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Environmental Performance Assessment: Life Cycle Assessment for Energy and Emissions of Reinforced Cement Stabilized Rammed Earth Residential Buildings in Nepal

Shrijan Basnet [a], Sushil Bahadur Bajracharya [b]

[a, b] *Department of Architecture, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] 078mseeb015.Shrijan@ioe.edu.np, [b] Sushil_bajracharya@ioe.edu.np

Abstract

Residential buildings primarily consume energy during their construction. In such structures, the operational energy is relatively low compared to the embodied energy. The objective of this study is to enhance understanding of energy and emissions in reinforced cement stabilized rammed earth (CSRE) residential buildings. The research evaluates the life cycle energy and emissions of the building from cradle to gate, in accordance with the guidelines established by ISO 14040 and ISO 14044 standards. The study presents the construction process, the materials utilized, and offers suggestions for future improvements to the structure's environmental performance. The research applies IFC 2017, ICE 2011, and IPCC 2018 standard data to determine the embodied energy. The environmental impacts are assessed based on ozone depletion potential (ODP), eutrophication potential (EP), acidification potential (AP), and photochemical ozone creation potential (POCP). The life cycle energy from cradle to gate of the studied Reinforced Cement Stabilized Rammed Earth (CSRE) Walls is 0.57 MJ/kg, and the life cycle energy from cradle to gate of the studied building is 3.5 GJ/m^2. Similarly, the life cycle carbon emission from cradle to gate for the walls is 0.059 kg/kg CO_2 eq., and that of the overall building is 0.33 T/m^2. The high thermal mass of the rammed earth wall minimizes the fluctuation of indoor air temperature compared to the outdoor temperature and maintains almost constant indoor humidity. The environmental performance of the structure in terms of energy and emissions is better than that of a that of a brick-masonry structure. Replacing reinforced CSRE walls with 10-inch brick masonry walls (in cement mortar 1:4) would increase the life cycle energy by 43.6%. and emission by 41%. The environmental performance of the structure can be improved by substituting the aluminum frame used in the doors and windows with a wooden frame. Replacing aluminum with wood used in doors and window frames can reduce life-cycle energy by 5.5% and carbon emissions by 16.8%. Based on the environmental performance of the structure, Reinforced CSRE is a suitable choice for the construction of residential buildings.

Keywords

Life Cycle Assessment, Rammed Earth, Energy, Emission, Impact Assessment, Sustainability

1. Introduction

It is known that the development of humanity began with the discovery of fire. This source of energy, which could only be created by humans, was primarily used for heating and lighting. Over time, humans gained the ability to transform one form of energy into another for a variety of applications. Unfortunately, this has led to an accelerating demand for global energy, exacerbating the energy crisis and environmental pollution [1]. Sustainability and energy efficiency are different terms but they are somehow related in terms of building. The global building classification systems classifies building based on different parameters which includes energy efficiency as on of the parameter.

The building practices in Nepal have shifted from sustainable, climate-resilient structures to those made primarily of brick. These vernacular houses, built by different communities, were more environmentally friendly and had lower initial costs. However, the widespread use of brick in modern housing construction has led to the emissions of significant amounts of carbon dioxide from the 1600 brick kilns in Nepal, which consume approximately one million tons of coal annually. These emissions account for 37% of the country's total carbon dioxide emissions [2]. As the standard of living improves, it is expected that there will be increased pressure on the environment, as evidenced by current trends. [3]. Building sector shares a huge share in terms of the overall energy consumption and carbon emission and can offer significant global mitigation potential for the increased carbon emission [4]. Building construction and operation are responsible for 30% of the global final consumption and are responsible for 27% of the total energy sector emission [5]. As the global contribution to the total energy used, total carbon emission and pollution from the building is high, adoption to sustainable and energy efficient measures during the construction phase can be an effective solution to different environmental problems [4].

Nepal has a very low level of urbanization, although in recent years, growth has been extremely rapid. Despite of the lack of proper urban amenities, the urban population of Nepal has reached to 66.08% by 2012 [6]. However, the growth is dynamic in recent years, energy consumption from the construction sector has increased by 25.08% in the fiscal year 2078/79 BS [7]. With this shift, the Reinforced Cement Concrete with brick masonry has become a favorable choice for the construction of residential building. The construction materials used in this type of structure has high embodied energy and emission, due to which the constructions practices are becoming less and less sustainable. This study emphasizes the importance of choosing sustainable alternatives (Rammed Earth Construction) which could potentially become an immediate replacement to the ongoing construction practice. This study highlights the growing need of life cycle assessment and Environment Product Declarations (EPDs) in the construction industry as a holistic comparison is essential for the policymakers for the building practices in the country.

Rammed earth construction is one such approach that utilizes local materials and has a lower environmental impact, as it consumes less energy and has lower emissions [3]. This article will conduct a life cycle assessment of various construction materials used in rammed earth residential buildings in Nepal.

2. Literature Review

2.1 Life cycle assessment

Life cycle assessment of a product can describe the entire processes the product goes through at various stages of its life [8]. It is classified into three stages which are manufacturing stage, product usage stage and its end of life stages.

The manufacturing stage starts with the raw material extraction process. First all the resources that are required for the product's manufacture are listed. For example: In the manufacture of instant noodles, popular in the country, the raw materials required are wheat, vegetable oil, spices, plastic, etc. The processes involved in the extraction of raw materials are studied and are taken for the study.

The second stage of the product is its operation stage. It studies the usage of product throughout its life. For example: A mobile phone consumes electricity for its operation and is used for multiple purposes. The input and output are closely monitored and the relevant data required for the study are noted. The repair and maintenance required during its operation are also studied.

The final stage is its end of life stage where the process involved to dismantle and dispose of the product is studied. The life cycle assessment is a detailed study of a product. The life cycle assessment (LCA) of buildings is a growing research area due to the increasing concern for sustainability and the impact of buildings on the environment.

Various studies on the life cycle of different products provide us the knowledge on the sustainability and environmental impacts from the product. . Stone, a traditional construction material, is studied for its properties. The study on the environmental impact of stone quarries showed that the environmental impact of stone production can be improved by the use of renewables [9]. Bamboo is a fast-growing and renewable material that is gaining popularity as a construction material due to its strength, flexibility, and sustainability and the mechanical characteristics could be improved by adding natural fiber or nanoparticles [10]. Based on the life cycle it can be said that inorganic cellulose is the insulation material with least environmental impact [11]. The operational energy consumption of buildings has also been widely studied. For example: In Greece, the 25% of the non-residential building are responsible for the 80% overall emission from residential sector [12]. The passive design strategies like natural ventilation, shading and day lighting would significantly reduce energy consumption [13].

The environment impact assessment of bamboo showed that the environmental impact in terms of greenhouse gas emissions and energy consumption was very less for the bamboo [14]. On investigating the end of life stage, recycled materials are found to produce less emission than in the sanitary landfill [15]. In similar study, the environmental impact of different end-of-life scenarios for a building, deconstruction and recycling had the lowest environmental impact [16].

2.1.1 Standards for life cycle assessment

ISO 14040 and ISO 14044: These are the foundational standards for life cycle assessment. ISO 14040 provides the framework and principles for conducting LCA, while ISO 14044 outlines the specific requirements and guidelines for performing LCA studies.

The life cycle framework is composed of 4 steps [17]:

1. Goal and Scope Definition
2. Inventory analysis
3. Impact Assessment
4. Interpretation

2.2 Alternate Construction Materials

Most of the houses in Nepal are of mud mortar with cement or brick [18]. This is the conventional construction system of Nepal. The housing system is slowly shifting to RCC buildings. Alternate construction materials like CSEB block, interlocking blocks, etc. are gaining attention in the recent years as they have the potential to reduce the environmental impact of construction and improve building resiliency. These materials are widely used by the National Reconstruction Authority for the construction of shelter for the earthquake victims. The main reason behind is the easiness to build a low cost housing structure and the usage of local material that makes the construction easy. One of the most widely used renewable materials in construction is wood. Numerous researches have looked into the mechanical qualities, longevity, and environmental effects of using wood in construction. And found out the mechanical properties of cross-laminated timber were found to be good, including high stiffness and strength [19]. The environmental impact of wood construction is significantly lower environmental impact compared to concrete and steel construction [20]. There is a growing need for the impact evaluation of different alternate construction in the construction industry.

2.3 Energy Use Scenario

Energy consumption worldwide has increased steadily since the start of the Industrial Revolution. The globe utilizes a tremendous amount of energy, with fossil fuels accounting for a large portion of that energy [24]. Energy supplies are not equally accessible, and global energy usage varies greatly. It appears that countries' energy consumption rises as their economies improve. A nation's economy is significantly

Table 1: Energy and Carbon inventory based on various literature [21, 22, 23]

S.N	Material	Embodied Energy (MJ/kg)	CO_2 emission (Kg CO_2 eq./Kg)	Source
1	Aggregate (Crusher)	0.11	0.009	IFC,2017
2	Brick (High Draught Zig zag Kiln)	6.5	0.59	IFC,2017
3	Glass (Toughened)	15	0.85	ICE,2011
4	Aluminum Section for Doors and Window	280	26	IFC,2017
5	Reinforcement Steel	30	2.6	IFC,2017
6	Plastic Formwork (ABS)*	15.88	3.1	ICE,2011
7	Timber (Frame)	63	2.4	IFC,2017
8	Timber (Flooring)	64	1.5	IFC,2017
9	Lime	5.5	0.74	ICE,2011
10	Plywood Formwork*	3	-0.31	IFC,2017
11	OPC Cement	6.4	0.91	IFC,2017
12	Sand (Crusher)	0.11	0.009	IFC,2017
13	Ceramics	10	0.65	ICE,2011
14	Recycled Clay tile	4.665	0.69	IFC,2017
15	Paint (One Coat)	10.2	0.53	ICE,2011
16	Paint (Double Coat)	20.4	1.06	
17	Diesel	42.5	2.945	IPCC,2018
18	Stone	0.11	0.009	IFC,2017
19	LPG	46.1	1.106	IPCC,2018
20	Hydroelectricity	(In KWh)	24	gCO_2 eq/KWH
21	Steel Section	30	2.5	IFC,2017

(*Can be used up to 6 times*)

impacted by the availability of energy. For some industries to thrive, nations must offer firms affordable, dependable energy. According to the International Energy Agency (IEA), the richest countries in the world of around 1 billion people consume 50% of the world's energy, while the poorest 20% consume only 4% [25]. Over the past few decades, energy use in buildings has skyrocketed. People are spending more time indoors as a result of population growth and a technologically oriented society, which has boosted demand for indoor environmental quality and building functions. "Building energy use currently accounts for over 40% of total primary energy consumption in the U.S. and European Union" [26]. However, if buildings are correctly designed, built, and operated, significant energy savings can be realized. Due to the substantial threat that energy shortages, carbon emissions, and their effects on our living environment pose, building energy efficiency can offer important solutions. Nepal's per capita electricity consumption is increasing dramatically but due to the improvement of energy effective technology in residential sector, its share is on a decreasing fashion.

2.4 Role of buildings in global and national energy use

Every phase of a building's life cycle results in varying degrees of energy use. Construction uses around 50% to 60% of all non-renewable resources, including water, energy, and raw materials [27]. Due of its energy usage, construction has a significant negative influence on the environment. For instance, a sizable portion of this consumption goes toward building materials. Energy is also used extensively in the transportation of the bulk of the goods [28]. Due to urbanization and population growth, energy consumption is rising quickly. Depending on the climate, kind of home, and degree of development, different regions have different requirements for residential energy. 30-40% of the energy utilized worldwide is used for construction operations each year [29]. Building energy use and its potential negative effects on the environment are subjects of rising concern.

2.5 Energy and Carbon Inventory

There are multiple datasets available in the market for the evaluation of embodied energy and carbon from various construction materials. Table 1 represents the embodied energy coefficient factor for energy and carbon emission from various datasets.

2.6 Impact assessment

The input of the LCA includes material resources and energy resources utilized for the manufacture, usage and disposal of the product. The output of LCA is the emission of various gases to the atmosphere. As emission of different gases can be measured separately, these gases can be classified into different impact categories based on the impacts on the environment as described by ISO 14044:2006. The impact category results for the materials contained in the India Construction Materials Database include the ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone formation potential (POCP, also known as smog creation potential). Table 2 represents the emission of various gases and evaluated in terms of impact. CML-IA version 4.1, as applied to EN 15804, serve as the foundation for these indicators [21]. Ozone Depletion Potential (ODP): This indicator indicates the depletion of stratospheric ozone and is measured in terms of Kg CFC-11 equivalent. Acidification Potential (AP): This indicates the acidification in soil and water and is measured in terms of Kg SO_2 equivalent. Eutrophication Potential (EP): This indicates the potential to over fertilize plants and soil due to excess of nutrients. It is measured in terms of Kg PO4 equivalent. Photochemical Ozone Creation Potential (POCP):

Table 2: impact category and its measurement [21]

S.N	Material Name	ODP (kg R11 eq.)	AP (kg SO_2 eq.)	EP (kg PO_4 eq.)	POCP (kg ethene eq.)
1	Aggregate (mixed gravel/crushed stone)	1.20E-13	0.000094	8.80E-06	6.90E-06
2	Air-dried sawn timber	4.80E-12	0.0035	3.10E-04	1.60E-04
3	Aluminum extruded profile (window frame)	8.90E-11	0.29	1.70E-02	1.40E-02
4	BOF Steel	5.70E-12	0.0073	4.80E-04	4.30E-04
5	Brick - High draught/zigzag kiln	4.30E-13	0.005	3.50E-04	2.20E-04
6	Cement (ordinary Portland cement, OPC)	2.80E-12	0.0027	3.40E-04	1.90E-04
7	Clay roof tile	5.00E-12	0.0063	3.80E-04	2.70E-04
8	DRI Steel	1.20E-11	0.0066	4.40E-04	3.80E-04
9	EAF Steel	1.50E-11	0.0087	4.00E-04	4.70E-04
10	Electrogalvanized steel sheet (“corrugated zinc”)	2.50E-11	0.017	9.20E-04	9.70E-04
11	Galvanized steel stud	2.70E-11	0.018	9.80E-04	1.00E-03
12	Plywood	2.20E-11	0.0044	8.00E-04	8.90E-04
13	Sand	1.20E-13	0.000094	8.80E-06	6.90E-06
14	Steel reinforcement (steel rebar)	1.50E-11	0.011	6.50E-04	6.10E-04
15	Steel section	1.50E-11	0.012	6.70E-04	6.30E-04
16	Timber window frame	5.50E-11	0.041	2.60E-03	4.50E-03
17	Wood block flooring	5.90E-11	0.027	1.90E-03	1.60E-03

It indicates the potential of formation of tropospheric ozone and is measured in terms of Kg ethene equivalent.

3. Research Methodology

3.1 Conceptual Framework

The conceptual framework used in the study can be seen in Figure 1. Background research is required for the selection of cases for conducting a life-cycle assessment of buildings. The various phases of the life cycle are studied for the inventory analysis, as suggested by ISO 14040.

3.1.1 Background research

A comprehensive review of existing literature on life cycle assessment (LCA) buildings, including studies conducted in national, regional, and international contexts, is done in order to gain a deeper understanding of the current state of knowledge on the topic. Different rammed earth building types are reviewed, and the buildings suitable for the study are analyzed. Many cases of earth construction practice used in the construction of residential buildings in Nepal were reviewed.

Sustainable Future Nepal is a private construction company involved in multiple projects involving rammed earth construction in the country. There are many cement-stabilized structures constructed by the company that were mostly used for institutional or commercial purposes. The building with sufficient living space, structural soundness, good aesthetics, and a modern design were the selection criteria for the study. Three buildings were chosen, and one of them was discovered to be in its operating phase, meeting the aforementioned requirements.

3.1.2 Research Design

A case study research design is employed to assess the current state of rammed earth construction in Nepal. The study utilizes a quantitative method to provide a comprehensive understanding of the life cycle of the building under study. The main source of data is the questionnaire survey with the key informants, along with the site inspection.

A total of 14 respondents were interviewed for the survey, which included 6 technical experts working on sustainable construction practices, including a contractor, two consultants (an architect and an engineer), a design engineer, and a site supervisor, to gain knowledge on the current state of rammed earth construction and its practices in Nepal. The non-technical expert included 3 respondents for the thermal comfort survey and 6 construction workers involved in the construction of the rammed earth building.

3.2 Research Method

This section outlines the framework as suggested by ISO 14040:2006.

3.2.1 Goal and Scope Definition

The objective of this research is to assess the Life Cycle Assessment of the Reinforced Concrete Residential Building in Nepal. The study evaluates quantities based on the standard building norms of the country, considering only the major construction materials used. The life cycle phase under examination is limited to the current phase of building construction. Since no Environmental Product Declarations (EPDs) are available for knowledge on energy and emission parameters, coefficients for embodied energy and emissions are derived from various standard datasets. Energy and emissions are calculated based on the quantities used. The study presents different scenarios of material substitution and compares them based on energy and emissions per square meter of the common floor area. The impacts of material substitution on the construction are also evaluated and compared.

3.2.2 Inventory Analysis

The primary sources of data utilized in this study are site inspections and questionnaire surveys of relevant

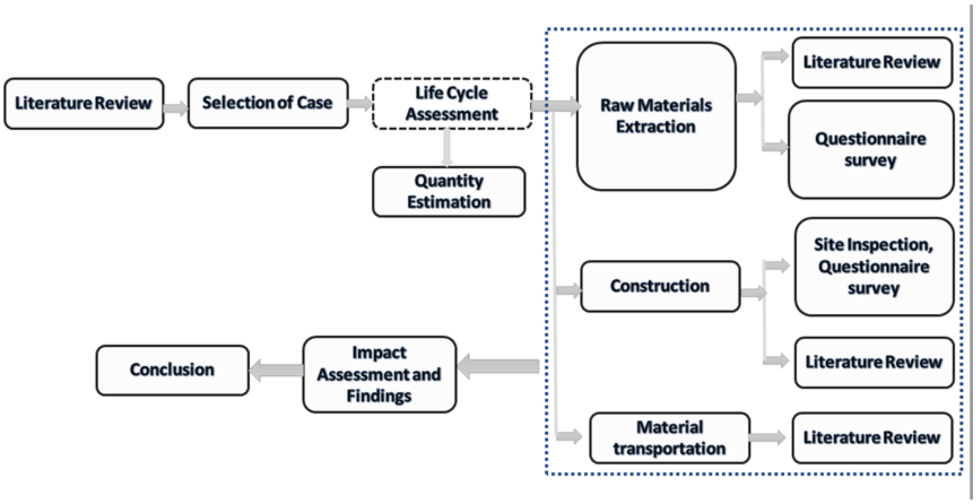

Figure 1: Conceptual Framework

stakeholders. An inventory of construction materials is assessed through an examination of design drawings and on-site measurements. While the energy mix in Nepal and India differs, a majority of the technology used in Nepal is imported from India. The Indian Construction Material database has been deemed suitable for evaluating embodied energy and emissions (as evidenced by Tables 1 and 2).

To address any missing data in the dataset, the ICE database (a globally recognized standard) and the IPCC database (which provides an inventory of energy and emissions from various types of fuels) are employed. The transportation distance is estimated using Google Earth, and the type of transportation vehicle used is based on the findings of Kurian (2021). The manpower utilized in construction is calculated in accordance with the Standard Building Code.

To evaluate the thermal performance of the building, a structured questionnaire is developed for occupants residing in the building, in addition to field measurements of indoor and outdoor temperature and humidity using a data logger. The questionnaire is administered through the Kobo Collect platform.

3.2.3 Impact assessment

The impacts to the environment is studied for the life cycle energy and emission from various construction material. Impacts are evaluated through four indicators which are Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Depletion Potential (POCP).

3.2.4 Interpretation

The total energy and the total CO_2 emission from different construction materials is studied and the areas for the improvement are recommended. Comparisons were made for the various construction materials involving the energy and emission from different construction materials. The study is accompanied by material substitution recommending the best design in terms of energy and emission.

4. Study Area

4.1 Background

The research was conducted on a residential property located in Godawari Municipality, Godawari, which was constructed by Sustainable Future Nepal and designed by Baha Spatial Agency. Mr. Basanta Shrestha owned the property, and the construction commenced in 2021, with completion in 2022. The building is currently in its operational stage and is situated 11 kilometers away from Kathmandu, as depicted in Figure 2.

The building selected for the study was found to be suitable for the purpose. It was constructed in 2022 and had been occupied for a period of six months. The design of the building was carried out by Architect Saurav Shrestha, and it featured an optimal orientation for solar gain, with the ceiling made of recycled materials that were sustainable in nature. The building provided adequate living space for its occupants.

Limited information was available for the study as the building was still in its operational stage. The research was restricted to obtaining information about the building's size and construction materials. The construction process of the building was studied through a separate project carried out by the same contractor. However, the study did not cover the building's cradle-to-grave lifecycle, and no information was available about its operation and end-of-life stage.

Figure 2: Reinforced Cement Stabilized Rammed Earth building at Godawari

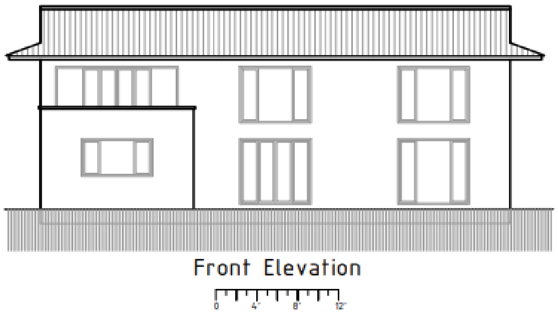

Figure 3: Front Elevation of the building

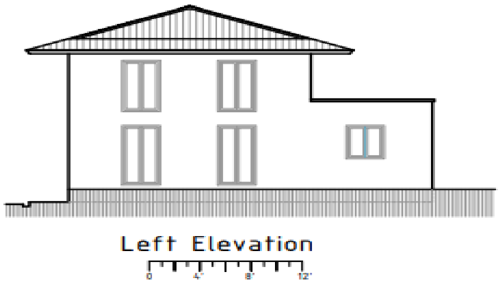

Figure 4: Left elevation of the building

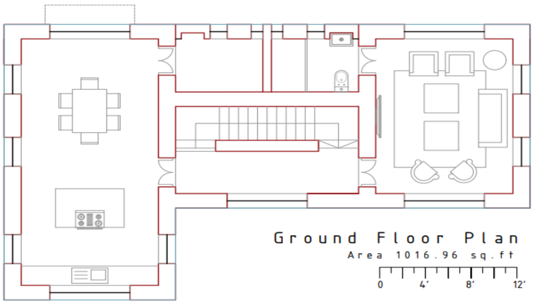

Figure 5: Ground Floor Plan of the building

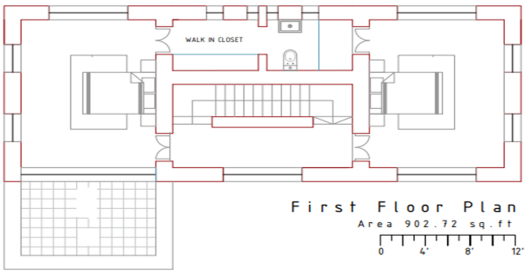

Figure 6: First Floor plan of the building

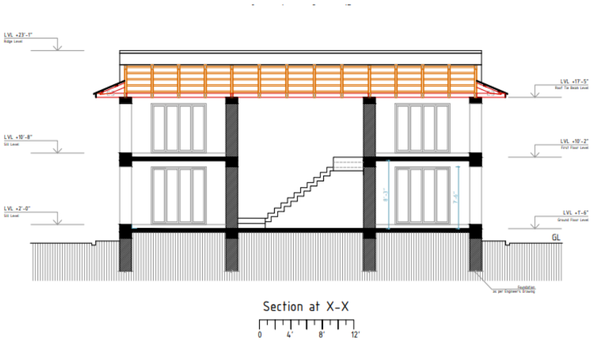

Figure 7: Longitudinal section of the building of the building

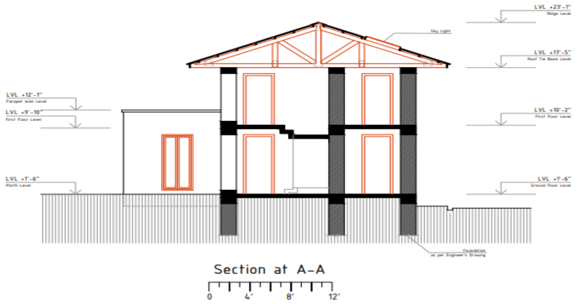

Figure 8: Cross section of the building of the building

4.2 Data collection

The findings of the questionnaire survey and site inspection unveiled the construction process of rammed earth walls and the different stages involved in building construction. The subsequent sections outline the stages associated with the construction of rammed earth walls.

Raw material extraction: The suitability of the earth at the construction site was adequate for the building process. The excavation process utilized a 1-ton excavator with a capacity of 0.63 m^3 that operated for 6 hours each day. The rest of the excavation was carried out by manual labor. Sand, stone dust, and aggregates were sourced from the nearby Rossi River. The 43-grade Shivam OPC cement, procured from the nearby Hardware store manufactured in Hetauda, Nepal. The stone dust, sand, and aggregates were processed through a crusher. The reinforcement steel were imported from Birgunj, Nepal.

Soil Drying: The soil was sun-dried for at least 3 days, depending on its moisture content. The moisture level was assessed through visual inspection of its adhesiveness during sieving. The soil required for ramming needed to be in a powdered form.

Soil Sieving: Soil sieving was carried out manually by laborers. The dried soil was sifted through a 4.75 mm sieve. Approximately 40% of the soil was retained on the sieve and processed through a 3KW corn grinding machine with a capacity of 50Kg/hour. The sieved soil was stored in a dry place to prevent moisture transfer. Figure 9 illustrates the soil drying and sieving process at the site.

Figure 9: Soil Drying and Sieving

Soil mixing: Soil mixing is done by manual labor operation where all the constituents are thoroughly mixed through shovel as seen in figure 10. This process could be replaced by concrete mixing equipment for the energy evaluation.

Figure 10: Mixing the rammed earth mixture manually

Soil Ramming: The formwork is adjusted to a height of 150 mm. the thickness of the wall is 450mm the mixture is rammed layer to layer through manual labor using Hardened rubber mallet hammers as seen in figure 11.

Figure 11: Ramming the Mixture

The major the construction components involved:

Construction of foundation: Load bearing walls are used as the structural component in the system. The process of construction of foundation includes site excavation, Laying 6 inches stone soling with 3 inches PCC. A lower tie beam connects the entire foundation which is connected to the plinth beam through reinforcement bars.

Construction of beams: Beam depth of 1 feet is then constructed of concrete of mix 1:1.5:3. The reinforcement in the rammed earth wall functions as a shear wall interconnected to beams which transmits the load to the foundation. tie beam of 8 inches ties the upper floor walls and ceiling and is connected to the first floor via 14 inches beam. Both the ground floor beam and the floor beam are of 14 inches.

Construction of roof slab: A wooden joist is interconnected to the floor beam and wooden flooring is laid over the surface.

Figure 12: Wood works for flooring

Construction of roof: Steel Truss frame is used for the construction of roof. The roof is connected to the building through 18 inches roof beam tied through steel brackets. Clay tiles are used as the roofing elements. These tiles are reused materials with lower environmental impacts.

Finishing Works: Finishing works in the rammed earth wall is far easier compared to other façades. Two coats of Linseed oil paint is applied over the surface as wall finish as shown in figure 13.

Figure 13: Applying Linseed oil finish at the walls

4.2.1 Primary Data

The primary construction activities and their corresponding materials are detailed in Table 4. This table provides a comprehensive list of the major construction works involved in the building's construction. Table 3 outlines the material composition and standard density employed in the construction of the rammed earth wall. The mass proportion of various materials utilized in the building's construction is illustrated in Figure 14. A total of 15 different construction materials were examined to determine their life cycle.

The construction of the rammed earth wall is a low-tech, labor-intensive process. The sources of construction materials were determined through a questionnaire survey, and the distances were approximated using Google Earth. The transportation of materials was considered from two different perspectives. For the thermal comfort analysis, temperature and humidity data loggers were installed at the site, as shown in Figures 15, 16, and 17. The loggers were in place for seven days to assess the variation in indoor and outdoor temperature. Internal temperatures were measured at different heights (0.1m and 1.5m) for this purpose. Additionally, a questionnaire survey was conducted among the building's occupants.

Table 3: Rammed earth Proportion used in the construction

S.N	Materials	Percentage composition	Density (Kg/m3)
1	Red Mud	35%	2640
2	Stone Dust	40%	1680
3	Sand	5%	1600
4	Cement	5%	1440
5	Aggregates	15%	1525

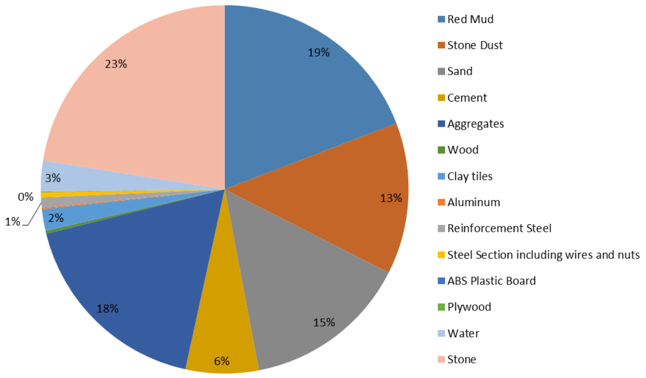

Figure 14: Mass flow diagram of the materials for the construction of Reinforced CSRE

Figure 15: Measurement of internal temperature at 0.1m height

Figure 16: Measurement of Outdoor Temperature

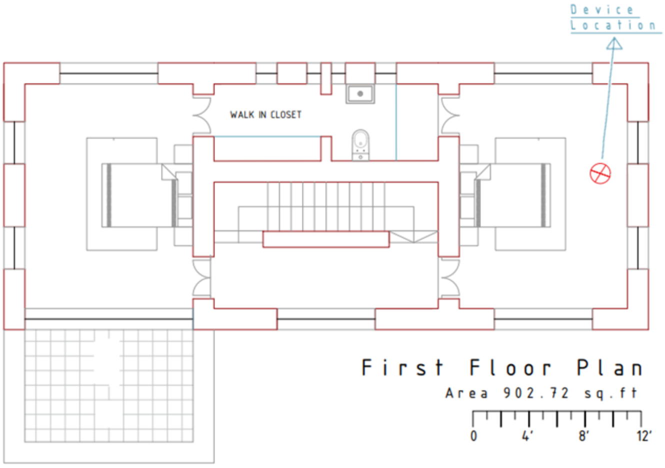

Figure 17: Device Location in the building

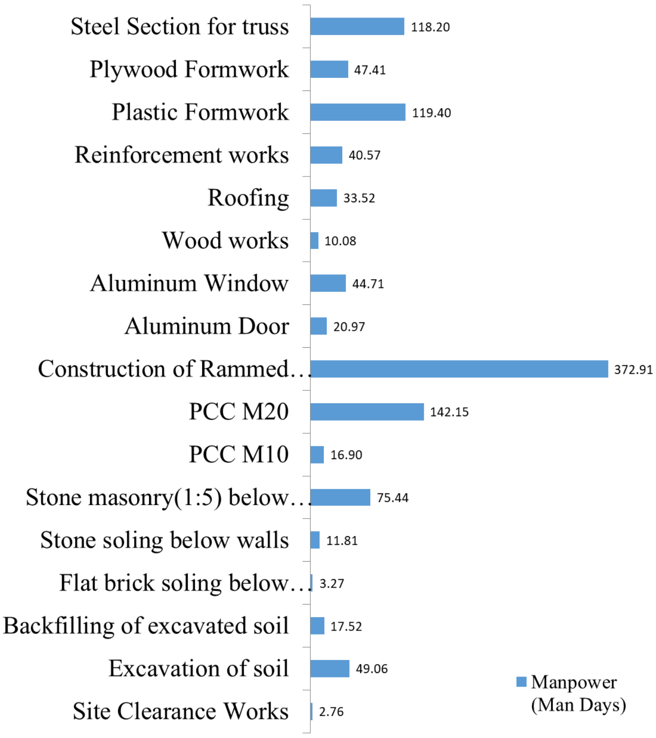

Figure 18: Man Power distribution for the construction of rammed earth building

Table 4: Measurement of Quantity of works used in the construction

SN	Description of Items	Unit	Total quantity
1	Site Clearance Works	Sq.m	119.80
2	Excavation of soil	Cu.m	70.08
3	Backfilling of excavated soil	Cum	35.04
4	Flat brick soling below foundation footings	Sq.m	5.95
5	Stone soling below walls	Cum	7.87
6	Stone masonry(1:5) below foundation walls	Cum	37.72
7	Providing and laying plain cement concrete M10 (1:3:6) using ordinary portland cement, sand and coarse aggregates for foundation footing	Cu.m	3.38
8	Providing and laying plain cement concrete M20(1:1.5:3) using ordinary portland cement, sand and coarse aggregates for beams and slabs	Cu.m	35.54
9	Construction of Rammed Earth walls	Cu.m	71.03
10	Fixing of Aluminium Section casement doors (Double Panel) in the section of 102x45x1.5mm	Sq.m	30.19
11	Supplying and fitting double PANEL window and Ventilation with sash (6'x5' area normally)	Sq.m	44.41
12	Providing well seasoned Sal wood for flooring with good finish of approved quality including fixing in position with necessary Strainers	Sq.m	62.97
13	Providing and placing Recycled Clay tiles for roofing	Sq.m	134.08
14	Providing, straightening, cleaning, cutting, fabricating, bending and placing Tor steel (Fe 500) Or TMT for stirrups & tie or includding 10% wastage for main reinforcement bars and binding the bars with 18 gauge annealed wire	KG	3120.89
15	Formwork centering & shuttering with hard plastic at any level with necessary steel propping, scaffolding, staging, supporting, cutting holes for utilization works etc.including providing final surface and oil & removal of forms	Sq.m	278.32
16	Formwork centering & shuttering with approved material such as shuttering Ply wood & at any level with necessary steel propping, scaffolding, staging, supporting, cutting holes for utilization works etc.including providing final surface and oil & removal of forms	Sq.m	110.51
17	Supply and installation of Steel Sections for truss	KG	1525.00

Table 5: Norms for the analysis of quantity used in rammed earth based on NBC

Construction of Rammed Earth walls all job complete						**Cum**
Source: NBC	Item of Works	Qty	Unit	Quantity of work	Total	Remarks
Norms for 1 Cum						
Labour	Unskilled Labour(Jayami)	0.75	No.	71.03	53.27	Ramming
	Skilled Labour(Sipalu)	0.5	No.	71.03	35.52	Mixing & Placing
	Unskilled Labour(Jayami)	3.5	No.	71.03	248.61	Mixing & Placing
	Unskilled Labour(Jayami)	0.5	No.	71.03	35.52	Seiving
Materials	Red Mud	0.38885	Cum	71.03	27.62	
	Stone Dust	0.4242	Cum	71.03	30.13	
	Sand	0.053025	Cum	71.03	3.77	
	Cement	76.356	KG	71.03	5423.61	
	Aggregates	0.14847	Cum	71.03	10.55	
Machines	Corn Grinder	3	Hr	71.03	213.09	Q/A (Electricity)

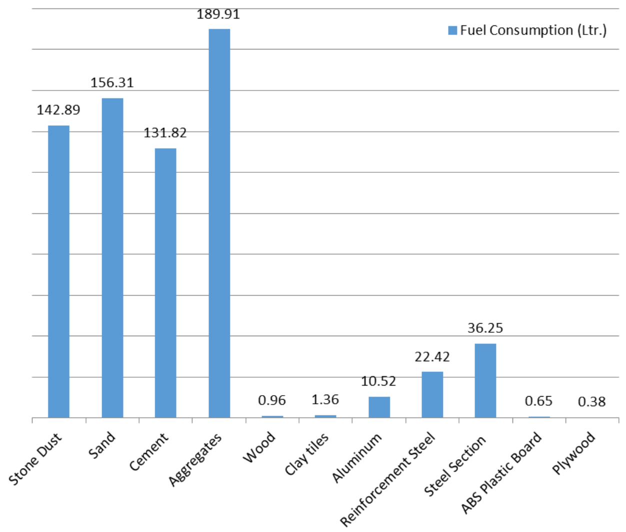

Figure 19: Fuel consumption for the transportation of various materials

Secondary Data: Relevant literature, reports, and existing studies on life cycle assessment, building materials, and design strategies are reviewed to inform the research and establish a knowledge base. The secondary data used is the inventory database for the embodied energy and emission as shown in table 1 and 2. There are two types of vehicles taken for the study i.e Light Duty Vehicle (LDV of capacity 1250 Kg) and Medium Duty Vehicle (MDV of capacity 8102 Kg) [30]. The number of trips is based on the type of vehicle used and the quantity of material required at the site. For the quantity of work, the manpower required are estimated through the standard building norms.

5. Discussion and Findings

5.1 Energy and Carbon Emission of Rammed Earth Wall

A total of six materials were utilized for the construction of rammed earth wall. The mass distribution of the construction materials can be seen in table 6. The life cycle energy from its cradle to gate is calculated using the formula:

$$E_{LCE_r} = E_{E_r} + E_{T_r} + E_{C_r}$$

$E_{\mathbf{LCE}_r}$: Life Cycle Energy of Reinforced CSRE walls.
$E_{\mathbf{E}_r}$: Embodied Energy from construction materials used in Reinforced CSRE walls.
$E_{\mathbf{T}_r}$: Transportation energy used for material transportation of Reinforced CSRE walls.
$E_{\mathbf{C}_r}$: Construction energy used in the construction of Reinforced CSRE walls.

The embodied energy from construction materials is calculated using the formula

$$E_{\mathrm{E}_r} = \sum_{i=1}^{n} M_i e_i$$

Where,

M_i= Mass of individual material (in Kg)

e_i= Embodied energy of the material ($Table1$) (in MJ/Kg)

The transportation energy for the transportation of material construction materials is calculated using the formula

$$E_{\mathrm{T}_r} = \sum M_j e_j$$

Where,

M_j= total mass of fuel used for the transportation of materials (in Kg)

e_j= Energy coefficient of the fuel ($Table1$) (in MJ/Kg)

The construction energy is calculated by estimating energy consumed by the man power and equipment used in the construction.

$$E_{\mathrm{C}_r} = \sum M_m.T.e_m + \sum M_e.e_e$$

Where,

M_m= total manpower used (in mandays)

T= Working time in a day (Hour)

e_m= Energy dissipation by normal human body (Watt)

Similarly for the carbon emission

$$C_{LCE_r} = C_{E_r} + C_{T_r} + C_{C_r}$$

$C_{\mathbf{LCE}_r}$: Life Cycle Energy of Reinforced CSRE walls.

$C_{\mathbf{E}_r}$: Embodied Carbon Emission from construction materials used in Reinforced CSRE walls.

$C_{\mathbf{T}_r}$: Embodied carbon from the material transportation of the Reinforced CSRE walls.

$C_{\mathbf{C}_r}$: Construction carbon emission for the construction of Reinforced CSRE walls.

The embodied carbon emission from construction materials is calculated using the formula

$$E_{\mathrm{E}_r} = \sum_{i=1}^{n} M_i e_i$$

Where,

M_i= Mass of individual material (in Kg)

e_i= Embodied carbon emission coefficient of the material ($Table1$) (in kg/Kg)

The transportation carbon emission for the transportation of material construction materials is calculated using the formula

$$E_{\mathrm{T}_r} = \sum M_j e_j$$

Where,

M_j= total mass of fuel used for the transportation of materials (in Kg)

e_j= Carbon emission coefficient of the fuel ($Table1$) (in kg/Kg)

Similarly, the construction emission is calculated by estimating fuel used in the operation.

$$C_{\mathrm{C}_r} = \sum M_e.e_e$$

Where,

M_e= total Fuel used by equipment

e_e= Carbon emission coefficient of fuel

Table 6: Energy and emission of Rammed Earth wall used as facade

S. N.	Materials	Total quantity used (Kg)	Total embodied energy (MJ)	Total carbon emission (KG)
1	Red Mud (Excavation Energy)	72917.44	442.85	26.08
2	Stone Dust	50620.37	5568.24	455.58
3	Sand	6026.23	662.88	54.23
4	Cement	5423.61	34711.11	4935.48
5	Aggregates	16082.51	1769.08	144.74
6	Reinforcement Steel	1314.04	39421.11	3416.50
	Total	152384.21	82575.28	9032.63

5.2 Life Cycle Energy and Emission

The cradle to gate stage in the life cycle assessment does not consider the operation stage and end of life stage . The life cycle energy is the sum of all the energy required in the process.Embodied energy and emission from various material in composition can be seen in figure 20 and figure 21 respectively.The energy and and emission are determined in a similar manner as above. Table 7 shows the overall energy and emission from the construction of Reinforced CSRE.

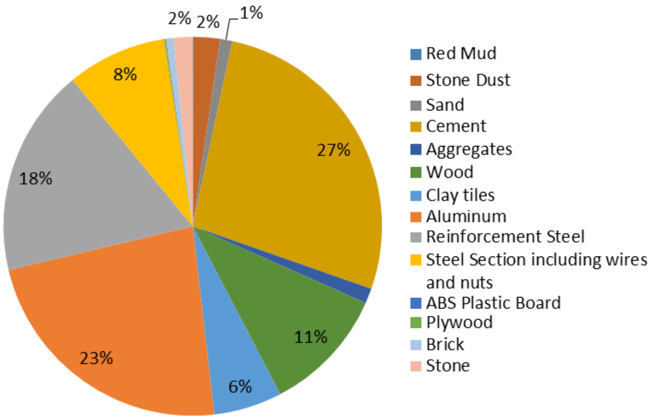

Figure 20: Embodied Energy of materials in composition

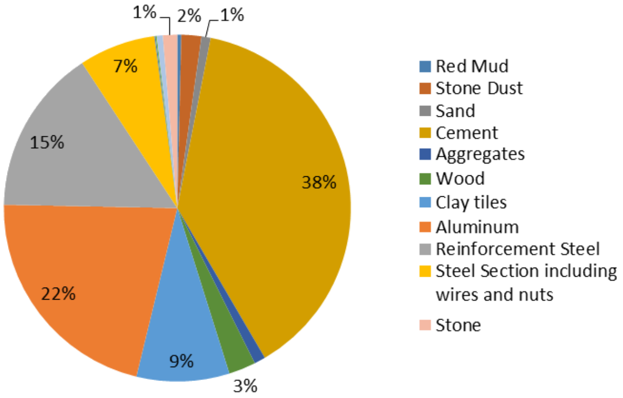

Figure 21: Embodied Carbon of materials in composition

Table 7: Cradle to gate life cycle assessment of Reinforced CSRE

Stages	Energy (GJ)	Carbon Emission (T)
Embodied Energy	579.25	57.62
Transportation Energy	39.80	2.50
Construction Energy	5.83	0.03
Total Life Cycle Energy	624.88	60.15

5.3 Assessment of Impacts

For the evaluation of impacts, the material quantity is multiplied by various impact assement coefficient provided by IFC,2017 following CML-IA as shown in table 2. The impacts from various construction materials can be seen in figure 22, 23, 24 and 25.

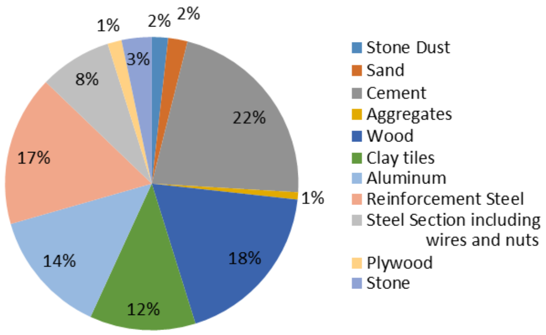

Figure 22: ODP for Reinforced CSRE

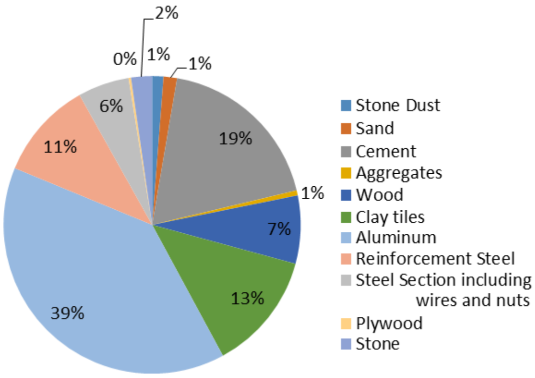

Figure 23: AP for Reinforced CSRE

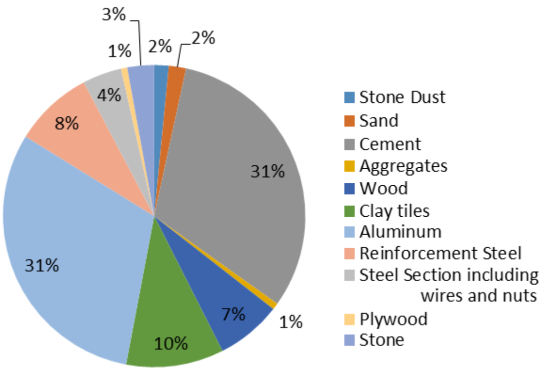

Figure 24: EP for Reinforced CSRE

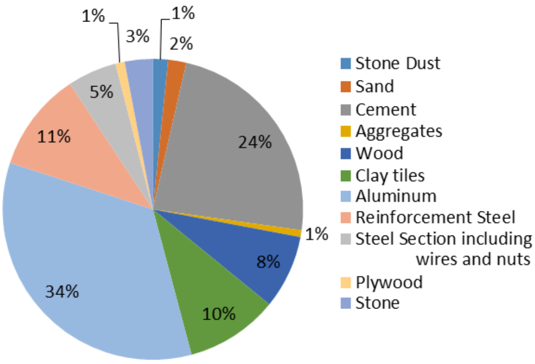

Figure 25: POPC for Reinforced CSRE building

5.4 Thermal comfort analysis

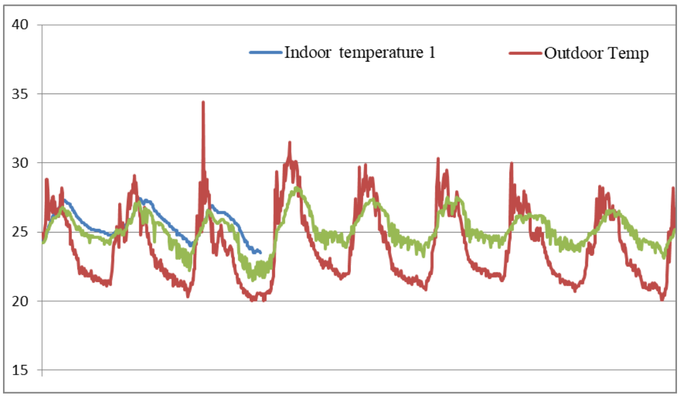

Figure 26: Variation of indoor and outdoor temperature

Figure 26 shows the variation of indoor and outdoor temperature. It can be said that due to high thermal mass, the fluctuation of indoor temperature is negligible compared to that of the outdoor surrounding temperature. This implies the building having lower energy requirements as it maintains a constant indoor temperature through its facade. A 100% user satisfaction was observed from the questionaire survey with the building habitants.

5.5 Material Substitution

Following Scenarios were considered for the material replacement of building under study:

Scenario 1: The rammed earth wall is replaced with 10 inches brick masonry wall. The substitution is done in the quantity of steel used, quantity of rammed earth with brick masonary with cement mortar (1:4) both the internal and external wall are of 10 inches. Table 8 shows the variation in energy and emission after its replacement,

Table 8: Cradle to gate life cycle assessment of Scenario 1

Stages	Energy (GJ)	Carbon Emission (T)
Embodied Energy	849.91	82.13
Transportation Energy	42.29	2.65
Construction Energy	5.12	0.03
Total Life Cycle Energy	897.32	84.81

Scenario 2: Replacing the Aluminum Doors and Windows with wood. The quantity of aluminum used is replaced by the quantity of wood required. Table 9 shows the variation in energy and emission after its replacement,

Table 9: Cradle to gate life cycle assessment of Scenario 2

Stages	Energy (GJ)	Carbon Emission (T)
Embodied Energy	545.52	47.54
Transportation Energy	39.42	2.47
Construction Energy	5.57	0.03
Total Life Cycle Energy	590.51	50.05

A comparative chart shown in figure 27 shows the variation of energy and emission after replacement scenarios.

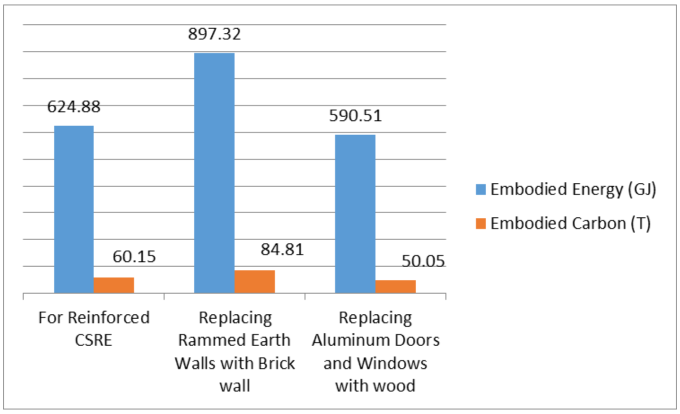

Figure 27: Embodied Energy and Embodied Carbon for various scenario.

5.6 Analysis of impact

The ODP, ADP, EP and POCP are compared for the various replacement scenarios as shown in figure 28 and 29.

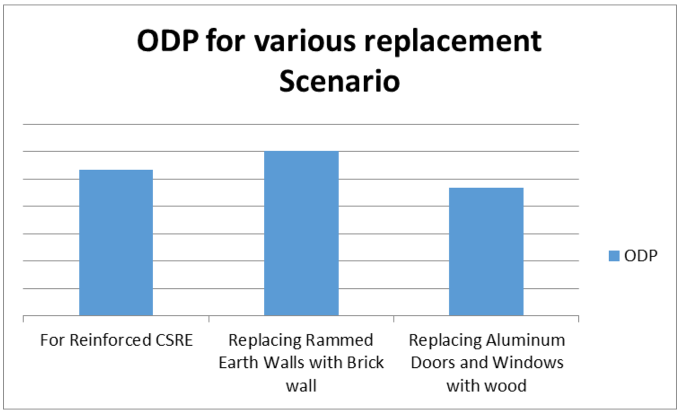

Figure 28: ODP for various replacement scenario

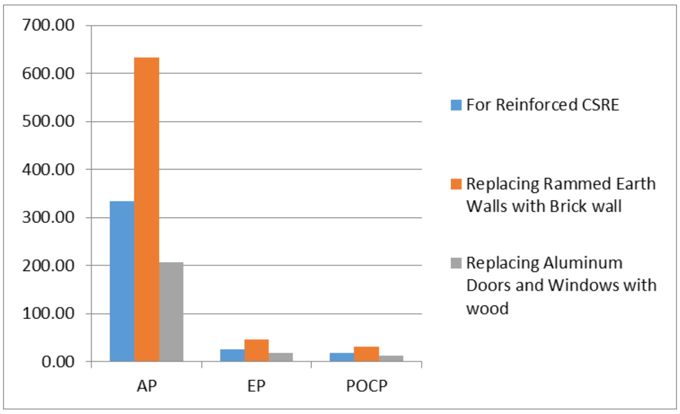

Figure 29: Environmental Impacts in various scenario.

5.7 Major Findings

- The entire energy used and emission from the building construction is centered on the use of Cement, Aluminum and Steel. Lowering the use of these materials would reduce significant energy use and the overall emission from the building.

- Replacing the aluminum doors and windows with wooden doors would reduce the overall lifecycle energy by 5.5%.
- Constructing 10 inches wall instead of rammed earth would increase its total lifecycle energy by 43.6%.
- Replacing the aluminum doors and windows with wooden doors would reduce the overall environmental impacts. Replacing the aluminum doors and windows with wooden doors would reduce the overall lifecycle emission by 16.8% and would significantly decrease the overall environmental impacts.
- Constructing 10 inches wall instead of rammed earth would increase its total lifecycle emission by 41%.
- The overall energy and emission of the building is very high compared to the studies found in the literature. The major difference of the study is the use of dataset. Although the overall energy and emission are higher than that of literature, the building is found more energy efficient with better thermal performance than the brick masonry structure.

6. Conclusion and Recommendations

6.1 Conclusion

In conclusion, the life cycle assessment of Reinforced CSRE building underscores the critical importance of material selection during its construction stage. Based on the literature review, the embodied energy of earth construction is less than 2.0 GJ/m^2; the life cycle energy of the studied Reinforced CSRE Building is 3.50 GJ/m^2, with a corresponding carbon emission of 60.15 T where majority of energy is used in its product stage. Out of the 15 different construction materials used in the construction, Stone followed by red mud and aggregates were the major construction materials. It is evident that choices such as aluminum doors and windows, cement, and reinforced steel have significantly amplified the overall environmental impacts.

Studies suggest the embodied energy of stabilized rammed earth wall ranges from 0.27MJ/Kg to 0.33 MJ/kg; the studied Reinforced CSRE walls has embodied energy of 0.57 MJkg, and the carbon emissions associated is 0.059 kg CO_2 eq./kg. The national building code of Nepal prohibits the height of the structure from 1.8m to 2.5m and length of unsupported wall to 10 times its thickness. Although the reinforcement steel used in the construction has elevated the overall energy and emission of the studied wall, it is a good compensation in terms of the suitable living area and the overall structural stability.

The thermal performance study revealed that the high thermal mass of the building has enabled to maintain almost constant indoor temperature and humidity in the building. This lowers the overall energy requirements in the building when subjected to controlled environmental conditions. Also, the users in the building are very satisfied with the thermal performance of the building.

The use of aluminum doors and windows, cement and reinforced steel has significantly increased the overall energy and magnified the overall environmental impacts. Environmental impacts in terms of ODP, AP, EP, EP and POCP show aluminum as the material with majority of highest environmental impacts. Replacing the aluminum doors and windows with wooden doors would reduce the overall lifecycle energy by 5.5% and the emission by 16.8%. This would also lower the overall environmental impacts from the building.

Brick Masonry Structure is a popular construction practice in Nepal. A reinforced CSRE wall is more sustainable option to the brick masonry construction. Study shows increase in life cycle energy, emissions and the overall impacts for the similar building after the replacement of the façade material to Brick Masonry in the structure. Therefore, it can be concluded that the choice of material is an important factor for the energy and emission control in building.

6.2 Recommendation

The building material which is available locally and doesn't require industrial processing yields low life cycle energy and emission as compared to that of industrial processed materials and should be emphasized for building construction. The use of local material for the construction of residential buildings can be recommended to improve its environmental performance. The total embodied energy of the rammed earth wall can be reduced by reducing the cement content in the proportion, use of alternate stabilizers with low embodied energy and emission can be recommended. The use of aluminum has maximum overall impacts. Thus, the use of wood for the construction of doors and windows can be recommended. Minimum proportion of aluminum is responsible for the huge environmental impacts. The aluminum are mostly imported from India or China in our country. Thus, it can be said that Nepal Government could restrict the import of aluminum so as to reduce the overall environmental impacts from the construction material.

Future researchers are recommended for the study of embodied energy as no data are available on the EPDs of our construction industry. Alternate construction material which is available locally has less environmental impacts which can be seen from the study. Declaring products in terms of its environmental performance is needed in context of Nepal as the country has a huge mitigation potential for carbon reduction from the booming building construction sector. Study incorporating the embodied energy and emission from the construction practices prevalent in our is found essential, as the energy mix is different, this would enhance the study of the life cycle assessment of products.

Although rammed earth construction offers significant potential for energy and emission savings, the high cost and low availability of skilled labor for construction may limit its widespread adoption. Moreover, the environmental benefits of this type of construction are not well known to many. To promote the adoption of this sustainable construction method, it may be necessary for the government to provide incentives or support.

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