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Embodied Energy in Concrete and Structural Masonry on Typical Brazilian Buildings

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Abstract**—**The AEC sector has an expressive environmental responsibility. Actually, most building materials have severe environmental impacts along their production cycle. Professionals enrolled in building design may choice the materials and techniques with less impact among the viable options. This work presents a study about embodied energy in materials of two typical Brazilian constructive alternatives. The construction options considered are reinforced concrete structure and structural masonry. The study was developed for the region of São Leopoldo, southern Brazil. Results indicated that the energy embodied in these two constructive systems is approximately 1.72 GJ·m^{-2} and 1.26 GJ·m^{-2}, respectively. It may be concluded that the embodied energy is lower in the structural masonry system, with a reduction around to 1/4 in relation to the traditional option. The results can be used to help design decisions.

Keywords**—**Civil construction, sustainability, embodied energy.

I. Introduction

THE exploitation of natural resources is significantly reducing the reserves of natural materials around the world. It can be observed that the materials employed in construction have a great responsibility in the environmental impacts. There are several methods of environmental assessment. They are classified into three groups: embodied energy (EE), life cycle analysis (LCA) and identification using more simplified procedures, such as LEED and BREAM [1].

According to [1], all materials have some environmental impact and there are still no methods to accurately assess the total impact of a building. Even the analysis of individual materials is complex. For these authors, the embodied energy is one of the most important measures for evaluating environmental impact, precisely because the use of non-renewable energy is the main reason for the general environmental degradation (through the release of CO^2; and some emissions, such as acid rain).

Significant amount of energy is consumed in the production, transportation and application of building materials. Thus, the choice of materials and components can be made based on the analysis of the energy used for its production, and those considered best materials that consume less energy in their production processes and application in construction. The incorporated energy can be defined as the amount of energy consumed for the production of a product, or a material or construction, and may be included the steps of extraction of raw material to the distribution of product on the market [2].

The energy consumed in the built environment can be divided into two categories: (i) the energy consumed in producing the building, including the energy required for production and transport of materials, assembly or application in the work, and (ii) energy required for operation and maintaining the building over the life cycle and for scrapping and removing residues. The two plots should be studied, and the design definitions on the choice of materials have impact on both. Furthermore, in the same country, there is a great difference in power consumption due to technological differences.

The objective of this work is to use the quantification of embodied energy to examine constructive alternatives in a third world context, presenting a comparative analysis between two alternatives of traditional buildings in southern Brazil. It was found that the masonry structural system has incorporated significantly less energy than the traditional structured concrete.

II. Literature Review

Some studies point to different embodied energy building standards. Gao et al. [3] examined three types of buildings in Japan, indicating about 2.38 GJ·m^{-2} for wooden buildings in traditional Japanese pattern, 2.65 GJ·m^{-2} for wood frame and 2.85 GJ·m^{-2} for steel frame. These authors calculated the energy reduction that would occur in these systems incorporated with the use of recycled materials, concluding that the gain in EE would be about 10%.

Thormark [4] considered constructions in Sweden, consisting of four two-storey houses, built with masonry and reinforced concrete slabs, obtaining energy for construction around to 5.53 GJ·m^{-2}.

Venkatarama Reddy and Jagadish [5] studied cases of constructions in India. One of the alternatives studied is built with walls and roof with adobe blocks with vaulted roofs and adobe stabilized (with the use of cement and lime), reaching 1.61 GJ·m^{-2}. The second alternative consists of structural masonry walls, floors and roof of reinforced concrete (reaching 2.92 GJ·m^{-2}). Finally, they calculate the embodied energy in homes built with reinforced concrete structure and masonry walls, coming to 4.21 GJ·m^{-2}. Also in India [6]

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examined constructions very similar to the first option of [5], with adobe walls and vaulted roof burned blocks, reaching 1.99 GJ·m^{-2} for old buildings and 2.30 GJ·m^{-2} for renewed units. Asif, et al. [7] estimated the embodied energy in two-story row houses in Scotland with concrete structure and wooden walls, finding 1.62 GJ·m^{-2}.

In Brazil, there are some specific studies about EE, such as masonry [8], ceramic bricks [9], and water heating [10], but there is still a long way to go. Tavares [11] is the author with the most complete study in the country, calculating the total embodied energy for an actual building. The study by [12] indicates an embodied energy of 5.45 GJ·m^{-2} for the implementation of a public library, built with masonry, reinforced concrete structure and ceramic tiles on roofs.

Some differences are explained by sources. After [13], different energies found for each type of steel, ranging from 14 to 31 GJ·m^{-2}, whereas other authors used the same energy factor for all existing types of steel construction. Moreover, there are variations in time and space, because the energy depends on the production process, which varies from one country to another, according to various technological and different energy matrices, for example.

III. Methodology

The work was developed based on a case study of a residential project, with the simulation of two alternative construction systems on the same basic design. We studied two traditional construction systems: (i) composed of reinforced concrete structure with masonry sealing closure of ceramic bricks, and (ii) a structural masonry system with ceramic blocks. These two building systems correspond to those adopted in most vertical buildings constructed in the region.

The study has a focus on the city of São Leopoldo, situated on southern Brazil (it have around 207 thousand inhabitants, and its centre is located on coordinates 29°45′39″ S; 51°9′8″ W). Building studied consists of a social housing construction with four floors; each floor has four apartments with 38.75 m², plus 55.0 m² of common use area by floor, for vertical and horizontal circulation, totaling a built area of 675.0 m² per building.

A. Building Systems Studied

Reinforced concrete is the most used system in the region until now. This system has pillars, beams and slabs in reinforced concrete, with the masonry walls built with clay bricks. This system is well known and very used in the region.

The second type on focus is structural masonry. It is a constructive process in which the walls play a structural function. Thus, the masonry has two functions, structural and closure of the building. Reinforced concrete slabs are supported by walls.

B. Scope of Review

To make a comparison of the environmental impacts of both construction processes, it is necessary to characterize constructive steps which will be encompassed and what impacts will be assessed. In this case, we chose to examine only the embodied energy, not considering emissions of greenhouse gases, for example.

Some elements are similar for both systems. In both cases, it was assumed the same kind of specification for internal and external coatings, flooring, waterproofing, painting, roofing, window frames, glazing, electrical, hydraulic, sewer, and fire systems. Thus, we chose to exclude these items because it does not influence the final result, which aims to compare the two systems.

The following items are excluded from the inventory, although forming part of the structure. At the foundation, only the beams are included. Piling, shallow or any other type of foundation was not considered. In the case these elements would be very similar for both proposals.

This study analyzed the stages of production and transportation of materials, application in construction of building and waste removal. The stages of operation, maintenance and demolition were not counted during the work because it is considered to be fairly similar for both building systems and there are no policies in the region for recycling or final destination after demolition.

For the reinforced concrete structure we considered the following items:

- Foundation beams, and structure – pillars, beams, and slabs: this item included formwork, concrete and steel;
- Masonry: ceramic bricks and mortar.
- In the case of structural masonry structure, the following items were considered:
- Foundation beams and slabs: included forms, concrete and steel;
- Masonry: structural walls composed of ceramics, mortar and steel.

C. Energy Embodied in Materials

As becomes very broad assessment of the total embodied energy, and due to lack of data needed for a complete analysis, some items were not included, such as energy required for transportation of employees, production of tools, energy expended by cranes and elevators, among others. It is understood that there are not significant to this study, besides being similar for both cases.

Materials used for the production of slabs and foundations, such as timber and steel are produced elsewhere and transported to the construction site, and there are benefited according to project needs. For example, crushed stone and cement are produced and transported to the Ready-Mixed Concrete Plants (RMCP), making dosing and delivery of concrete to work on concrete delivery trucks. Other materials such as timber and steel are produced and brought to the site directly.

Considering these peculiarities and elements from the literature, embodied energy values were taken from several references with preference to national data. Table I shows the energy values incorporated in the materials used in the buildings. The energy consumption includes the energy required for transportation to the site. The materials considered are detailed below.

1. Portland Cement

The manufacture of Portland cement involves a series of activities extending far tracking your entire production. In this case embodied energy to produce one ton of cement is about 6.0 GJ energy [1], [5], [13], [14]. The origin of the cement used in these buildings is distant of 15 km of transport from the factory to the construction site.

2. Lime

The lime production consumes 5.6 GJ·ton^{-1} [5], [11]. In this case, the source is to 150 km transport distance.

3. Steel and Derivatives

Steel used in buildings is provided by a fabric that serves the region and is located 13 km away from construction site. For the production of steel in form of bars, it is necessary a consumption of 30 GJ·ton^{-1}. Already when it adopts recycling, using scrap as raw material, power consumption drops to 11.025 GJ·ton^{-1} [1], [3], [13], [14]. Currently this fabric is using 70% waste for steelmaking. Thus, the weighted value is 16.7 GJ·ton^{-1}. We adopted 33.8 GJ·ton^{-1} to wires and 31.0 GJ·ton^{-1} for nails, following [11].

4. Sand

For this item was considered the energy consumed by river transport, as well as losses caused by the discharge of sand at the pier. The origin of the sand used is 40km from site. The boat capacity is 100m³, being powered by a diesel engine with an approximate consumption of 1 km/L, which runs on average 120km on a full tour, with an average loss to around 1% on the pier, resulting in 0.0285 GJ·ton^{-1}[8].

5. Crushed Stone

We adopted the consumption of 0.15 GJ·ton^{-1}[11]. The origin of the raw material is located 18km away from construction site.

6. Formwork and Shoring Timber

Following several authors, estimated energy consumption for the production of timber is 1.5 GJ·ton^{-1}. In case, the origin of the wood has an average distance of 60 km from sawmill to the construction site. The energy for timber for shoring is 0.5 GJ·ton^{-1}. For the plywood were used 8.0 GJ·ton^{-1}. It is originate from other region with a transport distance of 720km [1], [3], [11].

7. Ceramic Brick

The clay bricks have origin of same city, with an average distance of 10km from fabric to site. Following the work of [9], to obtain the results of this item has been considered virtually all processes for producing bricks, resulting in 2.5236 GJ·ton^{-1}.

8. Structural Blocks

The company that produces the concrete blocks is located 15km away from work and it is the only fabric in the region that produces this type of block, with structural features. Data relating to size and mass was obtained directly from the company's website, but embodied energy were used following [9], with 2.5236 GJ·ton^{-1}.

9. Transport

Transport distance has a great importance in construction, because in Brazil all materials are transported by trucks. For this it was considered an average consumption of 3.0 km/L to trucks used by the suppliers of cement, sand, crushed stone, timber, bricks and blocks, with a capacity of 5 tons per trip. The consumption of diesel followed the works of [8], [9].

10. Mortar

Mortar is prepared on site, using mixer. Energy required for the mixing of materials is 0.0020 GJ·ton^{-1} [1], and the energy for the production of materials is considered separately, as presented above.

TABLE I
EMBODIED ENERGY ON SELECTED BUILDING MATERIALS

Description	Distance to site (in km)	Density (in kg·m^{-3})	Embodied energy (in GJ·ton^{-1})
Cement	15	1500	6.0
Lime	150	1500	5.6
Sand	40	1500	0.0285
Crushed stone	18	1500	0.15
Steel – bar	13	7800	16.7
Steel – wire	13	7800	33.8
Steel – nails	13	7800	31.0
Timber	60	500	1.5
Timber - shores	60	500	0.5
Plywood	720	1000	8.0
Ceramic bricks – 10x15x20	10	1700	2.5236
Ceramic blocks – 19x19x39	15	1500	2.5236
Transport/Diesel (by km)	-	-	0.0010
Production of mortar	0	1250	0.0020
Production of concrete	0	2300	0.0025
Transport and pumping of concrete	2	2300	0.0050

*Source: see items C.1 to C.12.

11. Concrete

The production of concrete occurs on RMCP and the necessary materials as crushed stone, sand, cement, and water are transported to the production plant. This item considered energies for mixture at the plant and on drum mixer of delivery trucks, reaching 0.0025 GJ·ton^{-1} [1].

12. Transportation and Concrete Pumping

This item considered energy for transport (2km from RMCP plant to site) and pumping, reaching 0.0050 GJ·ton^{-1}.

IV. RESULTS

In this section are compared qualitatively and quantitatively the two types of structures, to evaluate the results. For both structure types, calculations and surveys of material were performed using structural engineering software. After calculation of each structure were calculated quantities of materials used therein.

Materials were measured in tonnes. For materials acquired in different measurement forms, such as sand, crushed stones, bricks and timber were measured the conventional unit, with quantities being converted by mass densities as indicated in Table I. Results to embodied energy in building systems investigated are presented in Tables II and III.

Table II presents materials used for the implementation of reinforced concrete structure (including foundation and structure), which was considered a 15 MPa concrete, and masonry required for execution of the project. The quantities of materials considering conventional waste (occurring within the construction site) for each type of service. For example, it was accounted 10% for brick waste (item 2.1 on Table II) and 8% to steel waste (item 1.2.1). At the end, it was considered waste removal (item 3). In this item, the calculated energy is the activity of collection and removal of these materials to landfills.

TABLE II
QUANTITATIVE AND EMBODIED ENERGY OF MATERIALS FOR REINFORCED CONCRETE STRUCTURE

Item	Description and basic quantities	Material - mass (in ton)	Embodied energy (in GJ)*	%
1.	**Foundation beam and structure**		**302.81**	26.82
1.1	Concrete - 86.5 m^3			
1.1.1	Cement	27.248	163.49	
1.1.2	Sand	72.868	2.08	
1.1.3	Crushed stone	92.486	11.63	
1.1.4	Water	12.845	0.04	
1.1.5	Concrete-production and application	198.950	2.88	
1.2	Reinforcement - 6.05 ton			
1.2.1	Steel-bar	6.534	109.20	
1.2.2	Steel-wire	0.091	2.72	
1.3	Beam formwork - 337.6 m^2			
1.3.1	Plywood	0.871	0.32	
1.3.2	Timber	2.671	3.34	
1.3.3	Shores. Ø 10cm (h=2.20m)	1.697	0.11	
1.3.4	Nails	0.084	2.53	
1.4	Slab formwork - 660.0 m^2			
1.4.1	Plywood	1.505	0.55	
1.4.2	Timber	0.990	1.24	
1.4.3	Shores. Ø 10cm (h=2.20m)	9.953	0.70	
1.4.4	Nails	0.066	1.98	
2.	**Bricks masonry - 998.96 m^2**		**859.99**	73.13
2.1	Ceramic bricks (0.14 x 0.19 x 0.09m)	305.682	774.48	
2.2	Mortar – 38.082 m^3			
2.2.1	Cement	6.930	41.68	
2.2.2	Lime	6.930	38.88	
2.2.3	Sand	69.453	4.76	
2.2.4	Water	4.615	0.0138	
2.2.5	Mortar-production and application	76.164	0.19	
3.	**Waste remove - 94.821 ton**		**0.95**	0.05
Total		898.631	**1163.75**	100.00

*Including transportation.

The parts considered of the building represent in total about 1,164 GJ of embodied energy (EE) and about 900 ton of mass (Table II). In unitary figures, these results correspond to 1.72 $GJ \cdot m^{-2}$ and 1.331 $ton \cdot m^{-2}$. As can be seen by figures in Table II, about 66.5% of the energy is used producing ceramic bricks (item 2.1 in Table II). In second place appears cement which is responsible for about 18% of embodied energy (items 1.1.1 and 2.2.1). Waste, embedded in quantitative presented in Table II (items1 and 2), represents about 10% of EE.

TABLE III
QUANTITATIVE AND EMBODIED ENERGY OF MATERIALS FOR STRUCTURAL MASONRY

Item	Description and basic quantities	Material - mass (in ton)	Embodied energy (in GJ)*	%
1.	**Foundation beams and structure; includes structural masonry mortars**		**243.81**	28.55
1.1	Concrete - 70.5 m^3			
1.1.1	Cement	22.207	133.25	
1.1.2	Sand	59.389	1.69	
1.1.3	Crushed stone	75.379	9.48	
1.1.4	Water	16.269	0.05	
1.1.5	Concrete-production and application	176.250	2.56	
1.2	Reinforcing - 4.93 ton			
1.2.1	Steel-bar	5.324	88.99	
1.2.2	Steel-wire	0.074	2.22	
1.3	Beam formwork – 60.0 m^2			
1.3.1	Plywood	0.155	0.06	
1.3.2	Timber	0.475	0.59	
1.3.3	Shores. Ø 10cm (h=2.20m)	0.302	0.02	
1.3.4	Nails	0.015	0.45	
1.4	Slab formwork - 660.0 m^2			
1.4.1	Plywood	1.505	0.55	
1.4.2	Timber	0.990	1.24	
1.4.3	Shores. Ø 10cm (h=2.20m)	9.953	0.70	
1.4.4	Nails	0.066	1.98	
2.	**Structural masonry – 1.206.72 m^2**		**609.96**	71.41
2.1	Ceramic blocks			
2.1.1	Full block (0.14 x 0.19 x 0.29)	162.966	413.71	
2.1.2	Half block (0.14 x 0.19 x 0.14)	4.491	11.40	
2.1.3	$1^{1/2}$ Block (0.14 x 0.19 x 0.44)	18.838	47.82	
2.1.4	U Block (0.14 x 0.19 x 0.29)	34.910	88.62	
2.2	Mortar – 19.31 m^3			
2.2.1	Cement	7.01	42.15	
2.2.2	Lime	0.701	3.93	
2.2.3	Sand	31.495	2.16	
2.2.4	Water	5.133	0.0154	
2.2.5	Mortar-production and application	64.895	0.16	
3.	**Waste remove – 30.805 ton**		**0.31**	0.04
Total		698.788	**854.08**	100.00

*Including transportation.

Table III presents materials needed for the implementation of structural masonry building. In this case the structure was divided into two groups, one for the foundation and other to structural masonry. This table also incorporates waste, considering common rates of 2.5% for blocks (item 2.1).

The building composed of the structural masonry has a total energy consumption of 854 GJ (1.26 GJ·m^{-2}), and a total mass about 700 ton (1.035 ton·m^{-2}), as reported in Table III. Ceramic blocks are responsible for 65.7% of the embodied energy (item 2.1 of Table III). Secondly, we have cement, with 20.5% of EE (item 1.1.1 and 2.2.1).

V. Discussion and Conclusion

This study indicated that the embodied energy in these two building systems is approximately1.72GJ·m^{-2}and 1.26GJ·m^{-2}, respectively. There is a difference of 0.46 GJ·m^{-2} in favor of the structural masonry (a reduction of more than 1/4 when compared to reinforced concrete option) to the analyzed items. If they added the services and materials that were not in the inventory life cycle, such as special foundations, coatings, flooring, fixtures, roof, etc., this percentage tends to decrease. However the difference on energy consumption remains, in absolute figures.

Part of the difference between the systems is due to the masonry type, which arises from the coverage area of the ceramic block over the brick, while the participation on EE of blocks and bricks are similar (both about 66%). It happens that, while the assembly formed by a block and its corresponding wall fills an area of 600 cm² (20x30cm) and has a mass of 6.5 kg, a ceramic brick occupies an area of 200 cm² (10x20cm) and has a mass of 2.7 kg under similar conditions. Thus, for the same occupied area filled by the ceramic block, it is necessary to use 3 ceramic bricks, which together add up to a mass of 8,1 kg, namely, 1.6 kg heavier than the mass of a block.

The quantity of mortar needed for ceramic tile also is superior to the block, because the brick is used throughout complete seal around it. Furthermore, it is necessary to do more horizontal and vertical layers due to the smaller size of the ceramic tile. In the structural block is only necessary to make two horizontal and two vertical joints shaped fillet, so that the voids on blocks are not filled. The quantity of mortar in the masonry structural system is about 50% of the bricks masonry.

Another advantage observed for the use of ceramic blocks which may be used to calculate structure is reducing loads in structure and foundations due to the difference in mass of the blocks with respect to brick, as well as reducing the amount of mortar needed to execution. But often this advantage is no longer used because in Brazilian structural standards set loading for each type of bricks or blocks which is recommended be 13 kN·m^{-3} in both cases.

As a negative aspect, structural masonry presents an impossibility to change inner layout of the apartments, because it is not economically viable to make openings for doors, windows or to remove walls. This characteristic decreases its ability to make changes in the building (flexibility for future use).

It is concluded that the embodied energy is smaller in the structured masonry system, with a reduction of26.7% relative to reinforced concrete option. The results can be used to aid design decisions.

Considering the presented results, one can conclude that the building using structured masonry is advantageous from the environmental point of view, in respect of embodied energy and mass of material required.

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