Analysis of Embodied Energy in the Construction of The Prototype of Rammed Earth Wall

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Analysis of Embodied Energy in the Construction of The Prototype of Rammed Earth Wall

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Abstract

The construction sector has become the main target for reducing carbon emissions and world energy consumption in this decade. Reducing the energy consumption of buildings is an effective strategy for reducing carbon emissions. To achieve this kind of condition, the selection of building materials is an important factor, so the attempt to examine alternative building materials needs to be made. One of the attempts is by maximizing the potential of soil as a raw material. The technology of rammed earth wall has existed for centuries and now it is considered a sustainable material, but it has not yet become a popular discourse of alternative building material in Indonesia. This research aims to analyze embodied energy in rammed earth applications. This preliminary research was conducted using the LCA inventory data method that was achieved by making a partial prototype of the rammed earth wall. This research resulted in several recommendations for rammed earth wall applications to reduce carbon emissions during the construction process.

Keywords: *Alternative Material; Energy Analysis; Rammed Earth Wall; Sustainable Material*

Introduction

The construction sector has an important role in supporting national economic development (Wirahadikusumah & Sahana, 2012). In 2017, IEA data shows that the contribution of the construction sector to world energy consumption is 40% and the amount of greenhouse gas (GHG) emissions (CO_2) is 28% (IEA, 2019). This is the impact of the construction sector, which is still implementing a linear pattern that only focuses on economic development and pays less attention to the impact on the environment.

In the era where the availability of natural resources is more limited, every industrial activity must consider the use of natural resources in every process to become more efficient, especially in a developing country like Indonesia. Efforts to reduce the negative impacts on the environment cannot be postponed. (Wirahadikusumah & Sahana, 2012). An example has been applied by the construction sector in Europe and the United States over the last fifteen years there has been an increasing interest in the use of materials that have a low level of embodied energy (EE) and reduce the level of exploitation of non-renewable materials (Melià et al., 2014).

In the context of sustainable design, a strategy that can be made is to use local and recyclable materials, one of which is earthen material (Serrano et al., 2016). Earth has been used as a building material for centuries ago until today, and the renewal of this material becomes interesting when other parameters are involved as an energy-efficient material with reachable price and availability and can be recycled (Serrano et al., 2016). Earth can be found at almost every construction site and obtaining the soil as the material does not require a large

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amount of energy and cost. As a local material, soil material can be produced and used immediately at construction sites or nearby locations where there is sufficient earth without requiring an industrial process. Although earth is non-renewable, it can be recycled and does not require special treatment.

Rammed earth has low GHG emissions, and it is an energy-efficient alternative for wall construction. The research conducted by Melia compared the embodied energy of several plaster materials such as hydraulic lime plaster, soil plaster, and cement plaster using the life cycle assessment (LCA) method from a cradle-to-gate perspective, the data obtained that soil plaster has the lowest amount of embodied energy. Another difference shown is the soil that contains energy, which reflects the lower electricity consumption during the production process compared to conventional plaster (Melià et al., 2014).

Life Cycle Assessment is a technical approach to assessing environmental impacts arising from the life cycle of a product, which is conducted in four scopes; starts from the extraction of raw materials (cradle-to-gate) through the process of materialization (gate-to-gate), distribution (cradle-to-grave), and use to material recycling (cradle-to-cradle) (Muralikrishna & Manickam, 2017). This LCA method aims to compare and give users recommendations of production models with minimum environmental impact.

Although construction with soil material has been proven to have the potential for GHG emissions and minimal energy consumption, in the construction process rammed earth still contributes to the amount of energy consumption and GHG emissions such as energy production; transportation, and use of stabilizer components, which will continue to affect the environmental impact assessment figures for rammed earth material applications. Thus, the rammed earth construction activity still needs to be analyzed for the energy of the rammed earth construction as an alternative material.

Information and databases on GHG emissions in the construction sector have been widely carried out by researchers abroad, so there are various information and databases for reference (Li et al., 2021). However, in Indonesia, quantitative data for GHG emissions and energy consumption of rammed earth are very limited, and with the existing database, carrying out a comprehensive assessment of all phases of the cycle would be very complex. Nevertheless, several studies have applied internationally standardized methods to evaluate environmental impacts on rammed earth. Therefore, this research will focus on analyzing the environmental impacts that are thought to be caused by rammed earth construction, especially GHG emissions and energy consumption in the pre-construction to construction phases. The research will produce data inventory, evaluation models, and calculation formulas from available theoretical and technical references.

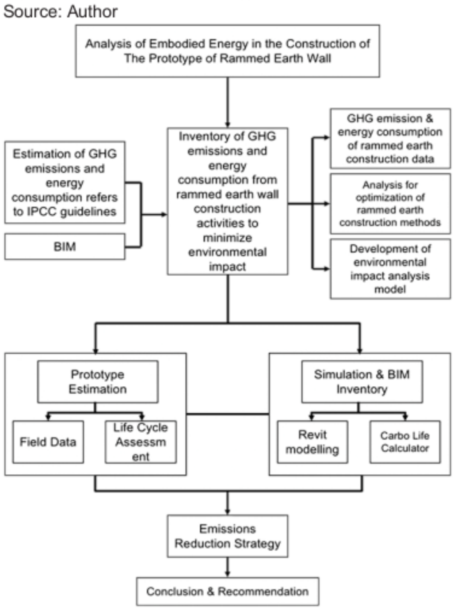
This article reports the estimation of GHG emissions and energy consumption in rammed earth wall works which also aims to: (1) enrich knowledge regarding GHG emissions and energy consumption during the pre-construction and construction phases of rammed earth walls; (2) present data on GHG emissions and energy consumption based on experimental demonstrations.

Methodology

The method used in this research is to analyze the Life Cycle Assessment (LCA) at the following stages: (1) Definition of a goal and scope in the form of prototyping and BIM analysis; (2) Inventory analysis in the cradle-to-gate phase, namely the partial cycle of a product that is studied from the time of resource extraction ('cradle') to the factory process ('gate') (before distribution to consumers or users), In this research, a study of the partial construction of a simple rammed earth building was conducted in Sleman, Yogyakarta. The data collected is estimated GHG emissions and energy consumption. Data collection techniques are direct assessment and observation of the partial prototype of cement stabilized rammed earth (CSRE) walls and literature studies in journals and research that has been done before. After identifying the required data, the embodied energy analysis or process analysis is carried out using the estimation method.

The application of BIM in research is to obtain supporting data, namely the value of GHG emissions from cement stabilized rammed earth (CSRE) at a certain volume based on a simulation analysis model created digitally with a combination of Revit software and inventory data from Carbo Life Calculator. Carbo Life Calculator can provide approximate data from the amount of material needed for a product to compare alternative materials with less GHG emissions in a project from the initial stage to project management.

Figure 1. Research Methodology
Source: Author



Result and Discussion

Prototyping

The prototypes in this study are two load-bearing walls with a size of each wall of 400 mm x 1200 mm and a thickness of 500 mm which had a west and north orientation. The prototyping process started from the material preparation stage which was carried out from February 2022 to March 2022 in Sleman Regency, D.I Yogyakarta. The stages of making the wall start from the wall facing north, which is done for ± 6 hours. Meanwhile, the wall facing west is made with a duration of ± 1 month due to the weather which tends to rain, and it is feared that it can damage the construction of the rammed earth wall.

Raw Soil Extraction

The analysis of GHG emissions and energy consumption in rammed earth applications has been carried out since the raw material extraction process. The earth was obtained from the excavation area at the foot of the Patuk area in Gunung Kidul, Yogyakarta. The selection of raw material sources is considered based on the nature and type of earth in the area which has a high clay content. It is known that the rammed earth wall material was transported from Patuk to Kalasan, Sleman which covered a distance of ± 21 km using a dump truck with a volume of 2.5 cubic or equivalent to 2500 kg (figure 2). The energy source used in this process is the use of diesel fuel which produces CO2eq emissions.

Figure 2. Soil transport
Source: Author

Pre-Construction Phase

1) Site Preparation

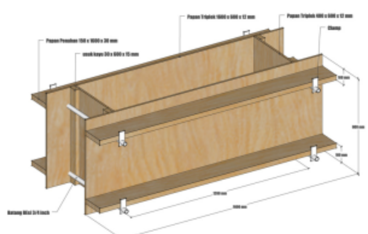
The site is part of the house's yard area with a size of 2400 mm x 2400 mm. The condition of the site base is partly in cast concrete, and the other part is soil. Site preparation is done by making a foundation with paving blocks in on-site areas that have not been cast on concrete (Figure 3). At this phase, the energy consumed is the transportation of paving blocks from the manufacturing place to the site. The paving block transportation is carried out by using a diesel-fuelled motor box vehicle with <1 km of a distance.

Figure 3. Site Preparation
Source: Author

2) Formwork Assembling

In the construction process, it is known to use the main tools in the form of formwork and a tamper stick to ram the soil into a rammed earth wall. The formwork itself consists of wood board components, iron rods, and clamps.

Figure 4. Formwork Design
Source: Author



a. Wooden Board

One formwork module consists of (1) two sheets of 1600 mm x 600 mm x 12 mm of plywood with four holes on the surface for iron rods, these board modules will be installed on the sides of the formwork, and (2) two sheets 400 mm x 600 mm x 12 mm of wooden boards to give a gap between one module to another. (3) four sheets of 150 mm x 1600 mm x 30 mm of wood planks as a retaining wooden board to hold plywood boards from the lateral forces of soil pressure during the tamping process.

b. Iron Rod

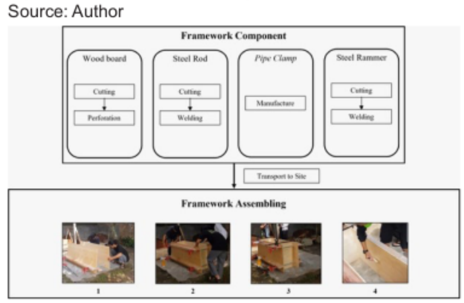
The function of the iron rod is to lock the retaining wooden board so that the formwork module does not shift during the soil tamping process. The type of pipe is hollow iron with an ¾ inch diameter. There are four pieces with a length of 1000 mm: two pieces to hold the top side and the other two pieces to hold the bottom side of the board. The place where the iron rod was obtained from a blacksmith workshop near the construction site which is <1 km away. Even though the manufacture of iron rods uses electrical energy to cut iron rods, this data is ignored because the energy use of the tool is not so significant (assuming the use of electricity to power the tools does not last for 1 minute). The energy consumption of transportation from the iron rod manufacturing place to the site consumes at least 0,25 liters of gasoline by motorbike.

c. Clamp

The clamp functions as a lock by clamping the two sides of the hollow iron rod. The pipe clamp has specifications for ¾ inch hollow iron, where the pipe clamp material is made of steel with a locking gear that functions to adjust the position of the pipe clamp. To make one formwork module, four pairs of pipe clamps are required. The energy consumed is transportation energy because the supply comes from Tanah Abang, Central Jakarta, which is sent using an expedition service to Kalasan, Sleman over a distance of ± 525 km by diesel-fuelled diesel colt truck and petalite gasoline-fuelled motorbike from the shipping warehouse to the location footprint.

These components are assembled into a formwork module that has a knock-down system or can be reassembled into parts, another function of the knock-down system is the flexibility of the formwork configuration for use in making various sides and angles of the rammed earth walls. Figure 5 below is shown the assembly of the framework.

Figure 5. Formwork Assembling
Source: Author



Construction Phase

The construction phase of the rammed earth wall begins when making a mixture of construction materials. The first stage is filtering the soil, filtering the soil needs to be done to break up the lumps of soil into smaller particles as shown in Figure 6. After filtering, the construction material is mixed on-site. The composition of the material mixture is 90% soil, 10% portland cement, and enough water to make the mixture moist and easy to blend when tamping. After the materials are well mixed, it is immediately rammed into the formwork module to prevent the cement from reacting and hardening. This process uses manual tools with manpower, so GHG emissions and energy consumption are considered insignificant.

Tamping is done by using a tamper made of an iron rod and iron plate until the mixture of materials is mixed evenly and densely (Figure 7). The time it takes for the soil to solidify in one layer of impact is ± 30 minutes – 1 hour. In one formwork module, the rammed earth wall is 500 mm high, to reach this height eight layers of soil tamping are needed.

From the explanation above, it is known that at the construction stage, activities are carried out with human power. The value of GHG emissions and energy consumption due to work done by manpower is ignored because the variables are still very wide, and the determinants are not significant.

Figure 6. Filtering & Mixing
Source: Author

Figure 7. Tamping Process
Source: Author

Figure 8. Formwork Dissembling After 24 Hours
Source: Author

Figure 9. Drying Process After 1 weeks
Source: Author

GHG Estimation and Energy Consumption

Based on the description of the work from the pre-construction phase to the construction phase, the activities that consume energy and have the potential to generate GHG emissions in the rammed earth wall construction process are at the stage of material transportation from the manufacturing place to the construction site location that has the distance, energy source, and different modes of transportation. Transportation modes have GHG emission values that can be estimated and analyzed from transportation activities.

Table 1. Rammed Earth Construction Fuel Consumption Data.

Material	Amount	Fuel Type	Calorific Value	Fuel Consumption
Soil	2.500 kg	Solar	41,868 MJ/liter	3 liters
Paving Block	100 kg	Gasoline (RON 90)	39,8583 MJ/liter	0,25 liter
Wood	16 kg	Gasoline (RON 90)	39,8583 MJ/liter	0,5 liter
Hollow steel rod	9 kg	Gasoline (RON 90)	39,8583 MJ/liter	0,25 liter
Clamp	5,4 kg	Gasoline & Solar	39,8583 MJ/liter & 41,868 MJ/liter	4,6 liter & 378 liters

Source: Author

1) Raw Soil Transportation

Input:
Diesel fuel consumption: 3 liters
Solar emission factor: 2,9249 kg CO_2/Liter
Diesel fuel calorific value: 41,868 MJ/L
Soil transported: 2500 kg

The estimation of energy consumption and GHG emissions in the process of transporting soil materials using diesel-fuelled dump trucks for every kg of soil transported is:

$$\text{GHG Emission (kgCO}_2\text{/kg)} = \frac{3\ \text{L} \times 2{,}9249\ \text{kgCO}_2\text{/L}}{2500\ \text{kg}} = 0{,}00350\ \text{kgCO}_2\text{/kg}$$

$$\text{Energy Consumption (MJ/kg)} = \frac{3\ \text{L} \times 41{,}868\ \text{MJ/L}}{2500\ \text{kg}} = 0{,}0502416\ \text{MJ/kg}$$

2) Paving Block Transportation

Input:
Fuel consumption: 0,25 liter
Solar emission factor: 2,59789 kg CO_2/Liter
Fuel calorific Value: 39,8583 MJ/L
Paving transported: 100 kg

$$\text{GHG Emission (kgCO}_2\text{/kg)} = \frac{0{,}25\ \text{L} \times 2{,}59789\text{kgCO}_2\text{/L}}{100\ \text{kg}} = 0{,}006494725\ \text{kgCO}_2\text{/kg}$$

$$\text{Energy Consumption (MJ/kg)} = \frac{0{,}25\ \text{L} \times 39{,}8583\ \text{MJ/L}}{100\ \text{kg}} = 0{,}09964575\ \text{MJ/kg}$$

3) Wooden Board Transportation

Input:
Gasoline consumption: 0,5 liter
Gasoline emission factor: 2,59789 kgCO_2/Liter
Gasoline calorific value: 39,8583 MJ/L
Board transported: 16 kg

$$\text{GHG emission (kgCO}_2\text{/kg)} = \frac{0{,}5\ \text{L} \times 2{,}59789\ \text{kgCO}_2\text{/L}}{16\ \text{kg}} = 1{,}245571875\ \text{kgCO}_2\text{/kg}$$

$$\text{Energy Consumption (MJ/kg)} = \frac{0{,}5\ \text{L} \times 39{,}8583\ \text{MJ/L}}{16\ \text{kg}} = 0{,}081184\ \text{MJ/kg}$$

4) Iron Rod Transportation

Input:
Gasoline consumption: 0,25 liter
Gasoline emission factor: 2,59789 kg CO_2/Liter
Gasoline calorific value: 39,8583 MJ/L
Iron rods transported: 9 kg

$$\text{Energy Consumption (MJ/kg)} = \frac{0{,}25\ \text{L} \times 39{,}8583\ \text{MJ/L}}{9\ \text{kg}} = 0{,}07216361\ \text{MJ/kg}$$

$$\text{GHG Emission (kgCO}_2\text{/kg)} = \frac{0{,}25\ \text{L} \times 2{,}59789\ \text{kgCO}_2\text{/L}}{9\ \text{kg}} = 1{,}107175\ \text{kgCO}_2\text{/kg}$$

5) Pipe Clamp Transportation

Input:
Fuel consumption:
- Diesel fuel: 378 liter
- Fuel: 4,6 liter
Emission factor:
- solar: 2,9249 kg CO_2/Liter
- fuel: 2,59789 kg CO_2/Liter
Calorific Value:
- Diesel fuel: 39,8583 MJ/L
- fuel: 41,868 MJ/L
Pipe clamp transported: 5,4 kg

$$GHGE_{solar}\ \text{(kgCO}_2\text{/kg)} = \frac{378\ \text{L} \times 2{,}9249\ \text{kgCO}_2\text{/L}}{5{,}4\ \text{kg}} = 204{,}743\ \text{kgCO}_2\text{/kg}$$

$$GHGE_{fuel}\ (kgCO_2/kg) = \frac{4{,}6\ L \times 2{,}59789\ kgCO_2/L}{5{,}4\ kg}$$

$$= 2{,}213\ kgCO_2/kg$$

$$Energy\ Consumption_{solar}\ (MJ/kg) = \frac{378\ L \times 41{,}868\ MJ/L}{5{,}4\ kg}$$

$$= 2930{,}76\ MJ/kg$$

$$Energy\ Consumption_{fuel}\ (MJ/kg) = \frac{4{,}6\ L \times 39{,}8583\ MJ/L}{5{,}4\ kg}$$

$$= 33{,}95337\ MJ/kg$$

$$_{total}(MJ/kg) = 2930{,}76\ MJ/kg + 33{,}95\ MJ/kg = 2964{,}71\ MJ/kg$$

Material `Analysis With BIM

The model on Revit is made based on the components of the material used, namely soil and cement stabilizers for a simple building with dimensions 2m x 2m x 2m, this building consist of 24 partial prototype bearing-wall modules that have been made. The materials shown are soil and cement as shown in the image below:

Figure 10. Simple Rammed Earth Wall Model in Revit.
Source: Author

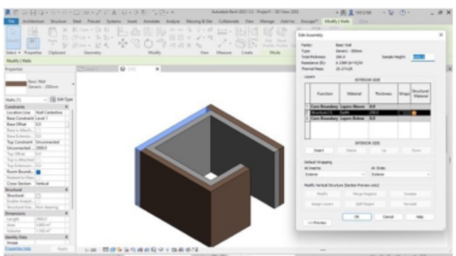
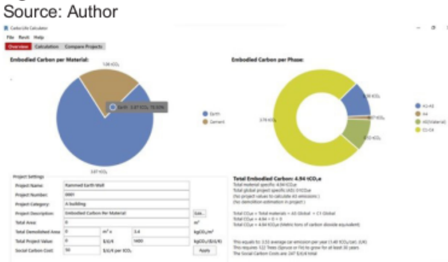
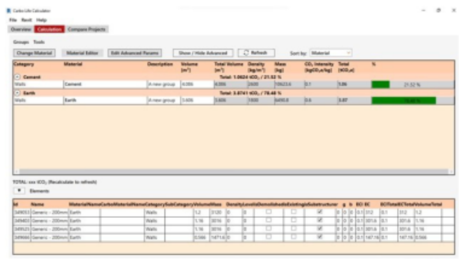


Figure 11. Carbo Life Calculator Interface.
Source: Author



A simple building model on Revit has connected to the GHG emission calculation plug-in Carbon Life Calculator. This plug-in has code to calculate the bill of quantity in the model based on the input type of material in the Carbon Life Calculator data inventory. The material data obtained is the GHG emission value for one building. Then the data is adjusted by dividing the overall GHG emission results into 24 wall modules. Thus, parallel data are obtained for GHG emission values per material with GHG emission values in each rammed earth wall construction process.

Figure 12. Carbo Life Calculator Calculation Data.
Source: Author



From the data above, it is found that the overall carbon emission intensity of this simple rammed earth wall building prototype is 0,1 + 0,6 = 0,7 $kgCO_2/kg$. Then if it is divided into one load-bearing wall module, the intensity of carbon emissions is 0,7 $kgCO_2/kg$: 24 = 0,02 $kgCO_2/kg$. This intensity includes soil and portland cement as wall stabilizers.

Discussion

In the construction of two rammed earth walls, the total GHG emission is ~207,115 $kgCO_2/kg$. Meanwhile, the total energy consumption is ~2968,06 MJ/kg with each estimation data described in table 2 as follows:

From the results of the calculations in table 2, it can be concluded that the pre-construction process needs to be considered in reducing energy consumption and developing rammed-earth construction methods. The existence of components that require transportation from outside the region results in fairly high energy consumption. Material transportation with more loads in one trip is considered to be able to reduce energy consumption, such as in the process of land transportation with a cargo of 2500 kg with a distance of 21 km, it only consumes energy as much as 0,0502416 MJ/kg. Compared with the transportation of paving block material with a load of 100 kg and a distance of 350 m, the energy consumption value is 0,09964575 MJ/kg. The comparison

Table 2. Estimated Energy Consumption and GHG Emissions Rammed Earth Wall

No	Phase	Process	Vol. (kg)	Energy Consumption (MJ/kg)	CO_2-e Emission (Kg CO_2/kg)
1	Extraction	Soil Transportation	2500	0,0502416	0,0350
		TOTAL		0,0502416	0,0350
2	Pre-construction	Paving block Transportation	100	0,09964575	0,006494725
		Wooden Board Transportation	16	1,24557188	0,081184
		Iron Rod Transportation	9	1,107175	0,07206361
		Pipe Clamp Transportation	5,4	2964,71337	206,956
		TOTAL		2968,06257	207,1157423
3	Construction	Material Mixing (soil: cement) 9:1	45: 5	-	0,0291

Source: Author

of GHG emissions shows the opposite result, where the number of loads does not affect the value of GHG emissions. The type of vehicle fuel and the distance traveled are the determining factors for the number of emission values. Meanwhile, based on BIM analysis, the value of material carbon consumption represented by the soil and cement stabilizer attached is 0,02 kgCO2/kg.

Conclusion and Recommendation

Conclusion

Based on the results of this study it can be concluded that:

1. The analysis was carried out on rammed earth construction as an alternative material, then obtained:

a. The transportation phase of formwork components for rammed earth construction has dominant GHG emission values and energy consumption over the entire pre-construction and construction process;
b. The estimation method in this research can be used for various schemes of rammed earth construction work because it can determine the most efficient processes in terms of reducing negative impacts on the environment;
c. GHG emissions for materials attached to rammed earth wall through BIM analysis show that construction materials for rammed earth wall applications are still relatively low compared to GHG emissions in transportation and other construction components.

2. The estimation method used in this research is still an analysis of the value of GHG emissions and energy consumption required in the pre-construction process and the construction of a simple prototype, it is not yet in further process.

Recommendation

1. Improving work efficiency by developing effective work plans and schedules to minimize energy consumption, especially transportation energy;
2. Prioritizing the use of soil as a basic material from sources closest to the construction site to assess its potential before sourcing from further locations;
3. Conduct a more complete study in environmental impact analysis to the stage of impact assessment and interpretation of results;
4. Selection of materials and construction equipment that considers the values of concern for the environment. For example, by designing formwork that can be used repeatedly and choosing a stabilizer that is more environmentally friendly;
5. In the BIM analysis process, it is necessary to add another material analysis (if there is a material other than soil and cement) which is applied according to construction needs.

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