LIFE CYCLE ASSESSMENT OF COMPOSITES USED FOR LOAD BEARING EARTH WALLS

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Abstract

There's no doubt that construction of buildings and cities are activities with important social, economic, and environmental effects. This important activity consumes huge amounts of energy and resources and generates significant amounts of emissions and waste throughout its life cycle [1]. In fact, the sector of building construction is responsible for significant environmental impacts. According to some studies, around 20% of the total impacts are related to manufacturing, construction, demolition processes and final disposal of building materials, elements and systems [2]. Furthermore, authorities and public instances such the European Commission encourage the research of more sustainable building materials.

According to recent studies, the manufacturing and construction of building structural elements (like, for example, columns, beams and walls) represent the largest proportion of embodied impacts. Some of these reports highlight the need to review of the materials and techniques we use today in order to make the building sector more sustainable [3]. The present work is the result of the investigation about new material options for the construction of structural load bearing walls developed by researchers from the University of Seville. The study is carried out to clarify the environmental performance of each assessed alternative. Some conventional and new materials based – especially those with low level of embodied energy; e.g. some composites materials such as earth blocks stabilized with natural fibers and alginates - are evaluated from the point of view their environmental consequences.

1. Introduction

Sustainable construction is a response to the growing awareness of the negative impact of buildings on the environment. Designers (architects and engineers) have an important stake, however, as the selection of materials and construction systems are of great importance. In the last years there has been a vigorous scientific activity to evaluate environmental impact associated with buildings, there is still a lack of standardized environmental analysis procedures focus on building technologies. In this sense, the application of the life cycle assessment (LCA) [4, 5] is helping to clarify the consequences on the environment of using certain building materials and elements such as composites, being one of the tools for the environmental assessment of solutions in the construction industry. Energy in buildings can be categorized into two types: firstly by energy for the maintenance/servicing of a building during its useful life and, in second term, by energy capital that goes into production of a building (embodied energy) using various building materials. Study of both types of energy consumption is required for complete understanding of building energy needs. Embodied energy of buildings can vary over wide limits depending upon the choice of building materials and building techniques. Reinforced concrete walls, fired clay brick masonry, concrete blocks masonry, bream and block slabs; represent common conventional systems forming the main structure of buildings in Spain. Similar building systems can be found in many other developed and developing countries. Alternative building technologies such as stabilized soil blocks can be used for minimizing the embodied energy of buildings [6-12]. Generally, the materials used for the structure of buildings represent more than 50% of the embodied energy in the building [13]. In this sense, the use of alternative materials, such as mortar/concrete blocks, stabilized soil blocks or fly-ashes, instead of materials with a high embodied energy such as reinforced concrete could save 20% of the cumulative energy over a 50-year life cycle [14]. In addition, recycling building materials [15, 16] is essential to reduce the embodied energy in the building. For instance, the use of recycled steel and aluminium confers savings of more than 50% in embodied energy [17].

Early studies focused on some stages of the life cycle of certain products date back to the late 60s and early 70s of the twentieth century. These investigations have been reflected in the existing literature. Energy requirements for production and processing of different building materials and the CO_2 emissions and the implications on environment have been studied by Buchanan and Honey [18], Suzuki et al. [19], Oka et al. [20], and Debnath et al. [21]. Some researchers have analyzed the proportion of embodied energy in materials used and life cycle assessed in conventional existing buildings [22, 23]. Other different approaches and simplifications can be considered in order to perform an LCA for building materials [24]. And there are numerous studies published in which the LCA is applied to evaluate the impact of different construction materials and solutions [25].

2. Research goal and methods

Material production industries have been attributed to be one of the largest fuel consuming sectors of the economy. This indicates that savings in fuel consumption in these industries could have a substantial impact on total fuel demand [26]. Moreover, environmental assessments that include energy use for materials production are very important for the implementation of improvement options to the life cycle of the product. Environmental assessments of material production can provide criteria for design decisions when choosing materials offering similar performance for a given application [27, 28].

From an environmental perspective, different conventional technologies of building walls have been compared to others based on the use of new low-impact materials. By identifying and quantifying the materials involved in the manufacturing processes and by using the life cycle assessment methodology, the environmental impacts associated with each studied building alternative has been identified. Summing up, the undertaken study identifies the processes that take part in each technology, quantifies their associated impacts and compares their environmental performance.

The goal of this research is to compare the environmental aspects and potential impacts associated with construction, maintenance, and disposal of walls in three storey buildings typology, determining the option with the lowest negative impact related to its mechanical and structural characteristics. The Life cycle analyzing cases studied were three models of housing blocks erected with load-bearing walls. These walls were different according to their material structure. The options under comparison involved conventional and unconventional building materials; therefore, the study compresses: Fired clay bricks masonry (BC), Concrete blocks masonry (CB), Reinforced concrete based wall (RC) and Stabilized soil blocks masonry (SS).

3. Conventional and unconventional materials used

The construction process involves some expenditure of energy and produces some waste. There are several important questions. How much of each manufactured material is used? Can materials that have less environmental impact be used? How much energy is used? How much waste is produced? What is the impact of the waste on the environment? Some of these questions can only be answered for a specific structure. Increasing attention is being given to the construction phase as part of global and regional efforts to make development more sustainable. To establish a standard of comparison, we have chosen common, and not so common, building materials widely used for a specific building typology. Such materials are the above mentioned: Fired clay bricks masonry (BC), Concrete blocks masonry (CB), Reinforced concrete based wall (RC), and the not common one is the stabilized soil blocks masonry (SS). Some features of the different construction system are explained in the following sections.

3.1. Fired clay bricks.

Bricks are made by means of shaping a plastic mass of clay and water, which is afterwards hardened by drying and firing. Bricks are among the oldest and most enduring of mankind's building materials. They require a considerable amount of thermal energy during the burning process because they are fired at temperatures between 1 000˚ and 1 200˚C, depending on the clay. Light-colour clays usually require higher firing temperatures than dark-colour ones. This translates into a thermal energy of 3.75–4.75 MJ per brick. An average value of 4.25 MJ per brick (standard size in Spain: 240mm x 115mm x 70mm) has been considered for the comparison and computation of energy content of buildings and masonry.

3.2. Concrete blocks.

Concrete blocks are light weight/low density blocks very commonly used for the construction of envelope walls in multi-storeyed buildings in many countries. They are also used for the construction of load bearing masonry walls to a limited extent. The basic composition of the blocks consists of cement, sand and coarse aggregates (less than 4mm size). The energy content of the block will mainly depend upon the cement percentage. Energy spent for crushing of coarse aggregate will also contribute to the block energy. The cement percentage generally varies between 7 and 10% by weight. Quality of the block, particularly compressive strength is the deciding factor for cement percentage. Energy content of the concrete block of size 400mm x 200mm x 200 mm will be in the range of 12.3–15.0 MJ.

3.3. Reinforced concrete wall.

Concrete is manufactured from aggregates (rock and sand), hydraulic cement, and water. It usually contains a small amount of some chemical admixture, and often contains a mineral admixture replacing some portion of the cement. A typical concrete formulation contains a large amount of coarse and fine aggregate, a moderate amount of cement and water, and a small amount of admixture. Most of these constituents are themselves manufactured products, by-products, or materials extracted by mining. In order to assess the environmental impact of concrete manufacture, it is necessary to consider the impact of each separate constituent. The constituent with the highest environmental impact is cement. Portland cement is usually manufactured by heating a mixture of limestone and shale in a kiln to a high temperature (approximately 1500°C), then intergrading the resulting clinker with gypsum to form a fine powder. Thus it is not surprising that the Portland cement has a rather high embodied energy. Considering only the average value of the energy required of cement we can talk about 5,85MJ/Kg. If it is calculated the energy required for concrete, considering all constituents, the number of average energy is 1,4MJ/Kg. The Concrete reinforcement is made with steel rods. The energy consumed in the production of steel is 42MJ/Kg.

3.4. Stabilized soil blocks.

The stabilized soil blocks considered in this research are made by the combination of clay soil, water, a natural polymer as a stabilizer and animal fiber reinforcement. The polymer used is calcium alginate, which is added to the mixture in the proportion of 1.2% by weight. Calcium alginate production is chemical synthesizing from wet chopped seaweed adding calcium chloride and sodium carbonate. The animal fiber is wool, used cut and raw, without washing or processing, the proportion used is 0,25%

by weight. Blocks are cured at room temperature. The energy consumption is mainly by transport and extracting because they are not fired or steam cured.

3.5. Mortars.

Mortar is a mixture of cementitious material and sand. It is used for the construction of masonry as well as plastering and rendering works. According the European standard [29] the mortar used for masonry shall provide a compressive strength of 7.5N/mm2 this implies a cement-sand ratio of 1-5. This ratio represents energy consumption in the production of 1300MJ/m3.

3.6 Embodied energy of the proposed models

Considering that three of the four types of wall are masonry solutions and the other one is a combination concrete and steel, the energy consumption is given by the sum of the proportions of the different components for each model. Masonry is an assemblage of masonry units (such as bricks/blocks) and mortar. Individual volumes of these two components in masonry will depend mainly upon the size of masonry unit. Energy content of masonry should include energy content of masonry units as well as mortar. Reinforced concrete used in walls will have a steel/concrete proportion related with the required resistance according to the specific construction use.

4. Structural parameters

As a study hypothesis, a three storey building (ground floor + two) has been taken because it is a very common type for housing. The structure of the building is supported by load-bearing walls. A first variation respect to the constituent material of the wall is established: Fired clay bricks masonry (BC), Concrete blocks masonry (CB), Reinforced concrete wall (RC) and Stabilised soil blocks masonry (SS). And a second variable is established with respect to the distance between walls (span): 3.00 m, 3.50 m, 4.00 m and 4.50 m., being these most common dimensions for such a building typology. The resulting construction system's sizing is calculated from a mechanical point of view, determining the section of the ground floor load bearing walls.

The software used to establish the structural assumptions of the models proposed is CYPECAD; which is intended for the analysis and design of building structures, subject to horizontal and vertical loads, for homes, buildings and civil engineering projects. This program is adapted to international regulations. The program automatically generates hypotheses of any user-defined combination according to the stated premises. The user can also define their own project situations to personalize the combinations to be taken into account in the calculations for the structural elements of the project. After the introduction of the physical parameters of the different materials and the building characteristics in the software described, the dimensioning of the walls is obtained. Results are showed in Table 1.

	Compressive strength (MPa)	Density (g/cm^2)	Wall's thickness (cm) Span between walls: 3,0 m	3,5 m	4,0 m	4,5 m	Total wall's mass (kg) Span between walls: 3,0 m	3,5 m	4,0 m	4,5 m
BC	5,00	1,40	0,29	0,29	0,33	0,38	122,107	122,107	140.431	145.453
CB	4,00	1,50	0,20	0,23	0,25	0,35	47.098	53.865	57.248	57.248
RC	25,00	2,50	0,25	0,25	0,25	0,25	130.996	130.996	130.996	130.996
SS	4,45	1,79	0,28	0,30	0,32	0,33	115.062	121.830	128.599	142.136

Note: BC: Fired clay bricks masonry; CB: Concrete blocks masonry; RC: Reinforced concrete based wall; SS: Stabilized soil blocks masonry

Table 1. Summary of the medium value of the wall's thickness and total mass obtained for each load bearing wall construction after structural calculations.

5. Scope and boundaries of the LCA work undertaken

The particular focus of the application of the LCA in this study is to obtain the values of the embodied energy and global warming potential impacts (GWP) categories associated with the construction of four types of bearing walls: fired clay bricks masonry (BC), concrete blocks masonry (CB), reinforced concrete based wall (RC), stabilised soil blocks masonry (SS). A three storey construction is evaluated. The total height of the evaluated construction is 9,90 m. The construction is built with three parallel walls 8,00 m long each one. Distances between walls of 3,00 m, 3,50 m, 4,00 m and 4,50 have been evaluated. According to the proposed framework, this study should answer the following question: a) what are the impacts produced by the processes related to the construction for each one of the combination proposed? According to the objective of this study the functional unit established is the total surface of walls in each case. The assessed system is composed of every process that take part in the production, construction, maintenance, deconstruction and final disposal of every component of the building structure as such. It is excluded every processes related to the operational phase of the dwelling. The system includes the following processes:

- Manufacturing of building products phase. For each building material involved in the building every good and service from cradle to gate are considered. The manufacturing of employed machinery and territorial infrastructure processes has been considered.
- Assembly and construction phase. It covers every process aimed at integrating all products and services in the site in each studied dwelling. The transportation of building materials from the factory to the site, the placement of building products has been considered
- Maintenance and repair phase. Includes all repair operations and maintenance of building components. The renewal of those materials which have a lower durability has been considered.
- Dismantling and demolition phase. Every process carried out at the end of the life of the building to remove and demolish the dwelling has taken in consideration: Demolition, removal of building elements and transportation of demolition materials to recycling or disposal have been included.
- Disposal and recycling phase. It covers all processes which demolition materials have after dismantling i.e. the deconstruction of building materials.

The environmental data of wool and algae have been extracted from the recent studies conducted by Biswas et al. [30] and Resurreccion et al. [31] respectively. The environmental data of the rest of building materials were obtained from the databases ECOINVENT V.2. The calculation procedure to obtain the life cycle inventory was the described by García Martínez [32].:

1. Identification and quantification of the initial building products and auxiliary materials- including replacement materials- that takes part in the life cycle.

2. Identification and quantification of the basic processes associated with the construction and deconstruction. The determination of the energy consumed during the construction and demolition is obtained using a similar procedure as described by Kellenberger et al. [33].

3. Determination of inputs and output of each unit process. The database ECOINVENT V.2, and published LCA studies has been used to obtain environmental information of unit process.

4. Inventory and Assessment. The impact assessment is carried out using the CML 2001 method in relation to the GWP impact category. The "cumulative energy demand" in relation to the embodied primary energy.

6. Results and discussion

To evaluate the results showed in table 1, the first question to be considered is the relationship between the compressive strength of the different wall materials, the different thickness required for the different floor walls and the different distances between walls. For the comparison we determined, as starting point, that the strength of fired clay bricks masonry, and stabilized soil blocks masonry is quite similar (between 5,00 and 4,00 MPa), while reinforced concrete based walls is five times higher, (25,00 Mpa). This difference assumes a little change in thickness in the case of short distances between walls. But it is going to increase as the distances are greater. This variation implies that reinforced concrete based walls are much thinner (20-40% less) for bigger distances (4,5 m), than the rest of building materials used for setting the comparison in this research. Another issue that is relevant is the influence of the block or brick format and the constituent materials of the walls. In this case, this difference implies that the concrete blocks masonry has less than half the mass of the remaining walls. This factor gets to be a mass increase up to three times between Reinforced concrete based walls and Concrete blocks masonry (for 3,0 m distance); or between Fired clay bricks masonry and Concrete blocks masonry (for 4,5 m distance). There is not a linear increase of the materials mass differences with increasing distance between walls.

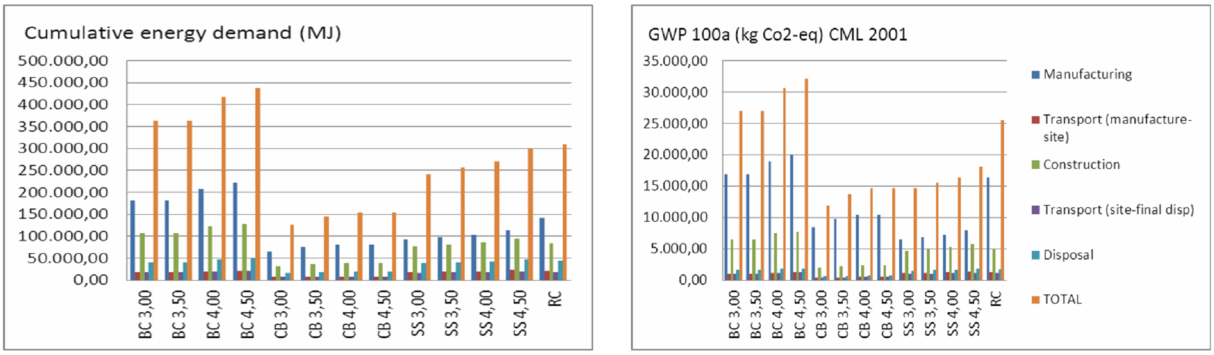

Figure 1. Cumulative energy demand (MJ) GWP 100a (kg Co2-eq) of each type of load bearing wall

A comparison of embodied energy values and global warming potential of individual type of wall is shown in Figure. 1. Regarding embodied energy, brick walls constructions (BC) represent the highest values; concrete blocks walls (CB) the lowest. The medium values for each type was 395.834,71 MJ and 145.027,43 MJ respectively. The medium values for stabilized soil wall (SS) and reinforced concrete walls (RC) were 266.562,54 MJ and 309.213,86 MJ. The contribution of the manufacturing phase to these results is significant, representing medium percentages in relation to the total stages from 38,11 % (SS) to 51,59 % (BC). Construction phase is also important, representing more than 25 % in all cases.

In relation to the global warming potential impact category, comparative results are similar: walls constructions (BC) represent the highest values and the concrete blocks walls (CB) the lowest. The medium values for each type was 29.188,97 kg CO2-eq and 13.716,86 kg-CO2-eq. The medium values for stabilized soil wall (SS) and reinforced concrete walls (RC) were 16.201,10 kg CO2-eq and 25.567,46 kg CO2-eq. The contribution of the manufacturing phase to these results is also significant, representing medium percentages in relation to the total stages from 44,07 % (SS) to 71,83 % (BC). Construction phase also contributes significantly to the total impact, representing medium values from 16,53% (CB) to 31,93 % (SS).

7. Conclusions

The significant findings from this study are as follows:

- For all the four cases studied, the LCA phases that more determine the final results are Manufacturing and Construction. In the Manufacturing process the embodied energy is 38-51% of the total amount and the CO_2 emissions represent a percentage ranging 44-72%. In the Construction phase the embodied energy involve 25,5-31,8% and the CO_2 emissions 16,5-32%.

- For all distances (span) between walls considered, stabilized soil blocks masonry (SS) have better overall results in the LCA than fired clay bricks masonry (BC) or reinforced concrete walls (RC).

- In the comparison of LCA results within the stabilized soil blocks masonry (SS) and the concrete blocks masonry (CB), for all distances between walls considered, SS achieve worse results than CB. The average embodied energy value calculated for SS, 280.000 MJ double that obtained for CB 140.000 MJ. Comparing SS and CB, the CO_2 emissions are less relevant representing only a difference of 12%, going from an average value of 16,000 kg of eq-CO_2 (SS) compared to 14,000 kg of eq-CO_2 (CB). These results are explained by the difference between total wall´s mass, which is 2-3 times higher for SS than for CB.

- The difference in LCA final results increases when increasing the span between walls. This establishes a relationship between the type and characteristics of the building and the choice of structural material from the point of view of embodied energy and the CO_2 emissions.

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