Embodied energy of alternative building materials and their impact on life cycle cost parameters

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Abstract

House construction all over the world is in need of many alternative building materials since the conventional materials are in short supply and also cause degradation of the environment as in clay, sand and coral mining. For popularization of alternative materials, it is necessary to ensure that they are generally cost effective. However, the cost effectiveness should not only be based on initial capital cost but the whole life cycle costing. This will include the cost of energy used in the production stage of such building materials, cost of casting and the energy used in the life span of the building usage. This research has investigated and developed the embodied energy of different building materials. This study also included the performance of different materials on operational energy. It is shown that the alternative building materials and systems would have either reduced or similar impact on life cycle cost, compared to the conventional building materials.

Key words: Embodied energy, building materials

1. Introduction

The increased awareness of environmental impacts, some restrictions were imposed on extraction of natural resources for the manufacturing of building materials. In order to quantify these effects, researchers have evaluated the emboded energy of different building materials which consists of energy used in manufacturing and transporting building material. The environmental issues to be addressed include the need to reduce the levels of CO_2 emmissions, reduction in authorization of new quarries, obligation to rehabilitate quarry workings and prohibition of material extraction from river beds etc.

The construction industries in many developing countries still use natural resources in large quantities such as clay, sand, lime, stones etc for the production of building materials. Some examples are burnt clay bricks and tiles that use clay, cement-sand blocks that use sand and cement, insitu cast concrete and pre-cast concrete products that use crushed aggregates produced from stones, cement produced using lime stone etc. This production process of raw materials will consume a considerable amount of energy for mining, transportation and burning. Thus, building materials can be a significant contributor to the total CO_2 emissions to the atmosphere. This will be in addition to the various other environmental impacts such as loss of valuable fertile land as clay mines, salt water intrusions into rivers, open pit lime stone mines, use of fire wood leading to deforestation etc.

Due to increased awareness of environmental impacts, in the recent past, there were some restrictions imposed on using natural resources for the manufacturing of building materials. As a result, the prices of conventional building materials have increased by a considerable amount. These price escalations and environmental concerns have promoted research and development on alternative materials.

In order to popularize alternative building materials, it is essential to evaluate the total performance of such materials in terms of strength, durability, cost, energy consumption and the environmental concerns.

One of the main cost components of alternative building materials is the energy used for manufacturing and transportation. This can be expressed as embodied energy. A detailed study into this energy is vital to determine the competitiveness of alternative materials and the green house gas emissions associated with these materials. Such a study can shed light on the true impact of building materials. This paper highlights a detailed study undertaken on alternative building materials and systems developed in Sri Lanka. It deals with the embodied energy and the possible effects of alternative materials on life cycle cost.

The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life. The objectives of life cycle costing are listed as follows (Woodward, 1997):

- To enable investment options to be more effectively evaluated.
- To consider the impact of all costs rather than only initial capital costs
- To assist in the effective management of completed buildings and projects
- To facilitate choice between competing alternatives.

2. Objectives and Methodology

The main objective of this research is to determine the embodied energy of alternative building materials available in Sri Lanka and to assess the effects on the life cycle cost parameters. These values are used to rank different material and building techniques in the order of embodied energy and life cycle cost. The following methodology is used:

1. The embodied energy of constituent materials was evaluated using various data available in literature with special reference to applicability of them in Sri Lanka.
2. These data for constituents were then used to evaluate the embodied energy of alternative materials with various options available for their use. They are compared with the embodied energy of conventional building materials.
3. The expected life spans and the impact on the running cost of buildings were assessed with respect to the tropical climatic conditions available in Sri Lanka.
4. All the above data was used to evaluate the impact made by each material and technique on life cycle cost of the building.

3. Need for sustainable alternatives

Sustainable construction is “using natural resources in such away that they meet the economic, social and cultural needs, but not depleting or degrading these resources to the point that they cannot meet these needs for future generations(Emmanual, 2004).

It is the duty of all building designers to weigh the environmental benefits against economic costs. In order to perform such cost benefit analysis for building materials, this study is focused on conventional and alternative building materials in the context – specific to take into account the local conditions, practices and norms.

There is a timely need for optimum utilization of available energy resources and raw materials to produce simple, energy efficient, environment friendly and sustainable building alternatives and techniques to satisfy the increasing demand for buildings. Generally the conventional materials used in Sri Lanka like cement, steel, burnt bricks, aluminum etc are energy intensive and transported over great distances. Extensive use of these materials can drain the energy resources and adversely affect the environment.

The environmental issues to be addressed include the need to reduce the levels of CO_2 emissions, reduction in the authorizations of new quarries, obligations to rehabilitate quarry workings, and the prohibition of material extraction from river beds.

Generally the conventional materials like steel, cement, aluminum, bricks are energy intensive and are transported over great distances. Extensive use of these materials can drain the energy resources and adversely affect the environment. On the other hand, it is difficult to meet the every growing demand for buildings by adopting only energy efficient traditional material and construction methods. Hence there is a need for optimum utilization of available energy resources and raw materials to produce sustainable building alternatives and techniques to satisfy the increasing demand for buildings.

In order to compare the competitiveness of alternative building materials and techniques, life cycle cost is very important. The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life. With the development of life cycle cost, different investment options can be effectively evaluated and facilitate the choice between competing alternatives.

In order to develop sustainable alternative building technologies, the following principles must be adhered to (Reddy, 2004):

- Minimize the use of high energy materials.
- Environment friendly technologies.
- Minimize transportation
- Maximize the use of local materials and resources.
- Decentralized production and maximum use of local skills.
- Use of renewable energy sources.

Major features/impacts of the alternative building technologies discussed in the previous sections can be highlighted as follows:

- Energy efficient, consuming less than half of the energy required for conventional building methods leading to energy conservation.
- Techniques are simple and employ maximum local resources and skills.
- Decentralized production systems and small scale operations that generate local employment.
- Reduce cost and energy involved in transportation of building products

(Reddy, 2004)

3. Alternative building materials

Price escalations associated with conventional building materials promoted research and development into alternative building materials and systems [1]. These materials have already been successfully used in a significant number of houses in Sri Lanka. The materials can be highlighted as follows:

1. Alternative materials for walls: These consist of cement stabilized soil blocks and stabilized rammed earth. The soil blocks can be manufactured as machine moulded [2] or hand moulded [1]. Cement stabilized rammed earth is manufactured with laterite soil with high sand content and cement as the stabilizing agent. The soil cement mixture is compacted in a set of steel slip form moulds using manual tamping methods. Figures 1 and 2 show the stabilized soil blocks and rammed earth construction.

2. The alternative slab systems: For multi storey buildings, a reinforced concrete (insitu cast) solid slab supported on beams is conventionally used. In these solid slabs, the concrete below the neutral axis serves little purpose other than protecting the steel reinforcement. The alternative slab systems consist of beams supporting shorter span slabs thus reducing the thickness and steel reinforcement requirements. The examples are the beam slab system developed at NERD (National Engineering Research and Development Center, Sri Lanka), the pre-cast beam slab system developed at University of Moratuwa [3].

3. The roof covering materials: An alternative roof covering material that can be manufactured as a cottage industry is micro-concrete roofing tiles [4]. Micro concrete tile has been introduced to Sri Lanka as an alternative roof covering material in the recent past. A bigger size MCR tile (0.6 m x 0.6 m) has been more popular in Sri Lanka. In order to limit the sand usage due to prevailing sand crisis in the country, the MCR tiles are now manufactured with cement, quarry dust and chip mix (mix proportion of 1 cement: 1.5 sand or quarry dust and 1 chips of 6 mm).

4. The basic parameters for embodied energy

Embodied energy is the energy needed in preparing and extracting the raw materials, energy for transportation of the same and the external energy applied to raw materials in producing or assembling the final product [5]. Some data available in literature for basic materials have been used in this study. They are presented in Table 1 as production energy and transportation energy.

This data can be used to determine the embodied energy of walling materials, roofing systems and slab systems. Some of the data available in literature is presented in Table 2. These can be used for comparison purposes with alternative materials. The embodied energy values considered in the evaluation of energy in alternative materials and systems are given in Table 3.

5. Embodied energy of alternative materials

This study is carried out for soil cement block walls, cement stabilized rammed earth walls, a pre-cast reinforced concrete beams slab systems and a roof with micro – concrete tiles.

5.1 Compressed Stabilized Earth Blocks (CSEB)

In tropical climatic conditions, laterite soils are commonly found as laterite hills. This soil is rich in Aluminum and Iron oxides which is an ideal material for block manufacturing. A slightly moist cement soil mix of 6% or more cement can be used for manufacturing blocks of wire cut brick appearance using manually operated machines with a minimum compaction ratio of 1.65 [2]. The blocks can be of various sizes depending on the mould. A commonly used size of 290 mm x 140 mm x 90 mm blocks was selected to determine the embodied energy. The main component of embodied energy would be due to the usage of cement and any transportation of soil.

According to the work study conducted, for a 10 m^2 area, 335 blocks are needed. The soil volume is 2.0 m^3 and no energy is allocated considering manual excavation. However, transportation energy is included for a hauling distance of 25 km since laterite soil is readily available in most of the locations in Sri Lanka. The volume of mortar used is 1.9 m^3. Cement is transported over a distance of 50 km. The weight of cement needed for making blocks is 175.7 kg. Using this data, the embodied energy of 10 m^2 of 140 mm thick block wall can be calculated and has been then converted to embodied energy per m^3 for comparison purposes.
Embodied energy in 2.0 m^3 of soil = 87.5 MJ
Embodied energy for 175.7 kg of cement = 1028 MJ
Embodied energy for 1.876 m^3 of mortar = 228 MJ (which contains 39 kg of cement and the energy is 228 MJ and the energy in sand is only 0.042 MJ which is negligible)
Total embodied energy for 10 m^2 of 140 mm wall = 1344 MJ
Embodied energy for 1 m^3 = 960 MJ

5.2 Cement stabilized rammed earth

Rammed earth technology was in use in many parts of Sri Lanka, but with thick walls such as 300 mm. However, a considerable improvement was achieved by cement stabilization and the use of continually rising slip form system shown in Figure 2.

This allows achieving sufficiently strong walls with a thickness of about 160 mm in single storey houses thus saving both soil and cement. Laterite soils with high sand content (40% - 60%) and even with hard lumps can be used with cement contents of 6% - 10%. The smooth finish resulting from the use of steel moulds allows to have walls without a plaster. Since there are no bed joints, there is no need for cement sand mortar and hence could minimize the sand usage with possible cost savings and environmental benefits.

For rammed earth walls, cement soil mix is compacted using a steel rammer that can induce dynamic compaction. This will result in a compaction ratio (the initial volume of soil to the compacted volume of wall) of about 2.0. Thus, for an area of 10 m^2 with a wall thickness of 160 mm, a volume of 3.2 m^3 of soil would be needed. The transportation distance for the soil is assumed to be 25 km. The amount of cement needed was 278 kg with 6% by the soil volume and assumed to have been transported over 50 km.

Embodied energy in 3.2 m^3 of soil = 140 MJ
Embodied energy for 278 kg of cement (6%) = 1626 MJ and 14 MJ (transport)
Embodied energy for 464 kg of cement (10%) = 2714 MJ and 23 MJ (transport)

Total embodied energy for 10 m^2 with 6% cement = 1780 MJ
Total embodied energy for 10 m^2 with 10% cement = 2877 MJ

Embodied energy for 1 m^3 with 6% cement = 1271 MJ
Embodied energy for 1 m^3 with 10% cement = 2055 MJ

5.3 Energy in pre-cast reinforced concrete slab system

Due to scarcity of good quality timber, reinforced concrete slabs are popular in many tropical countries including Sri Lanka. The conventional solid slabs designed for BS 8110: Part 1: 1997 suffers from several drawbacks such as inefficient use of concrete, need of formwork and false-work and reinforcement requirement governed by crack controlling needs instead of flexural behaviour in the case of supporting light loads. An alternative pre-cast reinforced concrete slab system was developed in order to optimize the labour and material components. This system consists of pre-cast beams placed at 1.5 m spacing supporting pre-cast slabs of 75 mm thickness; thus minimizing the need for any formwork and false-work [3]. It is shown in Figure 3. The lesser use of concrete and steel can lower the embodied energy while giving a cost saving of about 40 – 50%. The embodied energy is evaluated for a slab area of 3.6 m x 3.0 m which will need 24 pre-cast slab panels. The total concrete volume is 1.03 m^3. The steel weight is 72.6 kg. The steel is assumed to have been transported over 50 km distance.

Embodied energy in 1.03 m^3 of concrete = 2015.54 MJ
Embodied energy for 72.6.kg of steel = 3050 MJ
Embodied energy for 3.6 m x 3.0 m area = 5065.57 MJ (Energy consumed for formwork is ignored)
Embodied energy for 1 m^2 of the slab = 469 MJ

5.4 Micro concrete roofing tiles

Clay tiles and cement fiber sheets are the most popular roofing materials in Sri Lanka. Clay tiles have environmental concerns such as clay mining and shortage of good quality clay for tile manufacturing. Cement fibre sheets also has some environmental concerns including indoor thermal comfort. An alternative to above two roof covering materials is Micro Concrete roofing tiles (MCR tiles). These are manufactured with cement and aggregate mixes of 1:2 or 1:3 some times using 3-6 mm chips in addition to sand [10]. For low income housing, these tiles can be even hand moulded [10]. Raw material quantities for tile production were obtained from a commercial manufacturer. It is 2.83 m^3 of sand, 4.245 m^3 of chips and 3150 kg of cement for 1000 MCR tiles with the operational energy of the vibrating machine at 23 MJ. Aggregate and cement are transported over 50 km distance. The embodied energy of an MCR tile roof is 75 MJ per m^2. Total embodied energy with the timber frame work has been evaluated as 134 MJ with 450 mm rafter spacing and 300 mm joist spacing.

6 Comparison of building materials in terms of embodied energy

6.1 Comparison of walling materials

The comparison of embodied energy can be carried out on individual basis. For example, it is possible to compare 1 m^2 of 225 mm brick work with 160 mm rammed earth since both are ideal candidates for external walls in tropical climatic conditions. However, it will not shed light on the actual situations since they are used in different ways in practice. For brickwork, it is usual to have both internal and external plaster. Rammed earth walls can be used either without plaster or only with an internal plaster. Table 4 presents the comparison of embodied energy of different walling materials.

In the local context brick and cement block masonry work are generally finished with a cement, lime and sand plaster. This also consumes a considerable amount of energy. If 1:1:5 cement, lime and sand plaster is used, it has the embodied energy of 912 MJ minimum and 976 MJ maximum giving an average of 945 MJ for 10 m^2 wall area [9]. If a soil based plaster (mud plaster) is applied and the energy consumed in production is 849 MJ for 1:2:6 mortar and 773 MJ for 1:2:8 (cement, sand and soil) mortar. This is a considerable amount of energy which should be included for the walls with plaster for any embodied energy comparisons. For example, a 225 mm brick wall with both internal and external plaster has an embodied energy of 9745 MJ for a wall area of 10 m^2. An alternative to it with rammed earth without plaster will consume 3326 MJ for the wall area of 10 m^2.

As CSEB have a wire cut finish and the rammed earth is done with steel moulds both these walling materials can be finished without a plaster or only with an internal plaster. Since the earth appearance will give an aesthetically appealing finish it is not essential to apply the plaster on such walls. However for water proofing purposes soil based paint can be applied which consumes much less energy than that of a plaster.

Therefore when comparing the walling materials it is reasonable to include the plaster wherever necessary. A comparison of walling materials with finishes is given in Table 5 for a wall area of 10 m^2.

6.2 Roofing materials

Different roofing systems used in house construction is compared in terms of embodied energy in Table 6. The alternative roofing materials such as Micro Concrete Roofing tiles (MCR) tiles and Ferro Concrete Roofing tiles (FCR) tiles have a comparable embodied energy.

6.3 Slab systems

The embodied energy of different slab systems is compared in Table 7. The alternative slab systems have a competitive embodied energy and will have a lot of scope in the construction industry.

The data presented in Tables 5, 6 and 7 indicate that the embodied energy of alternative systems is either lower or comparable with most of the conventional systems. Therefore, it can be suggested that the alternative materials have the potential to either reduce or maintain the green house gas emissions associated with production and use of building materials. If these materials can be manufactured with less environmental impacts, they could be ideal candidates for replacement of conventional building materials.

7.0 Operational energy

The total energy consumed over the life span of a building will depend on the embodied energy, operational energy and replacement or maintenance energy needed [11], [12], [13]. The alternative materials and systems presented are all cement based products. Extensive testing carried out [1], [2], [3], [8] have indicated that those are of adequate strength. Since the cement based products tend to gain strength with age, the durability of the alternative materials will be comparable with conventional materials. For example a compressed stabilized earth block wall can be expected to last 50 – 100 years once suitable protective coatings are applied. Thus, the life cycle energy will primarily depend on the embodied energy and the operational energy. It is the responsibility of the engineers, architects and the clients to specify the use of technologies that reduce the consumption of resources over the lifetime of a building and to consider the life cycle costs in addition to the capital costs [14].

In tropical climatic conditions, the operational energy needed will be primarily for thermal comfort and lighting. The type of material may affect the energy needed for thermal comfort. In free running buildings, generally fans are needed to provide adequate comfort. In order to determine whether the alternative building materials will have any adverse impact on the indoor temperatures, measurements were taken in three sets of houses with different combinations of wall and roof materials. In order to isolate the effects of out door environment, three rooms facing east were compared. The results are shown in Charts 1 to 3. The details of the selected houses from each category are given in Table 8.

The charts indicate a similar trend with slightly lower maximum indoor temperatures with some time lag to the maximum out door temperatures. Although there may be marginal differences, it is unlikely to change the operational energy requirements. Thus, alternative building materials are unlikely to affect the life cycle energy of well planned passive houses to be used as free running spaces. However, another study conducted with the modals made by different walling materials have shown that the structure with rammed earth walls show the lowest indoor temperature during the daytime and cement block wall shows the maximum. There is a temperature difference of 2 to 3 ^{o}C in the peak values of the two materials. Compressed earth block wall and the brick wall are having indoor temperatures in the same range which is in between the two extreme cases.

When the night time readings are considered, cement block wall cools down faster. However throughout the day, the model with rammed earth wall behaves better in terms of indoor thermal comfort.

8. Conclusions

With the recent concerns expressed about green house gas emissions and the need to reduce them in future, it is extremely important to ensure that the alternative building materials will not give rise to higher energy demands. In this context, the detailed study presented in this paper has highlighted that cement and soil based alternative materials and systems researched and developed in Sri Lanka will have reduced impact on energy use. This is because they have less embodied energy while the houses will be similar with respect to thermal comfort and the life span.

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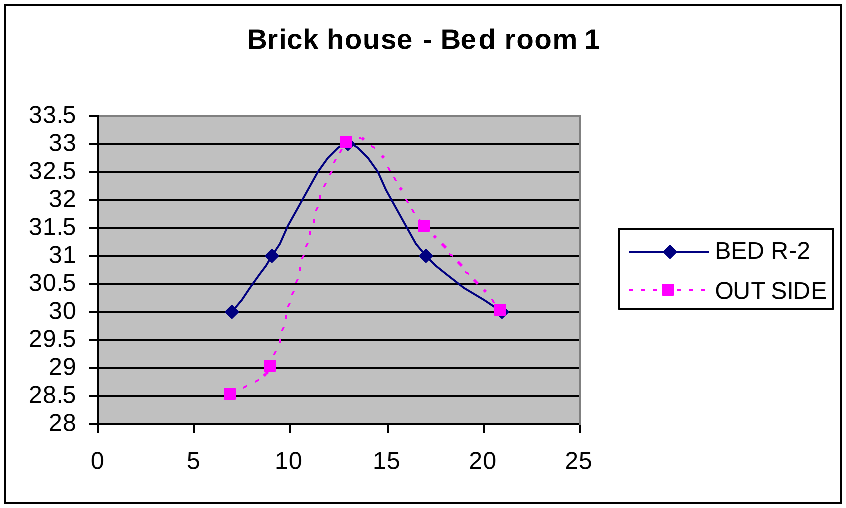

Chart 1: Indoor and outdoor temperature in brick house with clay tile roof

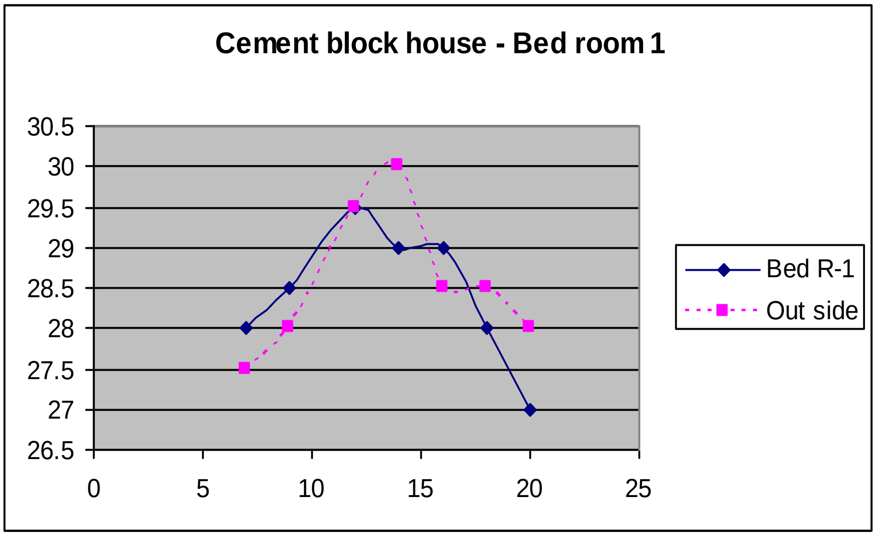

Chart 2: Indoor and outdoor temperature in cement block house with cement fiber roof

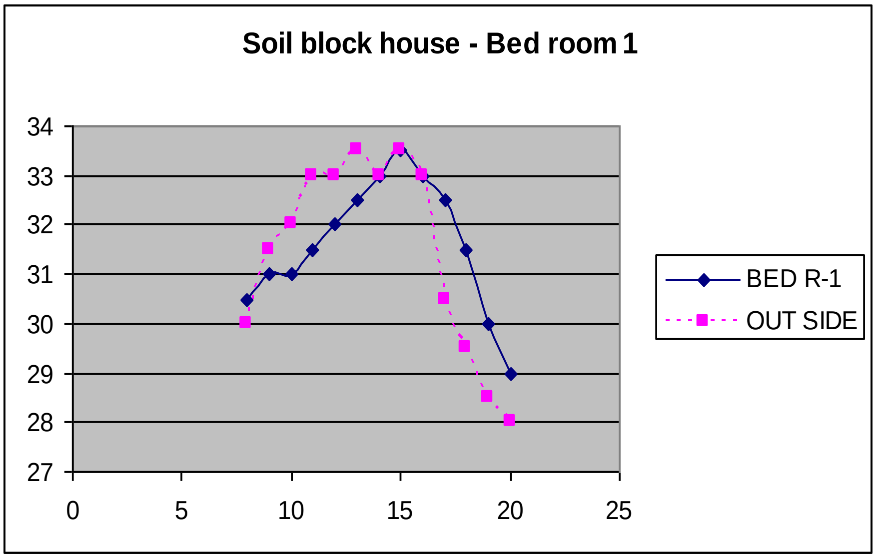

Chart 3: Indoor and outdoor temperature in soil block house with MCR tiles

Figure 1: A house constructed with stabilized soil blocks and MCR tiles

Figure 2: Rammed earth construction (A photograph taken at Center for Housing Planning and Building, Sri Lanka)

Figure 3: Pre-cast reinforced concrete beam slab system

Table 1: Embodied energy in production and transportation

Material	Energy in production (MJ)	Energy in Transportation (MJ)		
		25 km	50 km	100 km
Cement (kg)	5.85		50 (tonnes)	100 (tonnes)
Bricks (m^3)	2550		100	200
Steel (kg)	42		50 (tonnes)	100 (tones)
Sand (m^3)	--		87.5	175
aggregate(m^3)	20.5		87.5	175
Lime (kg)	5.63		87.5	175
Concrete (m^3) 1:2:4	1664			
Soil (m^3)	--		87.5	175
Cement mortar (m^3)	1268 (1:6 cement sand) 1006 (1:8 cement sand)			
Cement soil sand mortar (m^3)	849 for 1:2:6 mortar 773 for 1:2:8 mortar			

Table 2: Embodied energy in different building elements [2] [4] [6] [7] [8] [9]

Building element	Unit	Energy per unit (MJ)
Walling systems		
Burnt brick masonry	m^3	4841
Stabilized mud brick (SMB) masonry	m^3	646 with 6% cement 810 with 8% cement
Hollow concrete block masonry	m^3	819 with 7% cement 971 with 10% cement
Slab/roofing systems		
Reinforced concrete slab	m^2	730
SMB filler slab	m^2	590
Composite panel roof	m^2	560
Ribbed slab roof	m^2	490
Brick masonry vault roof	m^2	575
Stabilized soil block masonry vault roof	m^2	418
Ferro concrete tile roof	m^2	158
Clay tile roof		412.2
Cement fiber roof	m^2	74.6

Table 3: Embodied energy of different walling materials

Systems	Unit	Wall (MJ)	Average (MJ)	VI
Brick masonry	m^3	2141 [8] [6]- 4841 [7]	3491	
Hollow cement block masonry	m^3	819 – 971 [6]	895	
Cement stabilized block work without plaster	m^3	960	960	
Cement stabilized rammed earth	m^3	1271 – 2055	1663	

Table 5: Embodied energy of different walling materials with finishes

Walling system	Unit	Embodied Energy(MJ)	Average energy (MJ)	Energy of Finishes (MJ)	Total Energy (MJ)
Brick masonry with internal and external plaster (225 mm thick)	$10m^2$	4817.25 [8][6]- 10,892.25 [7]	7854 .75	1890	9745
Hollow concrete block masonry with internal and external plaster (200 mm thick)	$10\ m^2$	1638 – 1942 [6]	1790	1890	3680
Hollow concrete block masonry with internal plaster only(200 mm thick)	$10\ m^2$	1638 – 1942 [6]	1790	945	2735
Cement stabilized block work without plaster (240 mm thick)	$10\ m^2$	2304	2304	--	2304
Cement stabilized block work with internal plaster only (240 mm thick)	$10\ m^2$	2304	849 (mud plaster)		3153
Cement stabilized rammed earth without plaster (200 mm thick)	$10\ m^2$	2542 – 4111	3326.50		3326.50
Cement stabilized rammed earth with internal plaster (200 mm thick)	$10\ m^2$	2542 – 4111	3326.50	849	4175

Table 6: Embodied energy of different roofing materials

Description	Embodied energy per m^2

	of roof area (MJ)
Clay tiles	412.2 [9]
Cement fiber sheets	74.6 [9]
Ferro concrete tile roof (FCR)	158 [6] [8]
MCR roof	134

Table 7: Embodied energy of different floor slab systems

Description	Embodied energy per m^2 of slab area (MJ)
Reinforced concrete slab	516 [7] - 730 [6]
SMB filler slab	590 [6] [8]
Ribbed slab	490 [6] [8]
Pre-cast reinforced concrete slab system	469

Table 8: Details of the selected houses

House type	Walls	Roof	Ceiling	External wall colour
1	Bricks	Clay tiles	Cement fiber sheets	Cream

2	Cement blocks	Cement fiber sheets	Gypsum board	Cream
3	CSEB	Micro concrete tiles	Cement fiber sheets	Cream