Renewable Energy 34 (2009) 755–761

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Embodied energy analysis of adobe house

Ashish Shukla [a], G.N. Tiwari [b,*], M.S. Sodha [c]

[a] Centre for Energy Policy and Economics, Swiss Federal Institute of Technology, Zurich, Switzerland
[b] Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
[c] Department of Physics and Education, University of Lucknow, Lucknow, India

ARTICLE INFO

Article history:
Received 16 November 2007
Accepted 17 April 2008
Available online 24 June 2008

Keywords:
Embodied energy
Energy pay back time
Adobe house

ABSTRACT

In this paper an attempt has been made to develop a simple methodology to calculate embodied energy of the adobe house at Solar Energy Park, Indian Institute of Technology Delhi, New Delhi (28°35′N, 77°12′E) and its effect on the environment. The special feature of the adobe house is that, the whole house is constructed by using low energy intensive materials like soil, sand cow dung, etc. The embodied energy involved in construction of main structure, foundation, flooring, finishes, furniture, maintenance and electric work are 102 GJ, 214 GJ, 55 GJ, 5 GJ, 18 GJ, 59 GJ and 4 GJ, respectively. It is seen that the embodied energy involved in the maintenance of the adobe house (12% of total embodied energy) is significant. It has been found that approximately 370 GJ energy can be saved per year. The energy pay back time (EPBT) for the adobe house is 1.54 years. By using low energy intensive materials the mitigation of CO_2 in the environment is reduced by an amount 101 tonnes/year. The adobe house is more environmentally friendly house in comparison to conventional buildings.

1. Introduction

The selection of technologies and materials for the building construction should satisfy the needs of consumer, without affecting the environment. During the manufacturing process of several building materials greenhouse gases e.g. CO_2 are emitted in the environment. Worldwide designers are concentrating on minimizing the impact their building make on the environment. Energy requirements for the production and processing of different building materials and the CO_2 emissions have been studied by several scientists e.g. Suzuki et al. [1], Oka et al. [2] and Parikh and Tiwari [3]. Construction sector in India is responsible for the highest share (22%) of CO_2 emission [4] into the environment. In Indian construction industry annually 75 millions tones of cement, 10 million tones of steel and 70 billion tonnes of bricks are used. All such materials are high energy intensive and thus make more adverse effect on the environment. It has been shown [5] that the total embodied energy of a building can be reduced significantly when energy efficient or alternative building materials (lime, adobe, cow dung, etc.) are used.

The embodied energy analysis is an important tool for a holistic evaluation of the environmental impact a building makes on the environment. The embodied energy includes direct and indirect energy consumed for the entire production process [6]. During the life of a building energy is expended and the costs are incurred to maintain and operate it at habitat level [7]. Recently Australian researchers [8] highlighted the importance of both embodied and operating energy of a building. Life cycle energy analysis has been carried out for 25–50 years [9,10] and for 90 years [11] as well. Further none of these studies included operating or embodied energy requirement of appliances/equipment and furniture. However, all of them require frequent maintenance or replacement due to short useful life. A detailed life cycle energy analysis containing all this is carried out by Mithraratne and Vale [7] for life of 100 years. In the present study life of the adobe house is taken to be 40 years. The basic technology in construction of an adobe house is taken from native houses in villages of India and can be used in sub-urban regions as well. It is seen that the use of adobe, cow dung and other very low energy intensive material lead to very low emission of CO_2 in comparison to concrete or brick buildings. It is seen that the embodied energy in maintenance of adobe house is coming significant.

2. Design of adobe house

The building is situated in the urban area at Solar Energy Park, Indian Institute of Technology Delhi, New Delhi (28°35′N, 77°12′E). It is designed to provide an integrated office cum research space, with built-up area of 120 m^2. The longer side of the building is North–South facing.

* Corresponding author. Tel.: +91 11 2659 1258; fax: +91 11 2659 2208.
E-mail addresses: ashish.physik@gmail.com, ashukla@ethz.ch (A. Shukla), gntiwari@ces.iitd.ernet.in (G.N. Tiwari), msodha@rediffmail.com (M.S. Sodha).

0960-1481/$ – see front matter
doi:10.1016/j.renene.2008.04.002

Nomenclature

E	embodied energy (MJ/kg)
M	mass of materials used (kg)
V	volume of structure (m^3)

Greek symbols

ρ	density of materials used (kg/m^3)

Superscripts

ext	external
int	internal
t	total

Subscripts

i	different parts of adobe house

2.1. Space accommodation

The building consists of exhibition area and conference room, office space, student's workspace, computing equipment, laboratories, and utility space. The space of all the parts of building is given in Table 1.

2.2. Main structure and foundation

The roofing system of the building is designed to be spanned by domes and Nubian vaults. The building consists of three dome structures and three vault type structure (Fig. 1). The diameter of two small domes is 3.8 m whereas diameter of the big dome is 5.4 m. There is no use of reinforced cement concrete in lintels; they are made by burnt brick only. The factor of safety at the base of dome is calculated around 32. The foundations of the building are designed in such a way so that they can take up the horizontal thrust from the small domes and vaults. In the design of the foundation low still and high plinth are used.

2.3. Building materials

In the construction of the building materials with low energy content are used e.g. loam or mud. Burnt bricks are used only up to plinth level of the building to avoid dampness. The domes are built with stabilized soil blocks (6% stabilization with cement, made by simple mechanical hand press) and vaults are built by blocks stabilized with 4% cement (moulded by hand using simple wooden or steel moulds). These soil blocks are known as adobe. The dry and wet strengths of adobe are found to be 32 kg/cm^2 and 7 kg/cm^2. The exterior plastering of the building is made by mud mortar with conventional cow dung and sand. External surface of the building is also treated with spray of a hydrophobizing agent, which reduces the surface tension, and not allows water to stay on plaster. The construction specifications, which are used for various components of the adobe house, are given in Table 2.

3. Energy efficiency

The energy efficiency in the construction of adobe house is achieved in various phases.

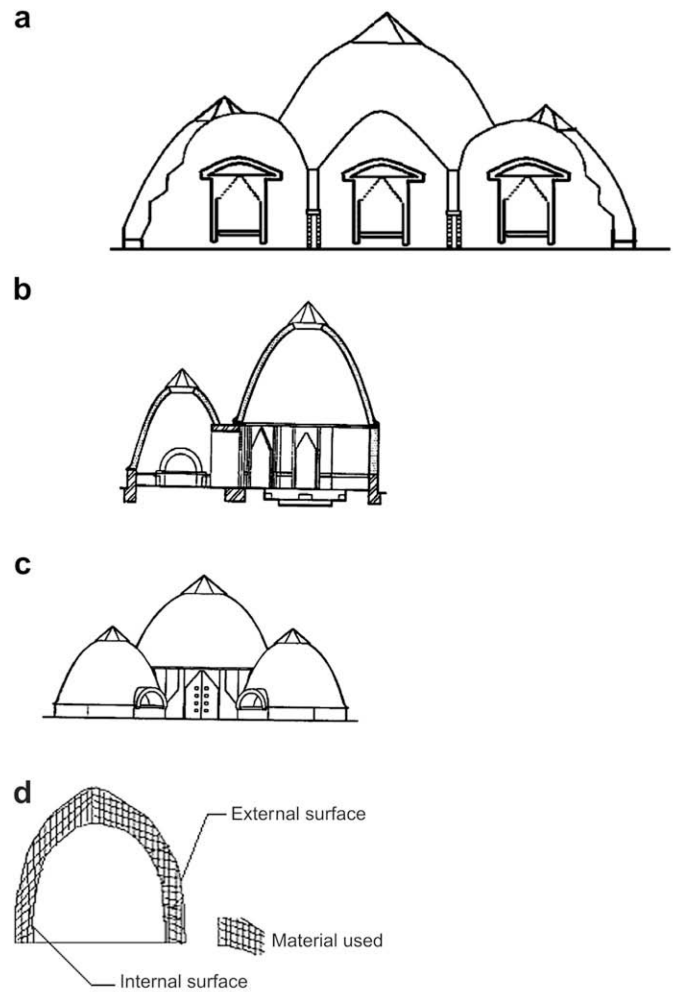

Fig. 1. (a) Front view of adobe house. (b) Side view of dome structures of adobe house. (c) Rear view of dome structures of adobe house. (d) Schematic diagram for material calculation for vault structure.

Table 1
Built-up area of different parts of adobe house

Function	Area in m^2
Exhibition area and conference room	25
Office space	22
Students workspace	12
Computing equipment	18
Laboratories	18
Utility space	10

Table 2
Specifications for various components of the building

Component of the adobe house	Specification used
Foundation	Plain cement concrete (1:5:10) with brick bats as coarse aggregate
Plinth	Burnt brick masonry with 1:4 cement mortar
Walls	Stabilized soil block (1 cement:6 sand:25 soil) masonry with soil cement mortar (1 cement:6 sand:20 soil)
Vault	Adobe (1 cement:8 sand:32 soil) masonry with mud mortar (1 cement:8 sand:30 soil)
Exterior finish	Mud–cow dung mortar (1 sand:1 soil:1 cow dung)
Interior finish	White wash with slaked lime

Table 3
Replacement cycle for building components and elements

Building component	Materials	Useful life in years
Main structure	Unbaked earth brick (adobe)	>40
	Baked earth brick	>60
	Concrete work	>100
	Mud plastering	>1
Floor	Cement flooring	>40
	Brick work, mortar, cavity ties, flashings	>40
Foundation	Concrete, brick ballast, cement and brick	>100
	work up to plinth level	>60
Electrical work	Wiring, switch board, power outlets	>40
Joinery	Iron window frames, external and internal doors, frames, door and window furniture, glazing	>60
Plumbing	Sanitary fittings, basins, sinks, baths, shower trays	>30
	Copper, PVC pipe	>50
	Towel rail, toilet paper holder	>20
Finishes	Repaint claddings, doors, frames, curtains	>8
	Repaint	>1
Furniture		>20
Appliances	Lighting	>1

3.1. Production

In the manufacture of a burnt brick nearly 2 kWh of the energy is consumed, while sun dried brick takes nothing if it made from the site of soil. The materials like cement and steel that are produced in industries take a lot of energy. In the construction of adobe house these materials are kept to a minimum.

3.2. Transportation

In the construction of the adobe house, the transportation costs are reduced significantly because adobes are produced at site from the soil excavated from the site itself. The mortar used for adobe also uses the site soil. The burnt bricks are used up to plinth level of an adobe house; this quantity of the burnt bricks is also very small.

3.3. Construction

The construction techniques used for the adobe house are highly labour intensive and avoid the use of expensive framework. During the construction of the adobe house only human energy is used and almost there is no use of mechanical energy.

Several other techniques are also used which helps in increasing the energy efficiency of adobe house e.g. appropriate design of overhangs, control of moisture by suitable walling material and proper orientation of wind.

4. Methodology to evaluate embodied energy

Simple mathematics has been used in calculating the embodied energy of the adobe house. Initially volume of the total material

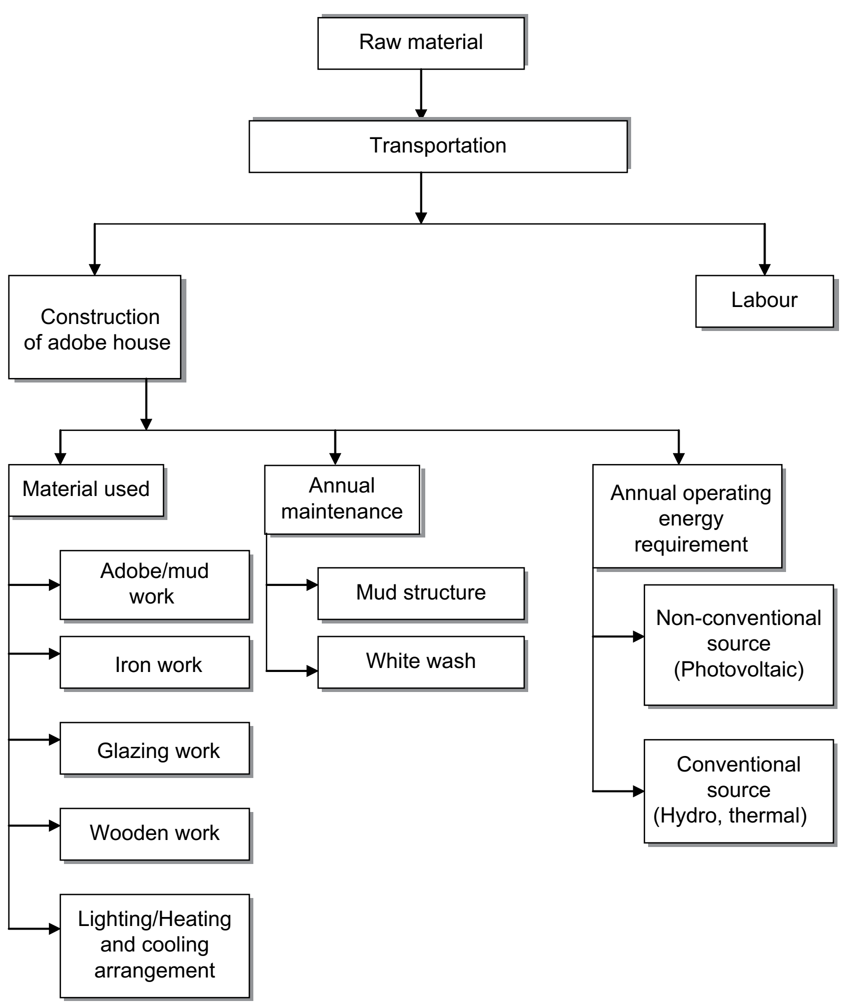

Fig. 2. Flow diagram for analysis of embodied energy.

Table 4
Mass and embodied energy of different materials used in construction of adobe house

Component of adobe house	Parts of component	Material used in different components	Mass of different material used (tonnes)	Embodied energy of different material used (GJ)
Main structure	Adobe	Cement	2.188	17.04
		Sand	19.472	1.55
		Soil	99.8	0
	Mud mortar	Cement	0.92	7.16
		Sand	8.176	0.65
		Soil	39.339	0
	Burnt brick work	Burnt brick	37.422	67.35
	Cement mortar	Cement	1.032	8.03
		Sand	4.59	0.36
Foundation	Brick work	Burnt brick	84.972	152.94
	Cement mortar	Cement	3.34	26.01
		Sand	14.848	1.18
	Brick ballast mixture	Brick ballast	12.043	21.67
		Cement	1.443	11.24
		Sand	16.04	1.2
Flooring	Materials of flooring	Brick ballast	22.04509	39.68
		Cement	0.93564	7.28
		Concrete	4.587	8.25
Finishes	Exterior	Sand	4.304	0.34
		Soil	55.145	4.41
		Cow dung	0.538	0.01
		Lime	0.095	0.0095
	Interior	Lime	0.086	0.0086
		Paint	0.0025	0.36
Furniture	Different furniture work	Woodwork	0.627	4.51
		Ironwork	0.25	13.50
Maintenance	Exterior	White cement	1	7.79
		Samosam	2.4	88.23
		Hydrophobizing agent	0.2	0.86
	Interior	White cement	0.6	0.30
		Samosam	1.6	0.27
		Paint	0.1	1.4
Electric work		PVC pipe	0.0175	1.82
		Copper wire	0.022	2.42

used is calculated and then the weight of the materials. Finally the weight of the material is multiplied by the embodied energy to give the embodied energy involved in that material.

$$V_i = \left(V_i^{\text{ext}} - V_i^{\text{int}}\right) \tag{1}$$

$$V_i^{\text{t}} = \sum_{i=1}^{6}\left(V_i^{\text{ext}} - V_i^{\text{int}}\right) \tag{2}$$

$$M_i = \left(V_i^{\text{ext}} - V_i^{\text{int}}\right)\rho_i \tag{3}$$

$$M_i^{\text{t}} = \sum_{i=1}^{6}\left(V_i^{\text{ext}} - V_i^{\text{int}}\right)\rho_i \tag{4}$$

Where $M_i^{\text{t}} = 2M_{\text{small dome}}^{\text{t}} + M_{\text{big dome}}^{\text{t}} + 3M_{\text{vault}}^{\text{t}}$;
$M_{\text{small dome}}^{\text{t}} = M_{\text{main structure}}^{\text{t}} + M_{\text{foundation}}^{\text{t}} + M_{\text{flooring}}^{\text{t}} + M_{\text{plastering}}^{\text{t}} + M_{\text{finishes}}^{\text{t}} + M_{\text{furniture}}^{\text{t}} + M_{\text{maintenance}}^{\text{t}} + M_{\text{electric work}}^{\text{t}}$;
$M_{\text{big dome}}^{\text{t}} = M_{\text{main structure}}^{\text{t}} + M_{\text{foundation}}^{\text{t}} + M_{\text{flooring}}^{\text{t}} + M_{\text{plastering}}^{\text{t}} + M_{\text{finishes}}^{\text{t}} + M_{\text{furniture}}^{\text{t}} + M_{\text{maintenance}}^{\text{t}} + M_{\text{electric work}}^{\text{t}}$;
$M_{\text{vault}}^{\text{t}} = M_{\text{main structure}}^{\text{t}} + M_{\text{foundation}}^{\text{t}} + M_{\text{flooring}}^{\text{t}} + M_{\text{plastering}} + M_{\text{finishes}}^{\text{t}} + M_{\text{furniture}}^{\text{t}} + M_{\text{maintenance}}^{\text{t}} + M_{\text{electric work}}^{\text{t}}$.

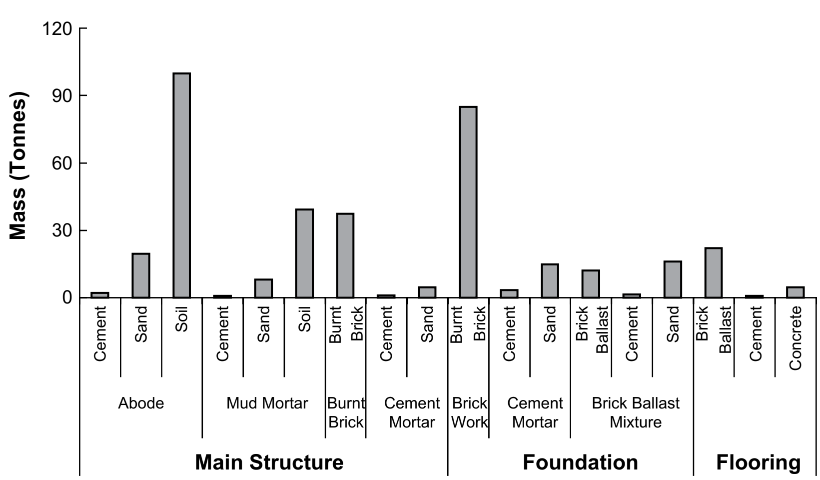

Fig. 3. Mass of material used in construction of main structure, foundation and flooring.

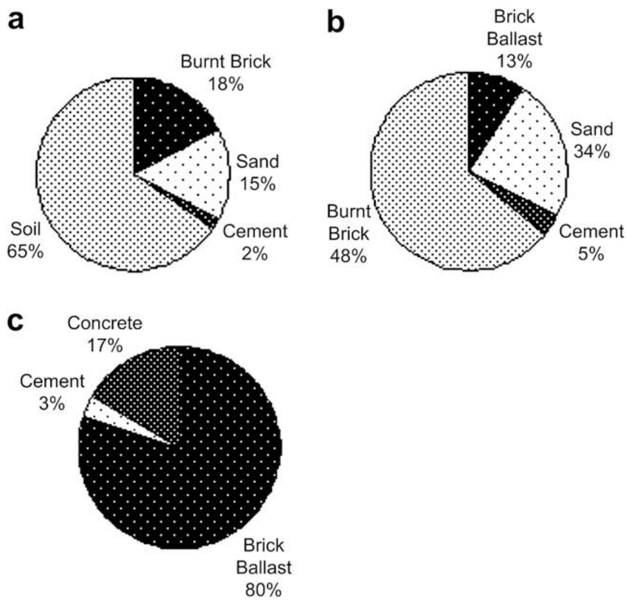

Fig. 4. Percentage distribution of different material for (a) main structure (b) foundation and (c) flooring.

The mass of the materials involved in construction of different components has been calculated. The embodied energy of the different component is calculated as:

$$E_{\text{embodied energy}} = \sum_{i=1}^{6} \left(V_i^{\text{ext}} - V_i^{\text{int}}\right) \rho_i E_i \tag{5}$$

$$E_{\text{life cycle energy requirement}} = \sum_{i=1}^{6} \left(V_i^{\text{ext}} - V_i^{\text{int}}\right) \rho_i E_i + E_{\text{maintenance}} + E_{\text{operating}} \tag{6}$$

4.1. Calculation of volume of material used for vault structure

The cross-section area of vault structure has been calculated using formula of area of triangle (1/2 base × height). The area has been multiplied by length of the vault structure to calculate the volume. Same procedure has been done using internal and external dimensions of the vault structure. The difference of two gives the volume of the material used. Table 2 has been used to calculate the volume of various materials used.

4.2. Calculation of volume of material used for dome structure

The volume of dome structure has been calculated by using formula $1/6\pi h(3r^2 + h^2)$. Here also volume using internal and external dimensions has been calculated and their difference gives volume of material used and hence used material is calculated from Table 2.

The sum of the embodied energy of all the components gives total embodied energy of the adobe house (Eq. (5)) and sum of the embodied energy, maintenance energy and operating energy gives life cycle energy requirement (Eq. (6)). CO_2 mitigation has been calculated from average carbon dioxide (CO_2) equivalent intensity for electricity generation from coal which is approximately 0.98 kg of CO_2/kWh [12].

$$CO_2 \text{ mitigation (kg)} = \text{Useful Energy (kWh)} \times 0.98 \text{ (kg/kWh)} \tag{7}$$

Energy pay back time (EPBT) is the number of years of useful life of adobe house to save same amount of energy used in the manufacturing of the adobe house.

$$\text{EPBT(year)} = \frac{\text{embodied energy}(E_{\text{input}})(\text{MJ})}{\text{reduction in heating/cooling load per year(MJ/year)}} \tag{8}$$

where, reduction in heating/cooling load $= mc(T_r - T_a)$.

5. Results and discussion

The embodied energy of the adobe house is calculated using Eq. (5). As adobe house is made of different materials, the replacement cycles of different material (Table 3) have been used while calculating the total embodied energy of the adobe house. The flow diagram (Fig. 2) has also been used in calculating the different material used in construction of the adobe house. In order to calculate the total material used in construction of adobe house, whole adobe house is divided into several parts e.g. main structure, foundation, flooring, furniture, finishes, electric work and maintenance.

Main structure of the adobe house is mainly made of adobe, mud mortar, burnt brick and cement mortar (Table 4). It is seen that

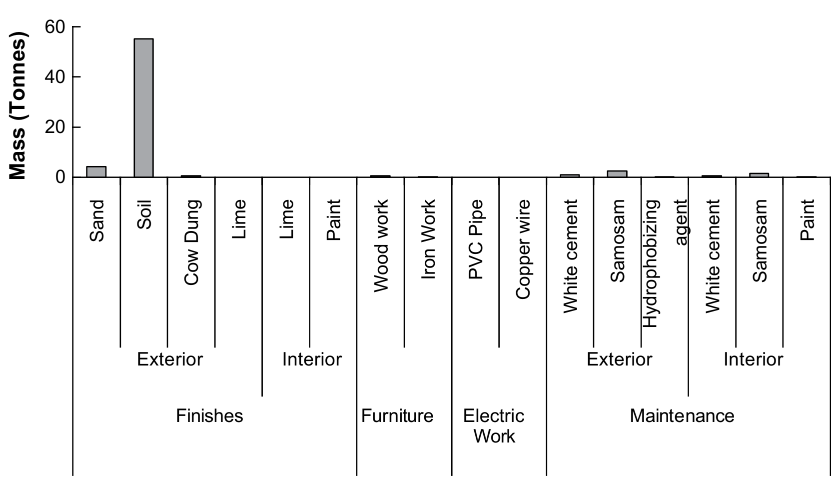

Fig. 5. Mass of material used in construction of finishes, furniture, electric work and maintenance.

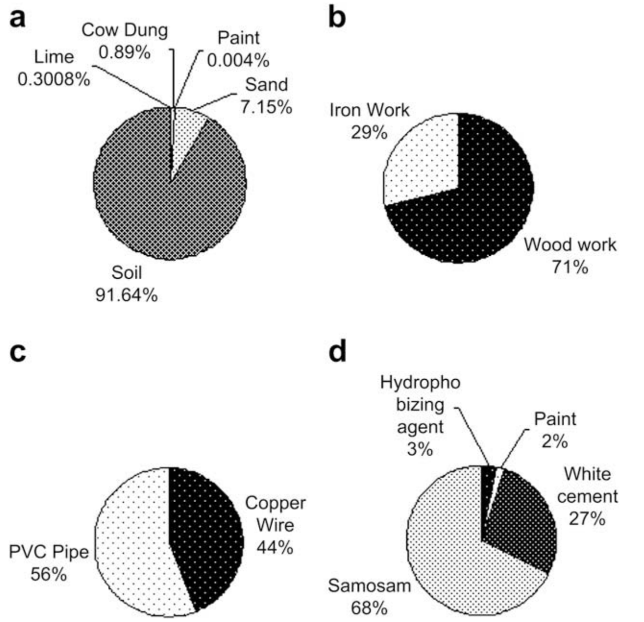

Fig. 6. Percentage distribution of different material for (a) finishes (b) furniture (c) electric work and (d) maintenance.

(Fig. 3) the soil is the major material (139.14 tonnes) used in the construction of main structure. It is seen that 37.42 tonnes of burnt bricks, 32.24 tonnes of sand and 4.1 tonnes of cement are used in main structure. The percentage values of different materials used in construction of main structure are 65% (soil), 18% (burnt brick), 15% (sand) and 2% (cement), as shown in Fig. 4a.

In the construction of foundation (Fig. 3), the burnt brick is used up to plinth. It can be seen (Fig. 3) that cement (4.78 tonnes), brick ballast (12.04 tonnes), sand (30.88 tonnes) and burnt bricks (42.48 tonnes) have been used in the construction of foundation. In the construction of foundation cement, brick ballast, sand and burnt bricks share 5%, 13%, 34% and 48% of total used material, respectively (Fig. 4b).

In the construction of flooring (Fig. 3) brick ballast (22.04 tonnes) and cement (0.93 tonnes) are used. The flooring also requires significant amount of concrete (4.58 tonnes). The percentage distribution of the different materials used in construction of flooring (Fig. 4c) is 80% (brick ballast), 3% (cement) and 17% (concrete).

In the exterior finish mud–cow dung mortar of specification (1 sand:1 soil:1 cow dung) has been used. The amount of cow dung, sand and soil used is 0.54 tonnes, 4.30 tonnes and 55.14 tonnes, respectively (Fig. 5). The white wash has also been done on the exterior surface of adobe house and 0.095 tonnes of the lime is consumed. The interior finish is achieved by white washing and painting of iron and wooden structure. The amounts of lime and paint used have been found to be 0.086 tonnes and 0.0025 tonnes, respectively (Fig. 5). It is seen that 92% soil is used in finishes (Fig. 6a).

Table 5
Embodied energy of different materials used in adobe house

Materials	Embodied energy (MJ/kg)
Burnt brick	1.8
Cement	7.79
Copper wire	110.2
Sand	0.08
Wood board from standing timber	7.2
Paint	144
Ironwork	54
PVC pipe	104.15
Soil (excavated from site itself)	0

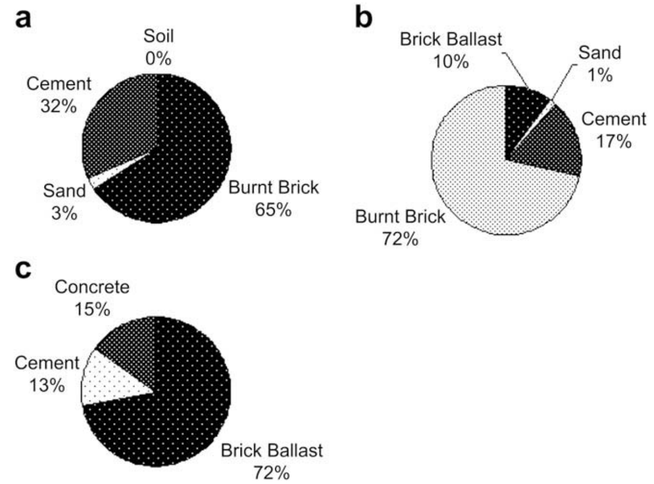

Fig. 7. Percentage distribution of embodied energy in (a) main structure, (b) foundation and (c) flooring.

The furniture of the adobe house consists of 0.62 tonnes of woodwork and 0.25 tonnes of ironwork. From Fig. 6b it can be seen that woodwork shares 71% of total furniture. In the electric work 0.0175 tonnes of PVC pipe and 0.022 tonnes of copper are used. In the electric work copper shares 56% of total material used.

The white cement (1 tonne), samosam (2.4 tonnes) and hydrophobizing agent (0.2 tonnes) have been used for exterior maintenance of adobe house for whole life. The interior maintenance of adobe house requires paint (0.1 tonnes), white cement (0.6 tonnes) and samosam (1.6 tonnes). The percentage distribution of different material used in the maintenance is given in Fig. 6d.

The embodied energy of different materials used in construction of adobe house is given in Table 5. It has been found that burnt bricks share maximum amount of energy (65% and 72%) in foundation and flooring (Fig. 7a,b). In the construction of flooring (Fig. 7c) brick ballast (72%) accounts for maximum embodied energy. The embodied energy involved in maintenance (Fig. 8) of adobe house is 10.4% of total energy involved in the construction and maintenance of the adobe house. In finishes, soil (86%); in furniture, ironwork (75%); in maintenance, samosam (52%); and in electric work, copper wire (57%) contributes to total embodied energy (Fig. 8). The

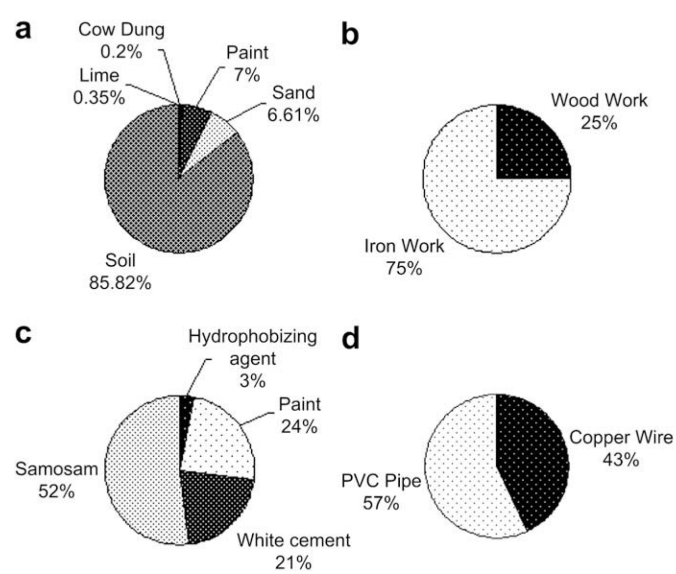

Fig. 8. Percentage distribution of embodied energy in (a) finishes, (b) furniture, (c) maintenance and (d) electric work.

embodied energy of the adobe house with life long maintenance is coming 475 GJ/100 m^2 built-up area. It has been found that life cycle energy reaches 552 GJ/100 m^2 built-up area when energy involved for (8 h in a day and 6 tubes light of 40 W) lighting is also added.

The embodied energy of conventional building has also been compared with adobe house. The embodied energy for 100 m^2 built-up area for conventional house made of burnt brick, concrete and cement is coming 720 GJ. It has been found that adobe house reduces the mitigation of CO_2 (Eq. (7)) into environment by 101 tonnes/year. The energy pay back time of the adobe house has also been calculated from Eq. (8) and the energy pay back time of the adobe house is 1.54 years.

6. Conclusions

The significant findings from this study are as follows:

(1) The embodied energy per 100 m^2 built-up area has been found to be 475 GJ and the embodied energy involved in maintenance of the adobe house (59 GJ) for useful life is significant.
(2) It has found that energy pay back time (EPBT) is 1.54 years for the adobe house under study.
(3) The heating/cooling load for the adobe house has been found to be 370 GJ and the adobe house reduces the mitigation of CO_2 by 101 tonnes/year.

Acknowledgements

One of the authors Dr. Ashish Shukla is grateful to Ministry of New and Renewable Energy (MNRE) Government of India for financial assistance and Er. Pankaj Shukla for valuable advice related to civil engineering aspects of buildings.

References

[1] Suzuki M, Oka T, Okada K. The estimation of energy consumption and CO_2 emission due to housing construction in Japan. Energy and Buildings 1995;22:165–9.
[2] Oka T, Suzuki M, Konnya T. The estimation of energy consumption and amount of pollutants due to the construction of buildings. Energy and Buildings 1993;19:303–11.
[3] Tiwari P, Parikh J. Cost of CO_2 reduction in building construction. Energy 1995;20(6):531–47.
[4] Working document of a project proposal on 'energy efficient and renewable energy sources project India', Document TA3-DA ARUN-95-001/1PDC, Development Alternatives, New Delhi; 1995.
[5] Reddy BVV, Jagadish KS. Embodied energy of common and alternative building materials and technologies. Energy and Buildings 2003;35:129–37.
[6] Nishimura K, Hondo H, Uchiyama Y. Derivation of energy-embodiment functions to estimate the embodied energy from the material content. Energy 1996;21(12):1247–56.
[7] Mithraratne N, Vale B. Life cycle energy analysis model for New Zealand houses. Building and Environment 2004;39(4):483–92.
[8] Fay R, Treloar G, Iyer-Raniga U. Life cycle energy analysis of buildings: a case study. Building Research and Information 2000;28(1):31–41.
[9] Buchanan AH, Honey BG. Energy and carbon dioxide implications of building construction. Energy and Buildings 1994;20:205–17.
[10] Jaques R. Energy efficiency building standards project: review of embodied energy. In: Proceedings of the embodied energy: the current state of play seminar. Geelong, Australia: Deakin University; 28–29th November 1996. p. 7–14.
[11] Johnstone IM. Energy and mass flows of housing: a model and example. Building and Environment 2001;36(1):27–41.
[12] Watt M, Johnson A, Ellis M, Outhred N. Life cycle air emission for PV power systems. Progress in Photovoltaic: Research Application 1998;6:127.