment (LCA) methodology, this research has identified that traditional materials, such as Portland cement and engineering bricks, are significant contributors to carbon emissions. In contrast, alternative materials like rammed earth bricks, fly ash, and blast furnace slag offer substantial carbon savings without compromising structural integrity. Because building data are limited, carbon factors have been assumed, especially for the C3–C4 incineration phase and can marginally influence outcomes.

The absence of consideration for doors, windows, and frames may have affected total emissions. However, the study's primary goal "material comparison" remains unaltered. The scenario analysis revealed that adopting these low-carbon materials can reduce embodied carbon by as much as 70%, contributing to both environmental sustainability and cost-effectiveness. As Pakistan faces rising urbanization and increasing housing deficits, transitioning to sustainable building materials is imperative for mitigating climate change impacts. Future policies and construction practices should prioritize the use of low-carbon alternatives to foster sustainable development and resilience against climate challenges.

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