Accepted manuscript of the article published in
Testing and Characterisation of Earth-based Building Materials and Elements : State-of-the-Art Report of the RILEM TC 274-TCE, part of the RILEM State-of-the-Art Reports book series (Volume 35), pp 261-296.
The final publication is available at Springer via https://doi.org/10.1007/978-3-030-83297-1_8

Chapter 8 Environmental potential of earth-based building materials: Key facts and issues from a Life Cycle Assessment perspective

Anne Ventura[1*], Claudiane Ouellet-Plamondon[2], Martin Röck[3,4], Torben Hecht[4], Vincent Roy[2], Paula Higuera[1], Thibaut Lecompte[5], Paulina Faria[6], Erwan Hamard[1], Jean-Claude Morel[7], Guillaume Habert[8]

[1] University Gustave Eiffel MAST/GPEM, Campus of Nantes, Route de Bouaye CS5004, FR-44344 cedex, France, anne.ventura@univ-eiffel.fr

[2] Département de génie de la construction, École de technologie supérieure, 1100, rue Notre-Dame Ouest, Montréal (Qc) Canada H3C 1K3

[3] KU Leuven, Faculty of Engineering Science, Architectural Engineering Unit, Kasteelpark Arenberg 1, 3001 Leuven, Belgium

[4] Graz University of Technology, Working Group Sustainable Construction, Waagner-Biro-Straße 100, 8020 Graz, Austria

[5] Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France

[6] CERIS and NOVA School of Science and Technology, NOVA University of Lisbon, 2829-516 Caparica, Portugal

[7] Faculty of Engineering, Environment & Computing, Coventry University, 3 Gulson Road, Coventry, CV1 2JH, UK

[8] Chair of Sustainable Construction, ETH Zurich, Switzerland

* Corresponding author: anne.ventura@univ-eiffel.fr

Abstract

The global challenge of large-scale climate change mitigation requires action also in the building and construction sector. From a life cycle perspective, and considering the mitigation timeframe, the issue of reducing embodied GHG emissions is gaining attention. Effective ways to reduce embodied GHG emissions have been proposed by the use of fast-growing, bio-based materials, due to carbon sequestered in the biomass. Another promising, yet largely under-explored option is to harness the environmental potentials and low embodied GHG emissions of earth-based materials for building construction. Earth construction dates back from 10.000-8.000 BC and has been derived in many vernacular construction techniques. More recently, some earthen techniques have been modified, using stabilizers, mainly cement and lime, to increase strength and water stability. The objective of this article is to compare existing literature performed on the LCAs applied to various earthen construction techniques and seek for key factors. Transports as well as binder stabilizations are very influent on the results. Climate, nature of local soil, and geographical context are very influent on functionalities of buildings, mix design and transports, themselves influencing environmental impacts. According to design choices and local context, earthen construction is not always better than concrete. This means that no universal solution can be recommended with the LCA of an earthen wall. The solution has to be adapted to the local context. All references comparing walls material to conventional materials at the building scale, find better environmental performances

of earthen walls compared to fired brick walls. However, a full comparison between earthen construction and conventional materials should account for the use phase: combining LCA models with thermal and durability models is a key research issue. Finally, it certainly would be useful to seek for solutions with best environmental performances in a local context, accounting for the nature of soil, the building's functional requirements as well as geographical and cultural specificities. Such an approach would ensure to lower environmental impacts but represents a drastic change in current construction practices. Whereas today building materials are standardized in order to fit with construction working practices, this paradigm shift would require to adapt construction working practices to the local material and context. As earthen construction is today, in many countries of the world, a re-emerging technique, and new professional practices are yet to be established, it seems possible to make this paradigm shift happen. Certainly, in the current context of the need to substantially reduce building-related GHG emissions, there is still strong potential in earth construction techniques for both research and building practice.

8.1. Introduction

The construction sector has for long been identified as one of the most contributing sectors to climate change with 30% of total greenhouse gases emissions in the world, mainly due to heating and cooling energy [1]. Moreover, recent studies have highlighted the growing importance of reducing buildings' material-related, embodied GHG emissions for effective climate change mitigation [2].

It is in this context that one can see a growing interest of civil engineering research on earthen construction. Earth construction dates back from 10.000-8.000 BC [3,4] and has been derived in many vernacular construction techniques. Earth can be implemented to build monolithic walls (rammed earth and cob techniques), using masonry units (adobe and Compressed Earth Blocks techniques), as infill of timber frame structures (wattle and daub and light earth techniques), as plasters to protect walls or as mortars either for earth and stone masonry units. Adobe are earth molded air-dried masonry units bedding with a mortar in order to build masonry walls. Adobes can have different dimensions and include, or not, plant fibers, namely if the earth clay content is high. If the clay content is low, they can be stabilized with air-slaked lime. The mortar can be of the same earth as the adobe or air lime-based. Compressed Earth Blocks (CEB) are produced by compacting humid earth in a manual or hydraulic press and joint with a mortar in order to build masonry walls. The CEB can have, or not, holes depending on the mold. A low content of binder is added to the earth to produce stabilized CEB [5]. The masonry units are layered with a mortar that can be earth-based or based on the binder that stabilizes the CEB. Cob walls are made by pilling successive portions of earth-plant fiber mixture, commonly without a formwork [6]. Rammed earth walls are made by compacting successive layers of humid earth inside a formwork until completing the formwork; afterwards, the formwork is disassembled and assembled for the adjacent rammed earth parcel and the process repeated [7].

More recently, some earthen techniques have been modified, using stabilizers to increase strength and water stability. Depending on the local availability of resources and of the construction technique, many different additives have been used from biopolymers such as Casein, starch or blood [8] to mineral additives such as bitumen or lime [9]. Currently the most common stabilizer is cement and is used depending on countries between 3 to 15% in mass of earth products [10].

One reason for the renewal of earth construction is the easiness of implementation as they do not require heavy industrial transformation processes. But the other key interest is that they can be used for excavated soils from earthworks which represent around 75% of total inert waste produced in Europe [11] and currently represent a raising problem for disposal around major urban centers. Finally, earthen construction may have lower environmental impacts in comparison with conventional materials such as cement concrete structures or fired brick masonry, which releases fossil CO_2 for their production [12].

Because environmental impacts of a building are not only provoked by the production of materials, but also by the use and end-of-life phases, it is important to estimate environmental impacts using Life Cycle Assessment (LCA) [13]. Environmental policies concerning the building sector have led to new incentives, tools and regulations, many based on LCA such as standards [14] in Europe. Today, to obtain a chance of spreading in the current practices, earthen construction has, among other aspects, to prove its environmental advantages through LCA studies. Moreover, in a long-term vision, new paradigms for construction practices must emerge towards at least minimal environmental impacts or at best environmental benefits, from the building sector. Earthen construction may be one among other possible solutions, especially if environmental innocuity can be reached.

However, the generic term “earthen construction” hides a wide variety of techniques, of dimensions and of mix designs, including or not additional materials, according to various types of soils, climate, and cultures around the World. Furthermore, existing traditional techniques have to adapt to current economic and regulation mechanisms, and evolve to save costs and to respect standard conformity. These adaptations can vary according to location, and they can require additional processes compared to traditional techniques such as the use of binders, of calibrated materials processed in quarries, or additional mechanical equipment, etc. These additional materials and processes often lead to additional environmental impacts. It is thus important to estimate how much environmental impacts earthen construction could generate considering their variety.

From these reasons, some countries developed their regional and national standards on earth construction. Indeed, earth construction is not limited to a specific climate zone. Standards exist for countries in Europe (Germany, France and Spain), Asia (Nepal, India and Sri Lanka), North and South America (USA, Peru, Chile, Bolivia, Brazil and Mexico) and Oceania (Australia and New Zealand)[15], meaning that earth construction can be versatile and has an expansion potential across the globe. These standards cover varied earth construction materials, from adobe to compressed stabilized earth blocks, from mortar to foundations, to floors and plasters, while also covering many technical aspects such as earth composition, molds, manufacturing, testing, structural design, construction methods, earthquake resistance and maintenance, just to name a few. However, there is still a lack of universally accepted standardization on the material production and construction methods as compared to the standards available on conventional materials, such as concrete or steel.

The objective of this article is thus to provide a review of existing literature performed on the LCAs applied to various earthen construction techniques. In the long term, this can help earthen construction actors to minimize their environmental impacts according to existing local conditions. The present review surveys the different construction techniques which have been analyzed and focuses on variability between studies. The article also wants to highlight key issues for LCA of earthen construction and future research to be done in the future.

8.2. Method

The article selection was conducted using Google Scholar as well as references collected from the different co-authors of the present paper. Because the number of available references is quite small, the review is not restricted to peer-reviewed articles but also includes reports and conference papers. The search included the following key words: earth construction (and derivatives such as earthen construction, earth buildings…) and other key words such as “energy”, “life cycle”, “impact” and “environment”. The review concerns 26 references found in the literature, ranging from 2001 to 2019, with among them: 19 peer-reviewed scientific journals, 5 reports (on-line publications and master’s thesis), and 2 conference proceedings.

References cover various earthen construction techniques and various countries (see Figure 8-1) and some cover more than one technique: 2 articles on cob [16,17] , 4 articles on CEB [18–21], 4 articles on adobe [22–25], 8 articles on rammed earth [26–33], one on earth plaster [34] and several other articles on various techniques not based on traditional methods.

References also cover life cycle phases differently. All references consider extraction and manufacturing steps, but only 9 of them consider the use phase. When included, the use phase is exclusively focused on maintenance aspects and does not consider thermal aspects and energy to achieve comfort and indoor air quality. Only 3 references consider the end-of-life phase.

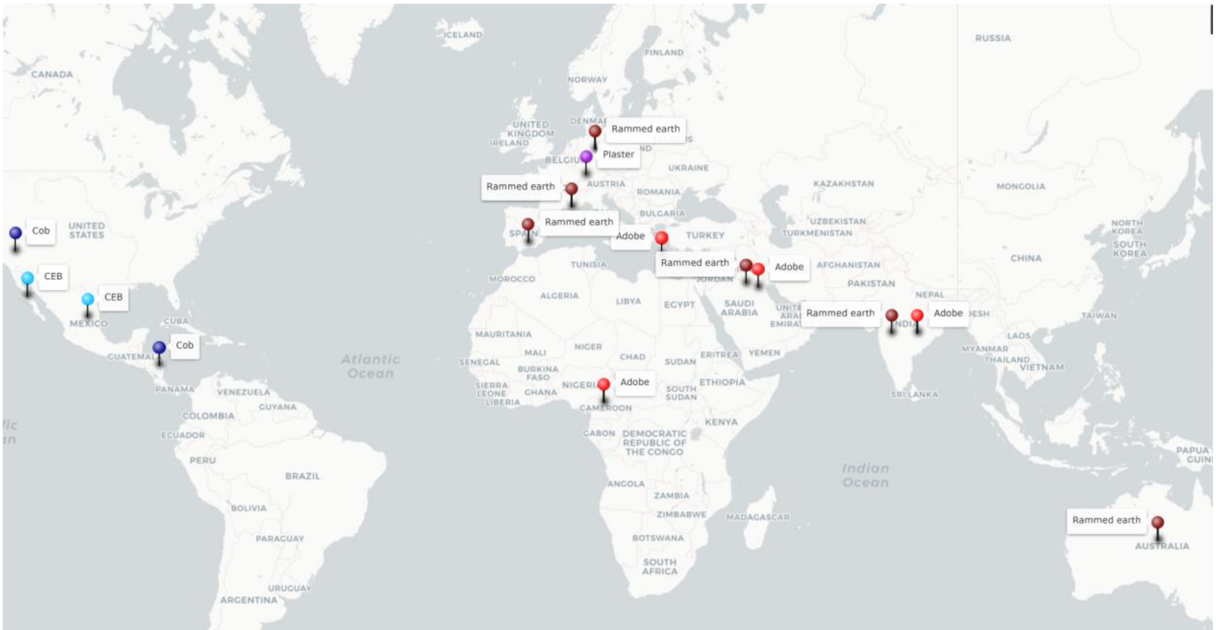


Figure 8-1. LCA and earthen constructions: locations and techniques found in the corpus of references

In general, LCA studies in the building sector can have different scales for different purposes. Some aim at comparing different materials and thus collect and provide results at material scale (one block, 1 kg…), others aim at comparing several possibilities of a given building elements (wall, window, roof…), and finally others aim at comparing entire buildings with different solutions including materials, elements, as well as usage scenarios. An increase of scale means an increase of choices and complexity of interpretation, because the number of possible parameters and possible interactions between choices drastically increase, but it also means comparing functions that are more similar. In the present article, the attention is focused on crude earth material used for walls. Thus, in order to allow comparisons between references, results were recalculated at 1 m² of the wall surface, when sufficient information was available to do so. Because many articles use different functional units, some assumptions and some calculations were necessary: they are all described in the **Erreur ! Source du renvoi introuvable.**. The calculation could not be performed for all references because some of them lacked sufficient information. Although some references provide indicators on many LCA impact categories, methods were generally different between references, and it was not possible to compare. Thus, the review focuses on energy. The term Cumulative Energy Demand (CED), is used by some authors [35], whereas others [21] use the term "saturated energy". In both cases, it corresponds to CED, defined by authors as the "energy required along the life cycle of a product, including energy of non-renewable fossil origin, nuclear, biomass or renewable of solar origin, geothermal, wind, and water" [21]. Other references [23,32,33,36–38] use the term "embodied energy" (EE). In this article, CED will be chosen because EE is a term commonly used in the building sector, but not the appellation for a specific indicator. EE of a product corresponds to a value of CED restricted to a cradle-to-gate system, i.e. use phase and end of life of the product are not considered. Further in the article, when values of CED and EE are compared, the use phase and end of life have been subtracted from CED values when needed. Thus, both terms "cradle-to-gate CED" or "embodied energy" are both used with the same meaning in this article. In LCA, the CED is the most common dedicated energy indicator: it represents the energy harvested in the ecosphere, also called "primary energy". However, despite its popularity, this single indicator can itself be defined quite differently according to existing standards [39], concerning harvested versus harvestable resources, the inclusion or not of renewables, fission and chemical energy sources. Thus, it is important to notice that some uncertainties of further presented results can be due to this lack of uniformity.

8.3. Extraction and production

8.3.1 Influence of clay content in raw earth

Venkatarama Reddy and Prasanna Kumar [33] measured compaction energy on experimental rammed earth wallettes and showed an increase from 125 to 150% with an increase of the clay fraction (from 21 to 31.6%). An increase in cement content also increased compaction energy, with a coupled interaction with clay content: a higher clay content required a higher addition of cement, which resulted in an additional increase of compaction energy. However, the importance of compaction energy was very small compared to total energy of the system.

8.3.2 Influence of binder in mix design

Influence of binder content is also interesting to observe. For references that made it possible (enough information provided), cradle to gate CED (or EE) has been calculated for 1 m² of wall and plotted versus binder content (see Figure 8-2). Binders are mainly cement and lime, but when it was different it has been indicated in Figure 8-2.

The figure shows a cluster of CED values between 0 and 400 MJ/m² for binders' contents ranging from 0 to 10%. Inside the cluster, it appears that LCA studies focusing on materials show CEDs values found slightly below studies focusing on wall scale.

Outside of this cluster, four outliers are observed. Two outliers provide high results with a low binder content [28,38]. Both concern studies conducted at building scale. The contribution of transport was found very high for one reference [28] and the binder is not cemented but a mix of trass mortar and geogrid, but no sufficient details are provided to analyze results from [38]. Another outlier [26] only founds around 90 MJ/m² of EE for a 30% binder content. In that specific solution, the binder was composed of flying ashes and carbid lime. The difference can directly be attributed to the type of binder used, because for other results from the same study [26] concerning materials containing cement, the EE was found consistent with the other references. Both flying ashes and carbid lime were obtained from waste valorization and the authors considered them as zero impact inputs. Another system model (end of waste or partition of valorization processes) would probably increase the impacts of that solution. Finally, the last outlier [35] shows a high EE value around 700 MJ/m² for a high cement content of 28%. This study is very specific as it does not correspond to a traditional earthen construction technique but to a sandwich panel including a polyurethane foam insulation.

CED values obtained with no binder (for both material and wall scales) are found the lowest. According to details provided by some authors [18], binders are responsible for more than 50% of the total energy consumption, thus it is likely to think that a change in cement content is very influent on CED. To check that idea, the CED of various cement contents of a mix design containing earth and binder in an average wall (thickness 0.4 m and density of earth dry density 2,000 kg/m^3) has been calculated, using the ecoinvent 3.3 cut-off database (market process at global scale, CED = 4.2 MJ/kg of Portland cement). It is represented in Figure 2 (dot line). Most of the CED values obtained at material or wall scales and using cement or lime as binders, provide results close to that trend, showing the predominance of these binders to CED in a cradle to gate system. Except the reference using carbid lime [26], two references using others binders, i.e. sodium silicate and sodium hydroxide [18] or trass mortar and geogrid [28], provide CED values largely above the line.

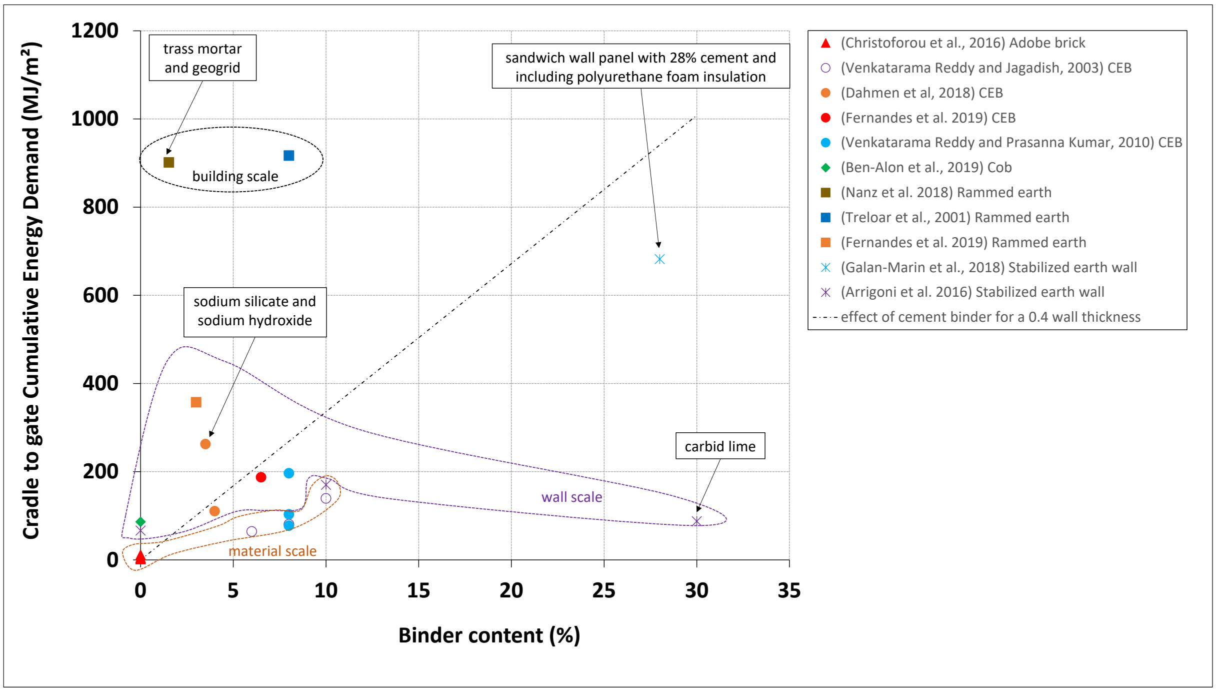


Figure 8-2. Influence of binder content on the cradle to gate Cumulative Energy Demand - shape is linked to construction technique: ○ CEB, □ Rammed earth, ◇ Cob, ⁎ Stabilized earth wall, △ Adobe – unless indicated otherwise, binders are cement or lime.

8.3.3 Influence of the scale of data collection

As observed in the previous section, there seem to be a tremendous difference between results when considered scales vary. To further analyze this initial observation, EE per m² of the wall have been plotted versus the volume of earth material considered in each studied in Figure 8-3 (log scale has been used for more convenient representation). There is a clear increase of EE with an increase if scale from material to wall and then to building. This can be explained by the higher complexity of the system studied and the additional materials considered from main material (where only earth is considered) to wall and buildings where many other materials are included.

At wall scale, one could explain the increase by the contribution of bedding mortar as well as construction operations, and possibly renders and plasters.

At building scale, the number of possible design choices drastically increases compared to material or wall scales. And these choices may interact one another, such as the interaction between the number of floors and wall thickness and/or cement content. In addition, the wall of a building also includes openings, that cannot be subtracted from the results if details are not provided. Furthermore, local conditions and cultural aspects will also play an important role concerning the use of insulators, external and internal coatings. Finally, whereas transport distances have to be assumed for studies at material or wall scales, they are better known at building scale, and may be quite high compared to assumptions. The building scale thus introduces a complexity that is not enough accurately described in existing references, to allow an accurate downscale and comparisons with material or wall scales. However, this complexity represents the actual practice, and highlights that a wall or a building cannot be resumed nor solely characterized by a material, at least in terms of environmental impacts.

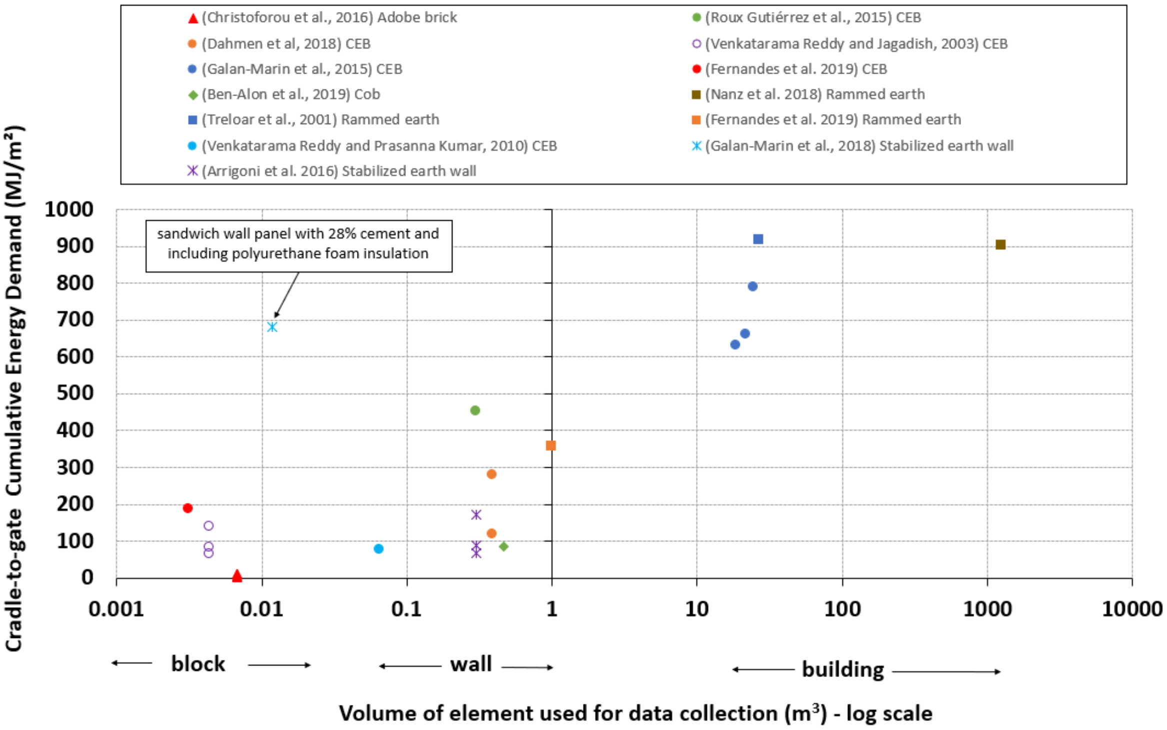


Figure 8-3. Influence of scale used for data collection – shapes of plots are linked to the construction technique: ○ CEB, □ Rammed earth, ◇ Cob, ⁎ Stabilized earth wall, △ Adobe

8.3.4 Influence of transports

Various results can be obtained from the corpus of reference. Some results are detailed below for LCAs at wall or building scales.

8.3.4.1. Wall scale

One study looked in detail about transportation-related impacts on adobe production [23]. They show that compared to soil extraction alone, soil transportation between the soil extraction site and the adobe manufacturing site on a 50 km distance multiplied both CED and GWP100 by a 3 factor [23]. The same study showed that adding a 100 km transport distance between a manufacturing site for adobe and the building site increased these two indicators by around 50% [23]. Including transports, CED for soil extraction was found to be around 4.7 MJ/m² for an adobe wall (thickness 0.15 m) [23].

This value can be compared to the CED = 5.5 MJ/m² obtained in a previous study [33] for a rammed earth wall (wall thickness 0.2 m, thin in comparison to common rammed earth walls) with soil transported on a 25 km distance. Although distances are different, as well as dry densities and total masses per square meter of the wall, orders of magnitudes are similar for both references. Results on transports are also provided for two cases of rammed earth walls in Germany [28]. For those two cases, transport contribution was found between 55% and 84% of total energy (see **Erreur ! Source du renvoi introuvable.** in the appendix).

On the contrary, a study concerning two stabilized earth blocks in California [18] found transports representing 22% and 9% of total energy (calculated from

in the appendix). This difference shows clearly that when only earth is used, transport is a predominant parameter to consider for environmental impact assessment. On the contrary, when earth is stabilized with cement, the impact of transport becomes a second order parameter, as it is the case for other industrialized building materials such as steel [40] or concrete [41].

8.3.4.2. Building scale

The comparison of a cob house to a concrete house located in Nicaragua and Costa Rica [17] also investigated the contribution of transport on climate change indicators. The authors showed that transports contributed to 25% of total GWP100 for the cob house.

Morel et al. [27] provided detailed scenarios of transports for three cases of buildings located in France (see **Erreur ! Source du renvoi introuvable.** in appendix). Calculation of energy c orresponding to transports was not conducted in the article, only total ton.km were provided, but the calculation has been done for the present review from data obtained in the article (see **Erreur ! Source du renvoi introuvable.** in appendix). The studied earthen buildings reduced o f around 80% the amount energy for transport compared to the current concrete building taken as a reference. Transport only contributed to around 2 % of total energy consumption for earthen buildings using local resources when it contributed to around 4% for the reference current concrete building.

The contribution of transports on environmental impacts for two rammed earth façades, one with on-site soil extraction, and the other with off-site soil extraction, was analyzed by Nanz et al. [28]. Two transport operations were distinguished:
- transports between soil extraction and manufacturing sites (A2 stage according to EN15804 [14]), with a distance of 0.61 km/m² for the on-site solution, and 7.93 km/m² for the off-site one [28];
- transports between the manufacturing and the construction site (A4 stage according to standard EN15804 [14]), with a distance of 0.13 km/m² for the on-site solution and null for the off-site one.

For the on-site solution, more than 98% of the materials were transported on a distance under 10 km to the production site.
For the off-site solution, the 1,061 tons of soil were excavated from a tunnel construction works, and were transported on a total distance of 9,143 km using trucks of 24 tons capacity. The total primary energy demand was found equal to 5,200 MJ/m². With a transportation credit

considering that this soil should have been transported to the nearest landfill 60 km away, the energy was then decreased to 3,833 MJ/m².

Globally, the total energy consumption of transports accounted for more than 55% for the on-site solution and 84% for the off-site solution [28] . This example shows that it is important to keep results on the A1-A3 phases disaggregated, and also clearly shows that transports have a considerable influence on environmental impacts for building materials with low carbon intensive production processes. On-site soil extraction is indeed an important factor to minimize environmental impacts.

8.3.5 Influence of the building's design

Galan-Marin et al. [42] compared the effect of environmental impacts for different heights of buildings. They found an increase from CED = 630 MJ/m² (and GWP = 38.9 kg CO_2 eq/m²) for one level, to CED = 788 MJ/m² (and GWP = 47.9 kg CO_2 eq/m²) for three levels. More precisely, adding one floor was found to increase both impacts of 4-5 % compared to the one-floor building, but adding one more floor was found to increase both impacts of 19 % compared to the two-floor building. The necessity to increase mechanical resistance of walls when building with three levels explains this result.

8.4. Use phase

8.4.1 Maintenance of earthen walls

The LCA of the maintenance phase of earthen buildings have been included in three LCAs studies [20,21,25]. However, none of the studies provide details on maintenance scenarios (i.e. descriptions of types and frequencies of maintenance operations).

Some results are provided on the total of construction and maintenance phase of a CEB wall stabilized with calcium hydroxide and located in Mexico [21] per 1 m² of CBE wall (see **Erreur ! Source du renvoi introuvable.** in the appendix). Their results showed that both construction and maintenance phases were well below the manufacturing phase, but the detail of maintenance compared to construction, as well as the value of service life considered, are not provided.

The LCA study on an adobe house with a 40-year life span [25] also provided results on maintenance, not detailing maintenance scenarios, but providing amounts of materials necessary to maintain interior and exterior walls. For exterior walls, white cement, samosam and hydrophobizing agent were used for rendering, and for interior walls, painted white cement-samosam plasters were used. This study [25] does not provide impacts of maintenance, only masses of materials, and those are found negligible compared to masses of materials for initial construction (see **Erreur ! Source du renvoi introuvable.** in the appendix).

8.4.2 Heating and cooling energy: thermal aspects

Thermal properties of materials are a key aspect of the usage phase of any building because they drastically influence the building's energy consumption during its service life. Several physical considerations of the materials have to be considered: thermal conductivity, thermal mass, as well as hygroscopic properties. In addition to materials' properties, the buildings' design and the construction method also play an important role for energy savings. These aspects are detailed below.

8.4.2.1. Material scale

Thermal conductivity reflects the ability of a material to transfer heat, and it is expressed in $W.m^{-1}.K^{-1}$. The thermal resistance of a material is calculated as the ratio between the materials' thickness and its conductivity. A material can be considered as a thermal insulator when its conductivity is at most 0.065 $W.m^{-1}.K^{-1}$ [43]. For earthen materials, the conductivity increases with the materials' water content. In a plastic physical state, with an important water content, earthen materials' conductivity was found around 2.4 $W.m^{-1}.K^{-1}$ and it could go down to 0.6 $W.m^{-1}.K^{-1}$ for a perfectly dried state [44]. Conductivity was linked to density considering that the water content is accounted in the density of an earthen material [45] as resumed in Table 8-1. Thermal resistances of earthen construction walls were found comparable to those of classical materials with an adequate thickness, at least 0.45 m [45].

Table 8-1. Relationship between the earthen construction technique, thermal conductivity and density [45]

Construction technique	**Density (kg/m^3)**	**Conductivity ($W.m^{-1}.K^{-1}$)**
Cob	1,450	0.60
Adobe	1,650	0.82
CEB (manual)	1,750	0.93
Rammed earth or CEB (mechanical)	2,000	1.20

Thermal inertia represents the ability of a material to resist to a change of temperature. The thermal mass, associated to the thermal conductivity of a material, plays a role in terms of the time necessary for a change of outside temperature to be transferred to the inside temperature, defined as time lag ϕ (Eq. 1). The decrement factor f (Eq. 2) represents the attenuation of the change of outside temperatures compared to the change of the inside temperatures.

$$\phi = t_{Toutside\_max} - t_{Tinside\_max} \tag{1}$$

With ϕ the time lag of temperature wave (hr), $t_{Toutside\_max}$ (hr) the time of the day at which the outside temperature is minimum, and $t_{Tinside\_max}$ the time of the day (hr) at which the inside temperature is maximum.

$$f = \frac{T_{inside\_max} - T_{inside\_min}}{T_{outside\_max} - T_{outside\_min}} \tag{2}$$

With f the decrement factor (no unit), T_{inside_max} (°C) the maximum inside temperature, T_{inside_min} (°C) the minimum inside temperature, $T_{outside\_max}$ (°C) the maximum outside temperature, and $T_{outside\_min}$ (°C) the minimum outside temperature.

Roux Gutiérrez Rubén et al. [21] measured thermal delays on eight different wall structures out of CEB. The time to reach maximum temperature was further measured on conventional wall structures from concrete blocks and fired bricks. The comparison showed that the time delay took five and a half hours longer with a CEB wall than with other materials. According to Baggs and Mortensen [46], the thermal mass of earthen walls (1,740 kJ/(m^3.K) for CEB and 1,300 kJ/(m^3.K) for adobe) was comparable to the one of a fired brick wall (1,360 kJ/(m^3.K)), below the one of cement concrete (2,060 kJ/(m^3.K)) and above the one of an autoclaved aerated concrete block (550 kJ/(m^3.K)). Asan [47] investigated the time lag and decrement factors of several building materials, including clayish earth and pure clay. Table 8-2 provides a part of his results about mineral bulk materials for the building. Thus, the thermal mass effects of clay were found of the same order of magnitude than concrete blocks and bricks, while earth layers were about twice higher regarding time lag and decrement factors [47]. According to Asan [47], it means that, due to thermal inertia, earthen walls buildings are fresher in summer and warmer in winter than conventional building systems.

Table 8-2. Time lag and decrement factors of several mineral building materials, after [47]

Material	**Thickness: 0.1 m**		**Thickness: 0.2 m**	
	Time lag ϕ (hours)	**Decrement factor f**	**Time lag ϕ (hours)**	**Decrement factor f**
Fired brick	2.83	0,343	6,65	0,137
Concrete block	2.88	0.312	6.81	0.118
Sandstone block	2.03	0.519	4.47	0.306
Pure clay layer	2.61	0.396	5.98	0.178
Cement layer	1.89	0.284	5.82	0.128
Earth layer	6.12	0.184	12.08	0.036

Hence, beyond thermal inertia, it is important to know if such thermal properties can lead to energy savings. Serrano et al. [29] made an experimental study in summer conditions in Spain using cubicles made of different materials. They compared two kinds of walls: rammed earth and fired brick masonry, with several insulation systems and roofs. They found that the energy consumption with 0.29 m of rammed earth associated with a bio-based insulation material (0.06 m) gave the same cooling consumption than 0.21 m of brick walls insulated with polyurethane (0.03 m). In this study, the theoretical transmittance was 0.563 W/(m².K) for the rammed earth wall, and 0.383 W/(m².K) for the insulated brick wall. The thermal mass of earthen material thus counterbalanced its lower theoretical transmittance. However, in the same study, rammed earth without insulation (theoretical transmittance of 2.429 W/(m².K)) consumed 18% to 37% more cooling energy than the reference brick wall. Thus, if thermal mass of the inner wall certainly is an asset, it is expected not sufficient for energy savings.

Earthen materials are hygroscopic materials, meaning that they tend to adsorb or attract humidity from the air and afterwards desorb or release that moisture. This ability is due to their porosity that allows water and water vapor to circulate into the wall [48,49]. This hygroscopicity plays a role into thermal behavior of the wall. When an earthen wall is exposed to sun radiations, water contained into pores can evaporate, the water vapor can circulate inside pores towards colder zones, and re-condense. Water condensation will release heat, due to water latent energy, and thus increase temperature. This knowledge on thermal behavior of earthen materials allows to expect energy savings during service life of buildings. It has to be considered on LCA studies.

8.4.2.2. Building scale

Although materials' thermal properties play an important role for buildings' heating and cooling energy consumptions, many other considerations also influence actual energy consumption. To fully benefit from the interesting thermal properties of earthen materials, buildings' design plays an important role. The actual energy savings due to the thermal mass of earthen constructions depends on the climate as well as on other design choices (buildings' orientation, windows, roof, ground floor).

For houses in New South Wales, Australia, Albayyaa et al. [50] questioned the design strategies in terms of passive solar and thermal mass of the walls. In their case study (transmittance of about 0.3 W/(m².K), NSW climate) they found that including thermal mass in the system allowed 35% of energy savings for both heating and cooling. In that specific case study [50], the energy savings due to the use of high thermal mass (brick) instead of low thermal mass (fibro concrete panels) per total floor area was found around 19 kWh/(yr.m²) of floor area (to be compared to 68.4 MJ/(yr.m²) of floor area for the fibro concrete panels). With a life span of 50 years, it leads to estimate energy consumption of 3.4 GJ/m² of floor area, that is drastically more important than the EE of the materials.

The construction technique was also investigated for the building walls in order to allow water vapor to circulate and favor walls' hygroscopic behavior. According to Minke [51], if water vapor cannot be evacuated it would reduce walls' mechanical resistance and favor biological colonization, such as mould. Renders (plaster applied outdoors) protect external walls from rain, but they should not be waterproof so they can be water vapor permeable. For interior walls, direct contact between the wall and indoor air or the use of a porous plaster more permeable than the exterior render, was recommended by Minke [51]. Compared to ancient techniques, recent earthen constructions now use classical concrete foundations and waterproof barriers applied on top of those foundations, that separate the wall from soil, avoiding water to rise by capillarity from the ground into the wall, thus optimizing hygroscopic transfers between interior and exterior.

This complexity certainly explains why no consolidated LCA results can be produced for building walls' service life.

8.5. End of life

A few references have considered an end-of-life scenario.

The study of a CEB considered inert landfill at the end of life stages and found: GWP100 = 3.4 kg CO2 eq/m² and CED = 48.11 MJ/m² [21], that represent 8.2% and 9.4% of the total life cycle, respectively.

On a stabilized CEB building case study [20], the inert landfill was also considered as end-of-life scenario. Results are not provided for 1 m² of the wall, but it is possible to estimate, from provided graphs, that the deconstruction and disposal operations contribute around 8-14% and 21-23% of total GWP100 and CED life cycle impacts, respectively.

The study of a stabilized earth façade panel included demolition and disposal phases [35]. From the outer to the inner wall, the façade is composed of a cement mortar render, polyurethane foam as thermal insulator between two layers of stabilized earth, and gypsum plaster inside. The end-of life scenario assumes the final disposal of each of these elements. The climate change indicator GWP100 results for the panel are found equal to 11.466 kg CO_2 eq/m² for demolition and 3.106 kg CO_2 eq/m² for disposal [35], that represents 38.9% of the total life cycle indicator. The CED results are found equal to 185.731 MJ/m² for demolition and 26.637 MJ/m² for disposal [28,35] that represents 42.1% of the total life cycle indicator. Details are also provided for the final disposal of stabilized earth material only [35]: GWP100 = 0.370 kg CO_2 eq/m² and CED = 10.242 MJ/m² that represent 0.6% and 1.1% of each total life cycle indicator, respectively.

Finally, it has to be noted that landfill impacts associated with earth materials are also considered sometimes as avoided impacts as a growing interest is seen for the use of excavated materials as earth construction products. In this case, the environmental impact associated with earth extraction is allocated to the excavation activities (not related with earth production) and earth production is avoiding an extra landfill impact. This raises the question of allocation [52] but for the moment, earth coming from excavation activities is clearly seen as a waste from the excavation activities.

8.6. Comparisons of earthen walls to other construction techniques

In this part, studies that performed comparisons between earthen construction and other more conventional materials are gathered. A distinction is made between studies that were conducted at wall scale to those that were conducted at building scale.

8.6.1 Comparisons at wall scale

EE and carbon of several scenarios of adobe have been compared to several other materials [23]: fired clayed brick, concrete blocks and hollow concrete blocks. However, the reference flows are different for the materials (1 kg, 1 brick, or 1m^3) compared in that reference, and no information is available to recalculate all values for 1 m². According to [53], in the Indian context, the EE of 1 m^3 of an earth-cement block masonry ranges from 646 to 810 MJ/m^3 that is lower than for hollow concrete block masonry (819 to 971 MJ/m^3), steam cured clayish earth block masonry (1,396 MJ/m^3) and fired clay brick masonry (2,141 MJ/m^3). However, cubic metre is either not relevant for comparison, as it does not correspond to similar functions.

One study compared various façades designed for similar thermal performance in the Spanish context [35]: a double-sheet façade of stabilized earth panels (SSPF), a double-sheet façade made of ceramic brick masonry (FCBF), a similar double-sheet façade of ceramic brick where the inner sheet is replaced with gypsum plasterboard (PBF), and another double-sheet façade of concrete block masonry (CBF). Although the walls have different total thicknesses (that correspond to different indoor living areas), authors obtained the following results by decreasing order on GWP100 in kg CO_2 eq/m²: 0.120 for FCBF, 0.103 for CBF, 0.093 for PBF and 0.057 for SSPF [35]. The same ranking between compared solution is obtained for CED in MJ/m²: 1.615 for FCBF, 1.453 for CBF, 1.241 for PBF and 0.895 for SSPF [35].

In the context of continental USA, another case study compared 4 different exterior load-bearing wall assemblies suitable for up to 2-story construction and having an insulation value meeting or exceeding the requirements of the USA regulation for warm-hot climates [16]: an insulated lightweight sheathed timber platform frame (W), an uninsulated concrete block masonry (CB), an insulated concrete block masonry (ICB) and a cob wall (COB). Authors obtained the following results by decreasing order on GWP100 in kg CO_2 eq/m²: 74.8 for ICB, 62.7 for CB, 53.1 for W and 13.2 for COB [16]. The same ranking between compared solution is obtained for CED in MJ/m²: 491 for ICB, 241 for W, 226 for CB and 86.4 for COB [16].

8.6.2 Comparisons at building scale

Some studies compared different types of walls for an identical building, thus accounting for their structural functions as well as comparable thermal performance, in order to design the building.

A residential building (one level) made of different wall materials have been compared in the Australian context [38]: rammed earth stabilized with 8% cement, brick veener, and fired brick masonry. EE has been recalculated from the buildings' wall surface for 1 m² of wall area (see appendixes) providing: 917, 2,460.4 and 2,717.4 MJ/m², respectively [38].

The case study of Nanz et al. [28] compared two buildings in the German context, each of them including a comparison between a rammed earth and a fired bricks façade. For the first building, the primary energy of the rammed earth façade is found 150 MJ/m² whereas the fired brick façade is found equal to 498 MJ/m^2. For the second building, the primary energy of the rammed earth façade is found 395 MJ/m^2 whereas the brick façade is found equal to 500 MJ/m^2.

In their case study, Galan-Marin et al. [42] considered a building with one, two or three story floors. Their results have been gathered in Figure 8-4. A stabilized earth wall (SS) is found to have similar GWP but higher CED than a concrete block wall (CB). A fired clay brick wall (FC) and a reinforced concrete wall (RC) are found largely higher for both indicators. Indicators per square metre of wall all increase with the number of floors, except the reinforced concrete wall, for which they remain stable. It is also noticeable that CED obtained by this study is one of the highest EE values of all references considered in the present article, with the highest cement content as previously shown in Figure 8-2.

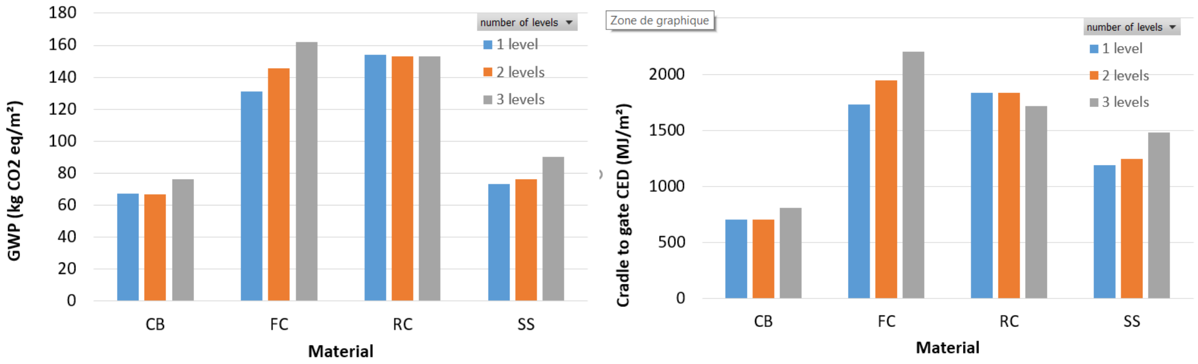


Figure 8-4. Global Warming Potential (GWP100) and Cumulative Energy Demand (CED) for the same building, according to the number of levels, after [42] – CB: concrete block masonry, FC: fire clay brick masonry, RC: reinforced concrete and SS: stabilized earth block masonry

8.7. General Discussion

The review highlights some influential aspects on LCA results, mainly the energy consumption indicators, for the three life cycle steps. One could easily conclude from that review that minimum transport and minimum binder content surely improve environmental aspects. Although these are surely key factors that should always be kept in mind by architects and building designers, they have to be further discussed.

Van Damme and Houben [10] modeled CO_2 intensity of earth mix designs by gained resistance (kg CO_2 eq/MPa) as a function of cement content. They showed that the binder addition in earth does not increase the resistance to a sufficient level to make it competitive, from an environmental point of view to cement based concrete: kg CO_2 eq/m^3/MPa seems much higher in stabilized earth construction than for conventional concrete. Thus, the need for using a binder can be questioned as several earthen techniques are available without a binder. However, this study considers that strength is the only function of using cement in earth construction and lack of sufficient consideration for the broader factors needed to make a fair comparison between stabilized earth, unstabilized earth and concrete blocks. In particular the fact that earth stabilization is used for weathering resistance and that earth in general provides wider benefits in terms of indoor comfort which are modified by stabilization [55]. In earthen walls durability should not be assessed only by strength. Weathering simulated tests are also very important [56]. Furthermore, the need for a high strength is very linked to the buildings design, Galan-

Marin et al. [42] showing that an increase in the number of floors would change the choice of a material regarding minimum values of GWP100 or CED (see Figure 8-4).

The functional requirements of building walls are numerous [57] and they are gathered in Table 8-3. Hence, the use of a binder can be required for durability or safety reasons, and this aspect is not considered by Van Damme and Houben [10]. Indeed, in countries with frequent flooding events or frequent pouring rains, binders are useful to avoid penetration of humidity and collapse of walls. The durability aspects are very dependent on the building's location. As an example, Bui et al. [58] studied the erosion of different rammed earth walls. Over a period of 20 years, the mean erosion depth of the examined walls was found 2 mm (0.5% of wall thickness) for walls stabilized with 5% dry weight of hydraulic lime, and 6.4 mm (1.6% of wall thickness) for unstabilized walls [58]. Thus, service life span would be reduced for unstabilized walls compared to stabilized ones. However, these results are typical of rammed earth walls of a given climate, that is wet continental in that study [58].

The use of wastes as stabilizers instead or at least partially replacing common binders, such as lime or cement replaced by artificial pozzolans, can contribute to reduce the environmental impact of earthen walls. That reduction will be directly correlated to the consumption of those energy intensive binders and the type of binder and, simultaneously, the reduction on waste landfilling [59].

Furthermore, the eventual need to stabilize local earth to use it as building material and water consumption also depend on the building technique. For instance, considering walls with similar thickness, to build an adobe wall consumes much more water in comparison to build a rammed earth wall. An earth with coarse aggregates may be directly used to build a rammed earth wall, while the coarse aggregate needs to be removed, by sieving, before using the earth to produce CEB, adobe or even cob. An earth with relatively low clay content can be used to build unstabilized rammed earth while a binder addition should be needed to use the same earth for CEB, abode or cob. All these aspects should be considered for environmental assessment.

As fully described in a previous part ($ 8.4.2), the thermal aspects are also very complex because saving heating and cooling energy requires to have an overview of correlated aspects. Materials' properties and mix design are important, and may be different according to local soil resources' properties, such as clay content. Wall design has to be considered, with possible additional layers enabling water permeability control and/or additional thermal insulation. The review (see §8.3.2) shows big differences in results between LCA studies conducted at masonry unit or material scale and studies at building scale. These differences are probably due to wall designs, generally not considered for studies at masonry unit or material scales. At building scales, wall design generates higher impacts because of additional layers, but that should be balanced with possible energy savings. The building design is also a key aspect especially concerning isolation of walls from foundations, orientation of façades in relationship with local climate. In fact, the application of compatible protective renders and capillary rise barriers can be fundamental for durability but also for thermal performance, depending on the earth technique, exposure and architectural design.

Table 8-3. Possible functions of a building wall – after [57]

Functionality	Description and possible measurable observation
Strength: ability to take up the loads due to its own weight, superimposed loads and lateral pressures	Materials’ resistance to compression
	Materials’ resistance to rotation
Durability	Wall ability to keep its functionalities in time
	Wall ability to resist current weather events in buildings’ location: wind or rain erosion
Thermal performance: ability to preserve desired temperature indoors	Materials’ ability to conduct heat flows
	Materials ability to adsorb and desorb water vapor
	Winter comfort: wall ability to preserve comfortable sensation indoors while outdoor temperature is low and ventilation rate is low
	Summer comfort: wall ability to preserve comfortable sensation indoors while outdoor temperature is high
Privacy: ability to preserve intimacy for inhabitants	Sound insulation: wall ability to absorb noise
	Sight insulation
Security: ability to temporary resist to exceptional aggressive events in order to allow safe evacuation	Fire: ability to resist a fire for a certain amount of time
	Seism: ability not to be ruined by a seism
	Water floods: ability not to be ruined by a flood
Safety: ability to be innocuous to health of inhabitants in usual conditions	Chemical inertia towards variable usage conditions

Several references confirm the high hygroscopicity of clayish earth materials as being one of the most advantageous in comparison to other building materials. It may depend on the type and content of clay [60], eventual stabilization [59] and on the surface of the wall. Therefore, earth walls may provide a contribution to passively equilibrate indoor relative humidity and so, reduce the energy consumption to achieve hygrothermal comfort. However, that aspect is not yet quantified on environmental assessment literature.

All references tend to confirm the influence of transport on the environmental performance of earthen construction. Using local material could appear as a very efficient way to lower environmental impacts, and a true added value of earthen construction materials compared to conventional ones. However, the notion of “local” is itself important: as shown by Nanz et al. [28], off-site soil extraction can still be local (distances around 10 km), and will drastically change the results.

Finally, end-of-life phases in existing references, all consider inert landfill scenarios. Clay is a material of natural origin and reintegration of the unsterilized material at the end of life has been described as unproblematic [21]. That is important because earth is not a renewable material. Although the recyclability of clay is documented in several publications [58,61,62], current LCAs do not consider such a scenario. Existing LCAs studies considering end-of-life phase all considered the use of stabilizers in the mix design. Stabilizers can be used to improve the properties of CEB [26], but according to [21,63], even if clay has been stabilized with lime or cement, its recyclability is only minimally impaired. The resultant earth product stabilized with lime turns out similar to a clay limestone; however, the same does not happen when it is stabilized with cement. The recycling scenario of unstabilized or air lime stabilized earth could thus be accounted as an alternative to the inert landfill for comparison.

Inert landfill scenarios also fail to highlight the fact that in the context of circular economy, using the earth coming from excavation sites of conventional buildings and infrastructure construction is an economically viable activity [64,65]. Actually, it becomes more and more difficult due to difficulty for quarry extension to access to natural sand and gravel around cities [66,67]. Furthermore, landfill costs for excavation materials are increasing due to space limitation and transport distance costs. Both aspects combined raise the interest to use excavation material directly as a building material becomes economically interesting [68]. From an environmental perspective, it means that impacts associated with extraction of earth are allocated to the main excavation activity (construction) and not earth production.

8.8. Conclusion

This review of existing LCAs applied to earthen construction concerns all current techniques: CEB and adobe masonry, cob and rammed earth monolithic walls, some plasters as well as some other particular techniques. This review provides some key points mainly concerning energy demand of earthen construction.

First, it shows that transports, even on small distances, as well as binder stabilizations are very influent on the results. If no cement stabilization is used, the transport of material seems to be the critical parameter. On the opposite, if cement stabilization is used, then the amount becomes the critical driver of environmental impact. However, it should not be concluded that it is necessary to eliminate binder stabilization from earthen techniques. The binder stabilization can prove useful for particular functions (durability or safety) in a given context of use, accounting for local specificities such as the nature of soil and the climate. If reducing transports is a generic advice to lower environmental impacts of earthen construction, and the use of local materials is strongly beneficial, the ability to use local soil, the need to prepare it by sieving and the need to add other materials to the earth mix also depends on the nature of the soil and the building technique.

This leads to the second point concerning local specificities. Climate, nature of local soil, and geographical context are very influent on functionalities of buildings, mix design and transports, themselves influencing environmental impacts. This means that no universal solution can be recommended with the LCA of an earthen wall. The solution has to be adapted to the local context. This also explains the absence of a universal standard for earth construction in favor of regional or national standards.

As a third point, it was not possible to provide a general ranking of different materials among all references, as existing studies use different sets of indicators and lack of sufficient information to enable conversions. Nevertheless, all references comparing wall material to conventional materials at the building scale, find better environmental performances of earthen walls compared to fired brick walls. However, for cement concrete walls, it is not always the case. Then, although one intuitively and commonly assumes that earthen construction has better environmental performances than conventional materials, our analysis shows that according to design choices and local situations earthen construction can have lower performances than concrete.

However, as a fourth point, a full comparison between earthen construction and conventional materials should account for the use and end-of life phases. These are key issues for future researches on LCA of earthen construction. For the use phase, combining LCA models with thermal and durability models is a key issue to enable life cycle performances. Concerning thermal models, there are still research needs to provide models accounting for all particular properties and behaviors of earthen materials as thermal insulators and hygrothermal passive buffers. Concerning durability, some combined approach already on carbonation of reinforced cement concrete[69], and this type of combined models should be extended to all construction materials when relevant. For the end-of-life phase, the existing references only consider inert landfills, and no study considers recyclability of the material or even reuse when the earth is not stabilized.

Finally, it certainly would be useful to seek for solutions with best environmental performances in a local context, accounting for the nature of soil, the building's functional requirements as well as geographical and cultural specificities. Such an approach would ensure to lower environmental impacts but represents a drastic change in current construction practices. Whereas today building materials are standardized in order to fit with construction working practices, this paradigm shift would require to adapt construction working practices to the local material and context. Some countries are paving the way with their standards for earthen construction across various continents. As earthen construction is today, in many countries of the world, a re-emerging technique, and new professional practices are yet to be established, it seems possible to make this paradigm shift happen. Certainly, in the current context of an urgent need to substantially reduce building-related GHG emissions, there is still strong potential in earth construction techniques for both research and building practice.

8.9. References

[1] UNEP Sustainable Building Initiative, Buildings and Climate Change - Summary for decision makers, 2009. http://www.unep.org/SBCI/pdfs/SBCI-BCCSummary.pdf (accessed September 8, 2014).

[2] M. Röck, M.R.M. Saade, M. Balouktsi, F.N. Rasmussen, H. Birgisdottir, R. Frischknecht, G. Habert, T. Lützkendorf, A. Passer, Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation, Appl. Energy. 258 (2020) 114107. https://doi.org/10.1016/j.apenergy.2019.114107.

[3] J. Cauvin, Naissance des divinités, naissance de l'agriculture, Cnrs, Paris, 2013.

[4] M. Sauvage, Les débuts de l'architecture au Proche-Orient, in: Mediterra 2009, 2009. https://www.academia.edu/24744074/LES_D%C3%89BUTS_DE_LARCHITECTURE_DE_TERRE_AU_PROCHE-ORIENT (accessed July 9, 2020).

[5] K.A.J. Ouedraogo, J.-E. Aubert, C. Tribout, G. Escadeillas, Is stabilization of earth bricks using low cement or lime contents relevant?, Constr. Build. Mater. 236 (2020) 117578. https://doi.org/10.1016/j.conbuildmat.2019.117578.

[6] E. Hamard, B. Cazacliu, A. Razakamanantsoa, J.-C. Morel, Cob, a vernacular earth construction process in the context of modern sustainable building, Build. Environ. 106 (2016) 103–119. https://doi.org/10.1016/j.buildenv.2016.06.009.

[7] J.L. Parracha, J. Lima, M.T. Freire, M. Ferreira, P. Faria, Vernacular Earthen Buildings from Leiria, Portugal – Material Characterization, Int. J. Archit. Herit. 0 (2019) 1–16. https://doi.org/10.1080/15583058.2019.1668986.

[8] A. Vissac, A. Bourgès, D. Gandreau, R. Anger, L. Fontaine, Argiles et biopolymères: les stabilisants naturels pour la construction en terre, CRAterre, Villefontaine, 2017. https://craterre.hypotheses.org/1370 (accessed July 23, 2020).

[9] H. Houben, H. Guillard, Earth Construction: A comprehensive guide, Practical Action Publishing, Rugby, Warwickshire, United Kingdom, 1989. https://doi.org/10.3362/9781780444826.

[10] H. Van Damme, H. Houben, Earth concrete. Stabilization revisited, Cem. Concr. Res. 114 (2018) 90–102. https://doi.org/10.1016/j.cemconres.2017.02.035.

[11] L. Rouvreau, P. Michel, S. Vaxelaire, J. Villeneuve, E. Jayr, E. Vernus, N. Buclet, V. Renault, A. de Cazenove, H. Vedrine, Déchets BTP: revue de l'existant (tâche 1), BRGM,

CSTB, INSA Valor,UTT CREID, 13 développement, 2010. http://infoterre.brgm.fr/rapports/RP-58935-FR.pdf (accessed December 21, 2015).

[12] B. Bajželj, J.M. Allwood, J.M. Cullen, Designing Climate Change Mitigation Plans That Add Up, Environ. Sci. Technol. 47 (2013) 8062–8069. https://doi.org/10.1021/es400399h.

[13] L. Floissac, A. Marcom, A.-S. Colas, Q.-B. Bui, J.-C. Morel, How to assess the sustainability of building construction …, in: Marseilles (France), 2009: p. 18.

[14] CEN, EN15804:A1 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, (2014).

[15] B.V. Venkatarama Reddy, J.-C. Morel, P. Faria, P. Fontana, D. Oliveira, I. Serclerat, Codes and standards on earth construction – a review, in: Rep. Rilem Tech. Comm. 274 Test. Characterisation Earth-Based Build. Mater. Elem., Springer, 2020.

[16] L. Ben-Alon, V. Loftness, K.A. Harries, G. DiPietro, E.C. Hameen, Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material, Build. Environ. 160 (2019) 1–10. https://doi.org/10.1016/j.buildenv.2019.05.028.

[17] M. Estrada, A case study of cob earth based building technique in Matagalpa , Nicaragua – LCA perspective and rate of adoption, Mid Sweden University, 2013.

[18] J. Dahmen, J. Kim, C.M. Ouellet-Plamondon, Life cycle assessment of emergent masonry blocks, J. Clean. Prod. 171 (2018) 1622–1637. https://doi.org/10.1016/j.jclepro.2017.10.044.

[19] J. Fernandes, M. Peixoto, R. Mateus, H. Gervásio, Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks, J. Clean. Prod. 241 (2019) 118286. https://doi.org/10.1016/j.jclepro.2019.118286.

[20] C. Galan-Marin, C. Rivera-Gomez, A. Garcia-Martinez, Embodied energy of conventional load-bearing walls versus natural stabilized earth blocks, Energy Build. 97 (2015) 146–154.

[21] S. Roux Gutiérrez Rubén, J. Velazquez Lozano, H. Rodríguez Deytz, Compressed earth blocks, their thermal delay and environmental impact, in: Energy Effic., Seville, 2015: p. 12.

[22] H. Abanda, J.H.M. Tah, G. Elambo Nkeng, Earth-block versus sandcrete-block houses: Embodied energy and CO2 assessment. Embodied energy and CO 2 assessment., Eco-Effic Mason Bricks Blocks Prop Durab. (2014) 481–514. https://doi.org/10.1016/B978-1-78242-305-8.00022-X.

[23] E. Christoforou, A. Kylili, P.A. Fokaides, I. Ioannou, Cradle to site Life Cycle Assessment (LCA) of adobe bricks, J. Clean. Prod. 112 (2016) 443–452. https://doi.org/10.1016/j.jclepro.2015.09.016.

[24] C. De Wolf, C. Cerezo, Z. Murtadhawi, A. Hajiah, A. Al Mumin, J. Ochsendorf, C. Reinhart, Life cycle building impact of a Middle Eastern residential neighborhood, Energy. 134 (2017) 336–348. https://doi.org/10.1016/j.energy.2017.06.026.

[25] A. Shukla, G.N. Tiwari, M.S. Sodha, Embodied energy analysis of adobe house, Renew. Energy. 34 (2009) 755–761. https://doi.org/10.1016/j.renene.2008.04.002.

[26] A. Arrigoni, D. Ciancio, C.T.S. Beckett, G. Dotelli, Improving rammed earth buildings' sustainability through life cyle assessment (LC), in: Expand. Boundaries Syst. Think. Built Environ., Zurich, 2016: p. 6.

[27] J.C. Morel, A. Mesbah, M. Oggero, P. Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Build. Environ. 36 (2001) 1119–1126. https://doi.org/10.1016/S0360-1323(00)00054-8.

[28] L. Nanz, M. Rauch, T. Honermann, T. Auer, Impacts on the Embodied Energy of Rammed Earth Façades During Production and Construction Stages, J. Facade Des. Eng. 7 (2018) 75–88. https://doi.org/10.7480/jfde.2019.1.2786.

[29] S. Serrano, A. de Gracia, L.F. Cabeza, Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions, Appl. Energy. 175 (2016) 180–188. https://doi.org/10.1016/j.apenergy.2016.05.010.

[30] S. Serrano, C. Barreneche, L. Rincón, D. Boer, L.F. Cabeza, Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA, Constr. Build. Mater. 47 (2013) 872–878. https://doi.org/10.1016/j.conbuildmat.2013.05.018.

[31] S. Serrano, C. Barreneche, L. Rincón, D. Boer, L.F. Cabeza, Stabilized rammed earth incorporating PCM: Optimization and improvement of thermal properties and Life Cycle Assessment, Energy Procedia. 30 (2012) 461–470. https://doi.org/10.1016/j.egypro.2012.11.055.

[32] B.V. Venkatarama Reddy, G. Leuzinger, V.S. Sreeram, Low embodied energy cement stabilised rammed earth building—A case study, Energy Build. 68 (2014) 541–546. https://doi.org/10.1016/j.enbuild.2013.09.051.

[33] B.V. Venkatarama Reddy, P. Prasanna Kumar, Embodied energy in cement stabilised rammed earth walls, Energy Build. 42 (2010) 380–385. https://doi.org/10.1016/j.enbuild.2009.10.005.

[34] P. Melià, G. Ruggieri, S. Sabbadini, G. Dotelli, Environmental impacts of natural and conventional building materials: a case study on earth plasters, J. Clean. Prod. 80 (2014) 179–186. https://doi.org/10.1016/j.jclepro.2014.05.073.

[35] C. Galan-Marin, A. Martínez-Rocamora, J. Solís-Guzmán, C. Rivera-Gómez, Natural Stabilized Earth Panels versus Conventional Façade Systems. Economic and Environmental Impact Assessment, Sustainability. 10 (2018) 1020. https://doi.org/10.3390/su10041020.

[36] H. Abanda, G.E. Nkeng, J.H.M. Tah, E.N.F. Ohandja, M.B. Ma,jia, 1 Department of Real Estate and Construction, Faculty of Technology, Design and Environment Oxford Brookes University, Oxford, OX3 0BP, UK;, Embodied Energy and CO2 Analyses of Mud-brick and Cement-block Houses, AIMS Energy. 2 (2014) 18–40. https://doi.org/10.3934/energy.2014.1.18.

[37] G. Habert, E. Castillo, E. Vincens, J.C. Morel, Power: A new paradigm for energy use in sustainable construction, Ecol. Indic. 23 (2012) 109–115. https://doi.org/10.1016/j.ecolind.2012.03.016.

[38] G.J. Treloar, C. Owen, R. Fay, Environmental assessment of rammed earth construction systems, Struct. Surv. 19 (2001) 99–106. https://doi.org/10.1108/02630800110393680.

[39] R. Frischknecht, F. Wyss, S. Büsser Knöpfel, T. Lützkendorf, M. Balouktsi, Cumulative energy demand in LCA: the energy harvested approach, Int. J. Life Cycle Assess. 20 (2015) 957–969. https://doi.org/10.1007/s11367-015-0897-4.

[40] F. Gomes, R. Brière, A. Feraille, G. Habert, S. Lasvaux, C. Tessier, Adaptation of environmental data to national and sectorial context: application for reinforcing steel sold on the French market, Int. J. Life Cycle Assess. 18 (2013) 926–938. https://doi.org/10.1007/s11367-013-0558-4.

[41] D.J.M. Flower, J.G. Sanjayan, Green house gas emissions due to concrete manufacture, Int. J. Life Cycle Assess. 12 (2007) 282. https://doi.org/10.1065/lca2007.05.327.

[42] C. Galan-Marin, C. Rivera-Gomez, A. Garcia-Martinez, Embodied energy of conventional load-bearing walls versus natural stabilized earth blocks, Energy Build. 97 (2015) 146–154.

[43] M. Moevus, R. Anger, L. Fontaine, Hygro-thermo-mechanical properties of earthen materials for construction : a literature review, in: Terra 2012, Lima, Peru, 2012. https://hal.archives-ouvertes.fr/hal-01005948 (accessed February 17, 2020).

[44] L. Soudani, M. Woloszyn, A. Fabbri, J.-C. Morel, A.-C. Grillet, Energy evaluation of rammed earth walls using long term in-situ measurements, Sol. Energy. 141 (2017) 70–80. https://doi.org/10.1016/j.solener.2016.11.002.

[45] K. Heathcote, The thermal performance of earth buildings, Inf. Constr. 63 (2011) 117–126. https://doi.org/10.3989/ic.10.024.

[46] D. Baggs, N. Mortensen, Thermal Mass in Building Design, Environ. Des. Guide. (2006) 1–9.

[47] H. Asan, Numerical computation of time lags and decrement factors for different building materials, Build. Environ. 41 (2006) 615–620. https://doi.org/10.1016/j.buildenv.2005.02.020.

[48] A. Fabbri, J.-C. Morel, D. Gallipoli, Assessing the performance of earth building materials: a review of recent developments, RILEM Tech. Lett. 3 (2018) 46–58. https://doi.org/10.21809/rilemtechlett.2018.71.

[49] T. Vinceslas, Caractérisation d’éco-matériaux terre-chanvre en prenant en compte la variabilité des ressources disponibles localement., 2019. http://www.theses.fr/s163971 (accessed February 17, 2020).

[50] H. Albayyaa, D. Hagare, S. Saha, Energy conservation in residential buildings by incorporating Passive Solar and Energy Efficiency Design Strategies and higher thermal mass, Energy Build. 182 (2019) 205–213. https://doi.org/10.1016/j.enbuild.2018.09.036.

[51] G. Minke, Building with Earth: Design and Technology of a Sustainable Architecture, Walter de Gruyter, 2012.

[52] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete, Resour. Conserv. Recycl. 54 (2010) 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001.

[53] B.V. Venkatarama Reddy, K.S. Jagadish, Embodied energy of common and alternative building materials and technologies, Energy Build. 35 (2003) 129–137. https://doi.org/10.1016/S0378-7788(01)00141-4.

[54] G.J. Treloar, C. Owen, R. Fay, Environmental assessment of rammed earth construction, Struct. Surv. 19 (2001) 99–106.

[55] A.T.M. Marsh, A. Heath, P. Walker, B.V.V. Reddy, G. Habert, Discussion of “Earth concrete. Stabilization revisited,” Cem. Concr. Res. 130 (2020) 105991. https://doi.org/10.1016/j.cemconres.2020.105991.

[56] C.T.S. Beckett, P.A. Jaquin, J.-C. Morel, Weathering the storm: A framework to assess the resistance of earthen structures to water damage, Constr. Build. Mater. 242 (2020) 118098. https://doi.org/10.1016/j.conbuildmat.2020.118098.

[57] C. Gobin, Analyse fonctionnelle et construction, Tech. Ing. (2003) 19.

[58] Q.B. Bui, J.C. Morel, B.V. Venkatarama Reddy, W. Ghayad, Durability of rammed earth walls exposed for 20 years to natural weathering, Build. Environ. 44 (2009) 912–919. https://doi.org/10.1016/j.buildenv.2008.07.001.

[59] A. Arrigoni, C. Beckett, D. Ciancio, G. Dotelli, Life cycle analysis of environmental impact vs. durability of stabilised rammed earth, Constr. Build. Mater. 142 (2017) 128–136. https://doi.org/10.1016/j.conbuildmat.2017.03.066.

[60] J. Lima, P. Faria, A.S. Silva, Earth Plasters: The Influence of Clay Mineralogy in the Plasters’ Properties, Int. J. Archit. Herit. 0 (2020) 1–16. https://doi.org/10.1080/15583058.2020.1727064.

[61] F. Pacheco-Torgal, Handbook of Recycled Concrete and Demolition Waste, Woodhead Publishing, Oxford (UK), 2013. https://doi.org/10.1533/9780857096906.1.

[62] P. Picuno, Use of traditional material in farm buildings for a sustainable rural environment, Int. J. Sustain. Built Environ. 5 (2016) 451–460. https://doi.org/10.1016/j.ijsbe.2016.05.005.

[63] F. Pacheco-Torgal, S. Jalali, Earth construction: Lessons from the past for future eco-efficient construction, Constr. Build. Mater. 29 (2012) 512–519. https://doi.org/10.1016/j.conbuildmat.2011.10.054.

[64] M. Kindermans, Sevran recycle ses terres, Echos. (2017) 1.

[65] T. Poupeau, Les remblais du supermétro seront transformés… en logements !, Le Parisien. (2019) 1.

[66] D. Ioannidou, G. Meylan, G. Sonnemann, G. Habert, Is gravel becoming scarce? Evaluating the local criticality of construction aggregates, Resour. Conserv. Recycl. 126 (2017) 25–33. https://doi.org/10.1016/j.resconrec.2017.07.016.

[67] D. Ioannidou, V. Nikias, R. Brière, S. Zerbi, G. Habert, Land-cover-based indicator to assess the accessibility of resources used in the construction sector, Resour. Conserv. Recycl. 94 (2015) 80–91. https://doi.org/10.1016/j.resconrec.2014.11.006.

[68] P. Lefebvre, BC architects & studies: The Act of Building - Biennale Architettura 2018, Exhibitions International, Antwerpen, 2018.

[69] A. Ventura, V.-L. Ta, T.S. Kiessé, S. Bonnet, Design of concrete : Setting a new basis for improving both durability and environmental performance, J. Ind. Ecol. n/a (n.d.). https://doi.org/10.1111/jiec.13059.

Appendix E Calculations of CED and GWP

Treloar et al. (2001) [38]

The LCA study is conducted on a building (Figure 8-5). To obtain a value for one square metre, the total wall surface is estimated.

Height : 2.4 m, perimeter : 12.3 + 7.2 +16.5 +7 + (12.3-7) = 41.4 m.

Total wall surface = 99.36 m².

With a global assumption of 10% of openings, the obtained surface is 89.424 m².

The article provides an embodied energy of 82 GJ for the building rammed earth walls, that is 917 MJ/m².

For other types of walls (brick veneer and hollow brick), the total EE are 220 and 243 GJ, respectively, that is 2,460.4 and 2.717.4 MJ/m², respectively.

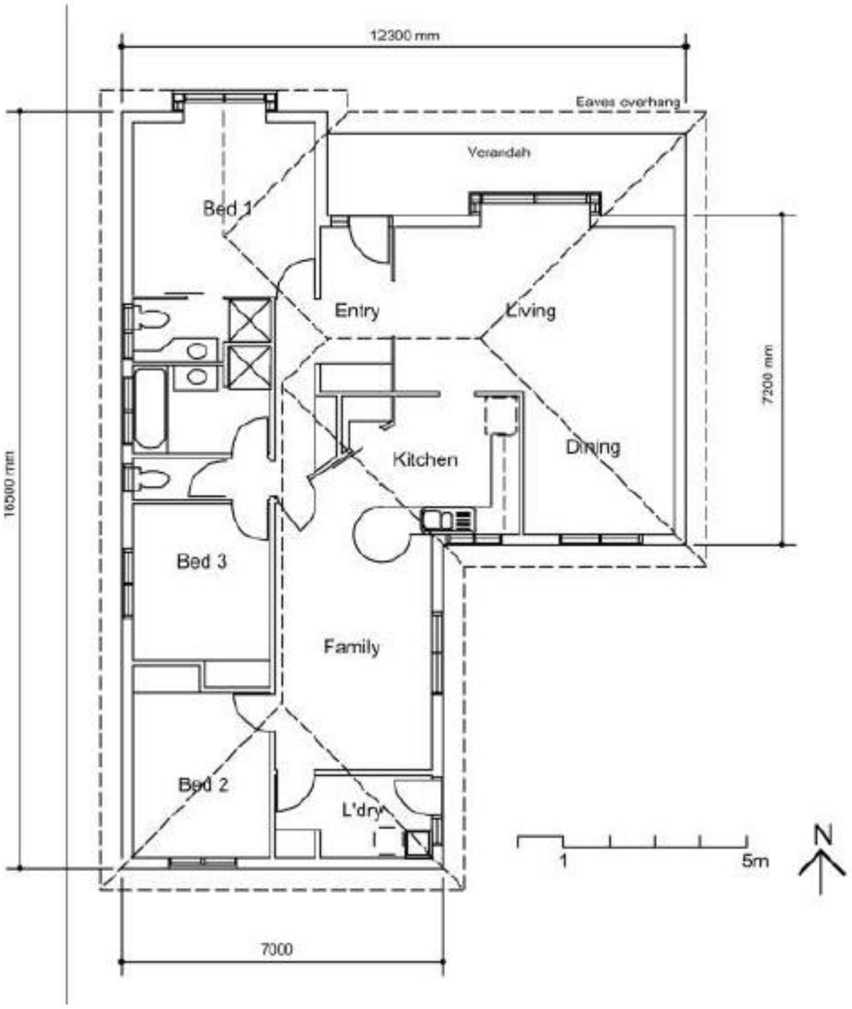


Figure 8-5 Building under study for LCA (Treloar et al., 2001)

Venkatarama Reddy and Jagadish (2003) [53]

Earth-cement block

Results are provided (table 5) for a cubic metre of earth-cement block masonry wall: 646 MJ/m^3 with 6% cement, and 810 MJ/m^3 with 8% cement. Size of blocks are 230 mm x 190 mm x 100 mm (volume = 0.00437 m^3) and height of blocks is assumed to be 100 mm.

The external surface of a block is thus 0.23 x 0.19 = 0.0437 m². Thus 22.88 blocks are necessary to cover 1 m² of the wall surface, that is 0.09998 m^3.

Thus, 1 m² of earth-cement block masonry wall requires 64.6 MJ/m² with 6% cement, and 81.0 MJ/m² with 8% cement.

Lime stabilized steam cured earth blocks

Results are provided (table 5) for a cubic metre of lime stabilized steam cured earth block walls: 1,396 MJ/m^3 with 10% lime. Size of blocks are 230 mm x 190 mm x 100 mm and height of blocks is assumed to be 100 mm.

The external surface of a block is thus 0.23 x 0.19 = 0.0437 m². Thus 22.88 blocks are necessary to cover 1 m² of the wall surface, that is 0.09998 m^3.

Thus, 1 m² of lime stabilized steam cured earth block requires 139.6 MJ/m².

Venkatarama Reddy and Prasanna Kumar (2010) [33]

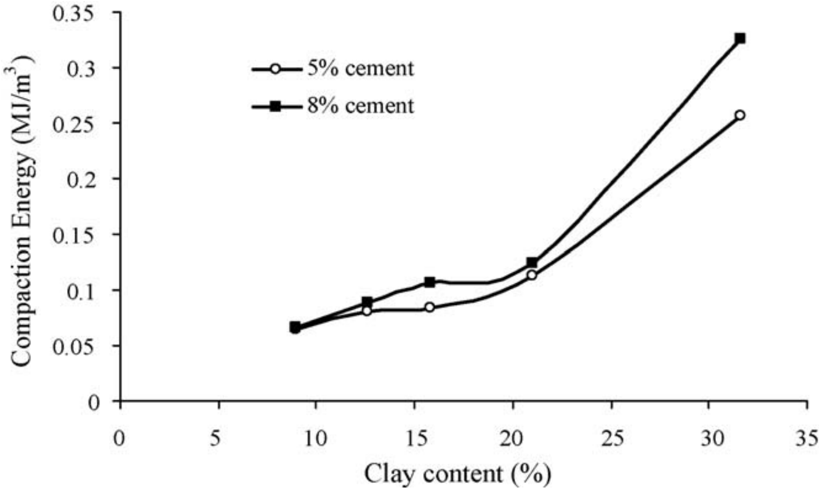


Figure 8-6 Compaction energy for experimental wallettes according to clay and cement contents [33].

Table 8-4 Original results [33] and calculations (grey cells) for 1 m² of wall

Parameter (unit)	**Building A**	**Building B**	**Experimental wallette**
Clay fraction of the mix (%)	16	12.6	15.8
Moulding water content (%)	10.6	10.8	11
Dry density (kg/m^3)	1,800	1,800	1,800
wall thickness (m)	0.2	0.375	0.15
Compacted in layers of thickness (mm)	35	100	100
Cement content (by weight) (%)	8	8	8
Energy in cement (MJ/m^3)	489.6	489.6	489.6
Compaction energy (MJ/m^3) (animate)	0.174	0.084	0.139
Number of observations	35	8	3
Standard deviation	0.059	0.016	0.009
Energy in mixing (MJ/m^3)	0	7.35	0
Energy in transportation of raw materials (MJ/m^3)	27.5	27.5	27.5
Total energy in rammed earth wall (MJ/m^3)	517.27	524.45	517.24
Surface of the wall (m²/m^3)	5	2.67	6.67
Soil extraction : Energy in transportation of raw materials (MJ/m²)	5.5	10.31	4.13
Construction : Energy for compaction (MJ/m²)	0.0348	0.0315	0.0209
Construction Energy for mixing (MJ/m²)	0	2.756	0
Construction : energy in cement (MJ/m²)	97.9	183.6	73.4
Total energy for construction (MJ/m²)	98.0	186.4	73.5
Total energy in rammed earth wall (MJ/m²)	103.45	196.67	77.59

Melià et al. (2014) [34]

All results are directly provided in the supplementary materials available on the journal's website

Galan-Marin et al. (2015) [42]

Table 8-5 Original results [20] and calculation or estimations (grey cells) to obtain total volume of walls and values for 1 m² of wall

Scenario / Unit			1	2	3	4	Average
Span between walls		m	3	3.5	4	4.5	3.75
Floor area		m²	48	56	64	72	60
Wall thickness		m	0.28	0.3	0.32	0.33	0.3075
Total volume of walls		m^3	18.6	21.6	24.6	26.9	22.9
Density		g/cm²	1.79	1.79	1.79	1.79	1.79
Total wall mass		kg/m²		121.83	128.599	142.136	130.855
Length of building		m	16	16	16	16	16
Width of building		m	6	7	8	9	7.5
Height of wall		m	2.4	2.4	2.4	2.4	2.4
Calculated wall surface	L1	m²	105.6	110.4	115.2	120	112.8
	L2	m²	211.2	220.8	230.4	240	225.6
	L3	m²	316.8	331.2	345.6	360	338.4
GWP /m² area	SS L1	kg CO2 eq					4386.23
	SS L2	kg CO2 eq					9112.18
	SS L3	kg CO2 eq					16201.1
GWP /m² wall	SS L1	kg CO2 eq					38.89
	SS L2	kg CO2 eq					40.39
	SS L3	kg CO2 eq					47.88
CED /m² area	SS L1	MJ					71,145.05
	SS L2	MJ					149,312.04
	SS L3	MJ					266,562.54
CED /m² wall	SS L1	MJ					630.72
	SS L2	MJ					661.84
	SS L3	MJ					787.71

Christoforou et al. (2016) [23]

Block dimension 0.30 m x 0.45 m x 0.05 m.

External surface : 0,05 x 0,3 = 0,015 m².

Number of blocks for 1 m² : 66.7 blocks/m².

Density 1544 kg/m3 for straw and 1568 kg/m3 for sawdust

Table 8-6 Intermediate calculated results for energy from [23]

Scenario (unit)		1	2	3	4	5	6
Diesel fuel Soil extraction	(kWh)	0.00728	0.00728	0.00728	0.00716	0.00716	0.00716
Diesel fuel Soil transportation	(kWh)	e	0.0124	0.0124	e	0.0122	0.0122
Diesel fuel Straw/Sawdust transportation	(kWh)	0.000312	0.000312	0.000312	0.000580	0.000580	0.000580
Diesel fuel Adobe brick transportation	(kWh)	e	e	0.0255	e	e	0.0255
Electricity Well water supply	(kWh)	6.08E-5	6.08E-5	6.08E-5	5.98E-5	5.98E-5	5.98E-5
Electricity Straw pre-mixing treatment	(kWh)	0.000122	0.000122	0.000122	e	e	e
Electricity Mixing	(kWh)	0.00141	0.00141	0.00141	0.00139	0.00139	0.00139
Total soil extraction	(MJ)	0.026208	0.070848	0.070848	0.025776	0.069696	0.069696
Total wall construction	(MJ)	0.00685728	0.00685728	0.09865728	0.00730728	0.00730728	0.09910728

Table 8-7 Calculated results for energy and GWP from [23]

	GWP		**Energy soil extraction (MJ)**		**Energy wall construction (MJ)**	
Scenario	**Results from article (1 block)**	**Results converted to 1 m²**	**Results from article (1 block)**	**Results converted to 1 m²**	**Results from article (1 block)**	**Results converted to 1 m²**
1	1.76E-03	0.117	0.026	1.748	0.007	0.457
2	5.41E-03	0.360	0.071	4.726	0.007	0.457
3	1.29E-02	0.860	0.071	4.726	0.099	6.580
4	1.70E-03	0.113	0.026	1.719	0.007	0.487
5	5.3E-03	0.353	0.070	4.649	0.007	0.487
6	1.28E-02	0.854	0.070	4.649	0.099	6.610

Dahmen et al. (2018) [18]

Values are given for one block of which dimension are 0.19 x 0.19 x 0.39 m.

The exposed surface area of one block is thus 0.19 x 0.39 = 0.0741 m², requiring 13.5 blocks to cover 1 m² of the wall. This factor has been applied to provided LCA results.

One block of stabilized soil is 0.00839 m^3, with a 2,100 kg/m^3 density, thus a mass of 17.619 kg. Its cement content has been calculated: 0.71 kg cement/block that is 4%.

Table 8-8 Calculated results for energy [18]

	Values for one masonry units		**Values for 1 m²**	
Resources (MJ)	**Stabilized earth block**	**Alkali activated block**	**Stabilized earth block**	**Alkali activated block**
Transportation	2.0	1.9	27.0	25.6
Manufacture	3.3	5.8	44.5	78.3
Cement	2.5	0.0	33.7	0.0
Fine aggregate	1.0	0.8	13.5	10.8
Sodium silicate		2.7	0.0	36.4
Sodium hydroxide		9.5	0.0	128.2
TOTAL	8.7	20.7	117.4	279.3

Fernandes et al. (2019) [19]

Results are given for 1m^3 of the wall.

CEB:

One block is sized 300 x 150 x 70 mm, with thus a volume of 0,00315 m^3.

The external surface of one block is 0.30 x 0.07 = 0.021 m².

For 1 m² surface area 47.62 blocks are required.

The binder content (lime) is 6.5 % of mass.

Rammed earth:

One cubic metre of dried wall weights 1,127.36 kg.

The wall thickness is 0,6 m, thus 1 m² surface area is 0,6 m^3.

Results have to be multiplied by 0.6.

The binder content (lime) is 3%.

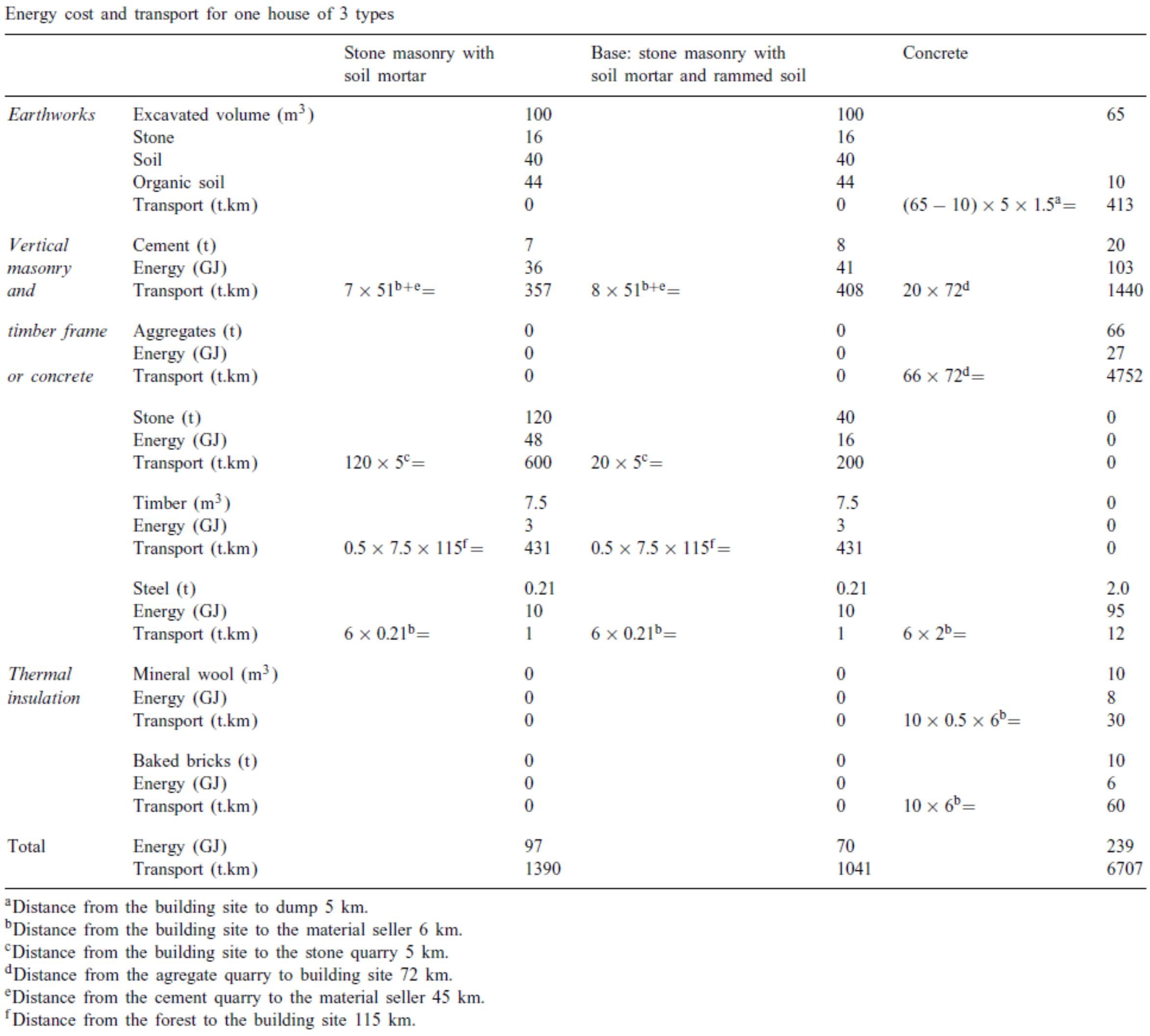
Appendix F Available results concerning transport

Morel et al. (2001) [27]

Assuming that transportation would occur in France, it is possible to calculate energy, i.e. around 1.5 MJ/(ton.km)

- For building A in stone masonry with earth mortar, total transport of 1,390 ton.km (Table 8-9) is found to be 2.1 GJ.
- For building B in stone masonry with earth mortar and rammed earth, total transport of 1,041 ton.km (Table 8-9) is found to be 1.6 GJ.
- For building C in concrete, total transport of 6,707 ton.km (Table 8-9) is found to be 10.2 GJ.

Table 8-9 Available information concerning transport [27]



Energy cost and transport for one house of 3 types

		Stone masonry with soil mortar		Base: stone masonry with soil mortar and rammed soil		Concrete	
Earthworks	Excavated volume (m^3)		100		100		65
	Stone		16		16		
	Soil		40		40		
	Organic soil		44		44		10
	Transport (t.km)		0		0	$(65-10)\times 5\times 1.5^{a}=$	413
Vertical masonry and	Cement (t)		7		8		20
	Energy (GJ)		36		41		103
	Transport (t.km)	$7\times 51^{b+e}=$	357	$8\times 51^{b+e}=$	408	20×72^{d}	1440
timber frame	Aggregates (t)		0		0		66
	Energy (GJ)		0		0		27
or concrete	Transport (t.km)		0		0	$66\times 72^{d}=$	4752
	Stone (t)		120		40		0
	Energy (GJ)		48		16		0
	Transport (t.km)	$120\times 5^{c}=$	600	$20\times 5^{c}=$	200		0
	Timber (m^3)		7.5		7.5		0
	Energy (GJ)		3		3		0
	Transport (t.km)	$0.5\times 7.5\times 115^{f}=$	431	$0.5\times 7.5\times 115^{f}=$	431		0
	Steel (t)		0.21		0.21		2.0
	Energy (GJ)		10		10		95
	Transport (t.km)	$6\times 0.21^{b}=$	1	$6\times 0.21^{b}=$	1	$6\times 2^{b}=$	12
Thermal insulation	Mineral wool (m^3)		0		0		10
	Energy (GJ)		0		0		8
	Transport (t.km)		0		0	$10\times 0.5\times 6^{b}=$	30
	Baked bricks (t)		0		0		10
	Energy (GJ)		0		0		6
	Transport (t.km)		0		0	$10\times 6^{b}=$	60
Total	Energy (GJ)		97		70		239
	Transport (t.km)		1390		1041		6707

[a] Distance from the building site to dump 5 km.
[b] Distance from the building site to the material seller 6 km.
[c] Distance from the building site to the stone quarry 5 km.
[d] Distance from the agregate quarry to building site 72 km.
[e] Distance from the cement quarry to the material seller 45 km.
[f] Distance from the forest to the building site 115 km.

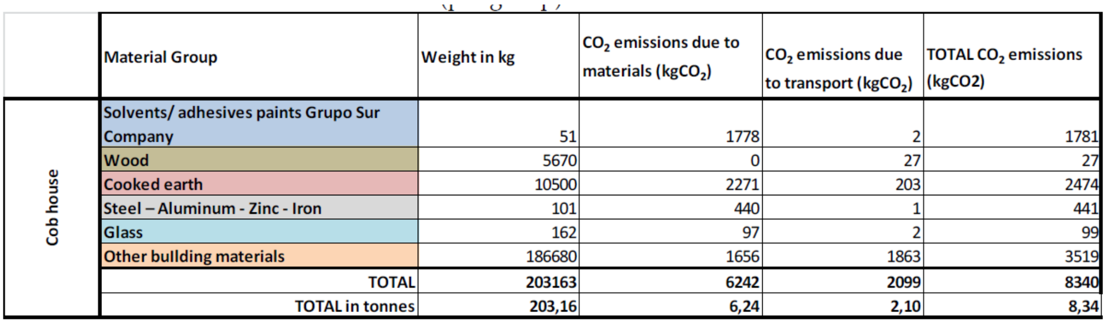
With these results, a proportion of transport compared to total energy consumed for construction is obtained (Table 8-10). The energy reduction due to the use of local materials can be calculated for buildings A and B compared to building C (Table 8-10).

Table 8-10 Contribution of transport calculated after [27]

Building	Description	Transport/total energy	Transport energy compared to building C
A	Stone masonry with earth mortar	2.1 %	-79 %
B	Stone masonry with earth mortar and rammed earth	2.2 %	-84%
C	Concrete	4.1 %	100 %

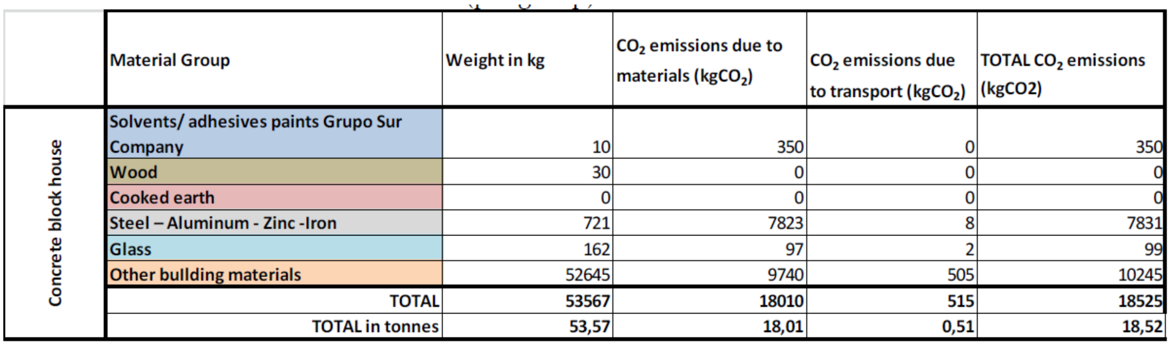
Estrada (2013) [17]

Table 8-11 Results of CO_2 emissions [17] for a cob house



	Material Group	Weight in kg	CO_2 emissions due to materials ($kgCO_2$)	CO_2 emissions due to transport ($kgCO_2$)	TOTAL CO_2 emissions (kgCO2)
Cob house	Solvents/ adhesives paints Grupo Sur Company	51	1778	2	1781
	Wood	5670	0	27	27
	Cooked earth	10500	2271	203	2474
	Steel – Aluminum - Zinc - Iron	101	440	1	441
	Glass	162	97	2	99
	Other building materials	186680	1656	1863	3519
	TOTAL	**203163**	**6242**	**2099**	**8340**
	TOTAL in tonnes	**203,16**	**6,24**	**2,10**	**8,34**

Table 8-12 Results of CO_2 emissions [17] for a concrete house



	Material Group	Weight in kg	CO_2 emissions due to materials ($kgCO_2$)	CO_2 emissions due to transport ($kgCO_2$)	TOTAL CO_2 emissions (kgCO2)
Concrete block house	Solvents/ adhesives paints Grupo Sur Company	10	350	0	350
	Wood	30	0	0	0
	Cooked earth	0	0	0	0
	Steel – Aluminum - Zinc -Iron	721	7823	8	7831
	Glass	162	97	2	99
	Other building materials	52645	9740	505	10245
	TOTAL	**53567**	**18010**	**515**	**18525**
	TOTAL in tonnes	**53,57**	**18,01**	**0,51**	**18,52**

For a cob house, contribution of transport is around 25% of total emission, whereas for concrete house it is 2.7%.

Nanz et al. (2018) [28]

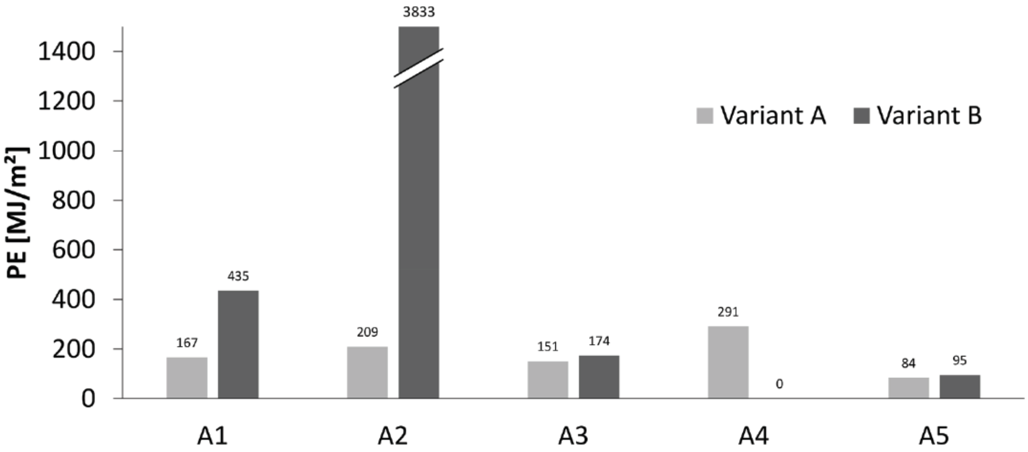


Figure 8-7. Primary energy demand for the two variants studied - transports correspond to A2 and A4 stages [28]

Variant A: total PE = 902 MJ/m², A2 + A4 = 500 MJ/m², transport = 55%

Variant B: total PE = 4,537 MJ/m², A2 + A4 = 3,833 MJ/m², transport = 84%

Appendix G Available results concerning the maintenance phase

Table 8-13 LCA results for 1 m² of the CEB wall stabilized with Calcium Hydroxide [21]

Impact category	MP and manufacturing	Construction and maintenance	End purpose	TOTAL
Thinning of the ozone layer (kg CFC-11 eq)	1.08E-06	1.04E-07	1.32E-08	**1.20E-06**
Climate change (kg CO_2 eq)	35.74	2.04	3.40	**41.18**
Photochemical oxidants - smog (kg O_3 eq)	6.34	0.07	1.01	**7.42**
Acidification (mol H+ eq)	12.24	0.18	1.86	**14.28**
Eutrophication (kg N eq)	1.50E-02	2.47E-04	1.97E-03	**1.72E-02**
Human health: carcinogens (HTU)	2.88E-07	1.41E-09	4.73E-08	**3.37E-07**
SH: non-carcinogens (HTU)	3.49E-06	7.37E-08	4.56E-07	**4.02E-06**
SH: respiratory effects (kg MP10 eq)	1.83E-02	6.62E-04	2.57E-03	**2.15E-02**
Ecotoxicity (ETU)	50.89	0.04	8.73	**59.66**
Use of agricultural and urban soil (m^2a)	11.21	0.00	0.02	**11.24**
Water resources’ depletion (m^3)	0.41	1.43	0.00	**1.84**
Mineral resources’ depletion (kg Fe eq)	3.51E-02	3.07E-03	4.70E-06	**3.82E-02**
Fossil resources’ depletion (kg Petroleum eq)	8.85	0.23	1.14	**10.22**
Saturated energy (MJ)	451.14	11.85	48.11	**511.10**
HTU: Human Toxicity Unit (Toxicity cases/kg $_{\text{emission}}$). ETU: Ecosystems’ Toxicity Unit (PAF m^3 day /kg $_{\text{emitted}}$). PAF: Potentially Affected Fraction of species.				

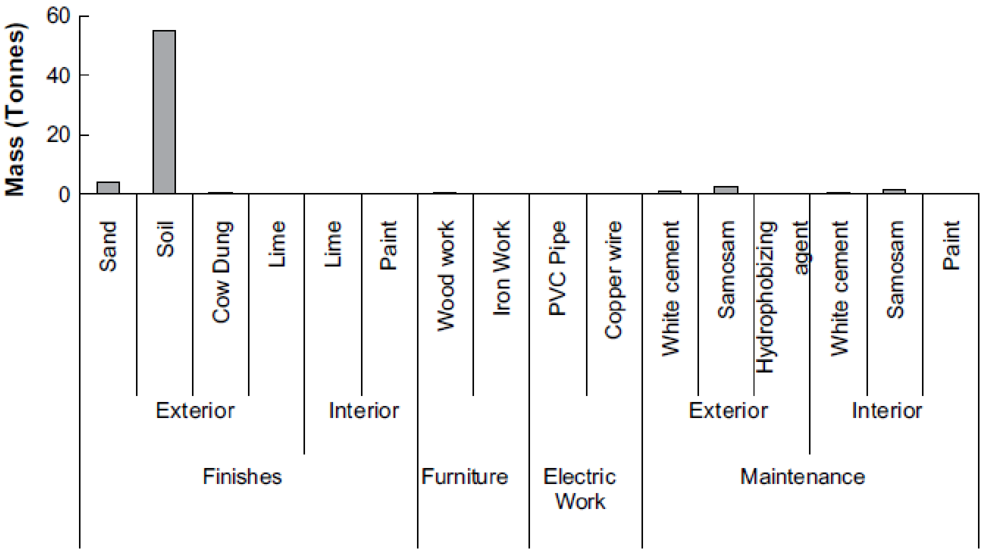


Figure 8-8 Masses of materials for life phases of an adobe house in India [25]