Environmental Life Cycle Analysis of Earthen Building Materials

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Introduction

The building industry is one of the largest consumers of natural resources, both renewable and non-renewable, being responsible for almost a third of all carbon emissions and for consuming more energy and raw materials than any other economic sector (Mota *et al.*, 2012).

During the last decades, architecture has been based on the use of industrially-produced materials, with a low thermal resistance, e.g., large glass surfaces, making buildings extremely vulnerable to outdoor temperature fluctuations. The result was the construction of buildings with a high level of dependence on air-conditioning systems to ensure adequate indoor comfort conditions (Petter, 2011), raising the significance of the building sector in the overall energy consumption. Beyond this, industrially-produced materials are normally produced through energy-intensive manufacturing processes and have considerable environmental impacts, while natural materials, such as timber and earth, normally have low or neutral potential environmental impacts in a life cycle perspective (Mota *et al.*, 2012).

Modern buildings generate important externalities on the environment at local, regional, national and global scales (Ingrao *et al.*, 2018). Nowadays, energy efficiency and sustainability of buildings are important research issues. In the life cycle assessment of buildings, the environmental impacts linked to all life cycle stages of products are estimated (Ingrao *et al.*, 2018). One of the environmental parameters of major relevance in this assessment is the Global Warming Potential, related to greenhouse gases (GHG) emissions, in particular, carbon dioxide, which is closely related to the operational energy consumption and embodied energy of building elements (Stephan and Stephan, 2016). Embodied energy is the amount of energy used to manufacture, transport, assemble and maintain the different building elements, from cradle to the end of the life cycle. The operational energy is the energy used in heating and cooling systems, lighting and in the operation of building's integrated systems (Stephan and Stephan, 2016). To achieve a carbon neutral built environment, it is necessary to optimize both the embodied and operational energy (Dixit, 2019). Nowadays, most of the focus to reduce the life cycle energy consumption in the building sector is put in increasing the energy efficiency during the operation phase. For instance, the European Union is promoting the construction of nearly Zero Energy Buildings (nZEB), by targeting that by 2020 on all new European buildings must be nZEB. While buildings become more energy efficient during the operation phase, the importance of the amount of embodied energy in the life cycle energy balance is increasing, thus pushing the need to find alternative materials to those with high embodied energy (Ramesh, 2012) and more efficient manufacturing processes.

The life cycle assessment (LCA) method allows the evaluation of the potential life cycle environmental impacts and of the total embodied energy of a product or service. The implementation of an LCA study in the product stage is very important since it allows evaluating which are the processes with higher impact and how changing them can contribute to improving the environmental performance of the product. One way to communicate the results from an LCA analysis is to develop the Environmental Product Declaration (EPD) of the product under study. EPDs follow a business-to-business communication format but can also be used by architects, engineers, owners, constructors and consumers to support decision-making in the choice for products with lower potential environmental impact.

In Portugal, it has been estimated for a conventional building (with a lifetime of 50 years) that the embodied energy in building materials is about 6%–20% of the total energy consumed during the buildings' life cycle (Mateus *et al.*, 2007). Additionally, the study carried out by Mota *et al.* (2012) has shown that materials like ceramic tiles, concrete and alkyd paint are the ones that contribute most to the overall life cycle environmental impacts. In this sense, reducing the embodied energy in materials is a premise to reduce the environmental impacts and achieve more efficient and sustainable buildings. It can also contribute to decreasing the cost of materials and in particular of the life cycle cost of a building as a whole (Ramesh, 2012).

Using alternative materials and techniques, like the vernacular ones (lime, earth, adobe, vaulted ceilings, etc.), it is possible to significantly reduce the total embodied energy of a building, as well as the environmental impacts (Fernandes *et al.*, 2013). Understanding that construction materials have important environmental impacts, vernacular materials have, from the sustainability point of view, several advantages. Usually, the most environmental advantages related to this type of materials are: no need for transportation, since they are local materials; lower energy-intensive production processes; and, consequently, lower embodied energy and CO_2 emissions. Furthermore, they are natural materials, often organic, renewable and biodegradable, with better adaptability to the local climate conditions and durability, allowing to improve the environmental performance of a building also in a cradle-to-cradle approach (Singh *et al.*, 2011).

Besides the environmental advantages, these materials allow for social and economic benefits. The local production of materials is not only economically cheaper but also creates jobs (Fernandes *et al.*, 2013). The need for skilled workmanship will result on education and training opportunities on these vernacular building systems, contributing to improve the qualifications of the several construction stakeholders, being also crucial for policymakers (e.g., politicians, sociologists and economists) who take decisions about the built environment (Oliver, 2006). In terms of creating a healthy indoor environment, these materials have low

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toxicity, no volatile organic compounds and, some of them, have properties that contribute to regulating the temperature and indoor air quality (Berge, 2009), as referred in the example of earthen architecture. In terms of economy, Goodman (Berge, 2009) argues that an industry of ecological construction must have their production units near the place of consumption, using local renewable resources, focusing on processes that require little energy and produce reduced pollution. In order to promote and implement this goal, it is necessary to involve the local authorities. Each side has its own idiosyncrasies that must be taken into consideration in the definition of specific policies adapted to the different contexts (Dumreicher and Kolb, 2008). Supporting sustainable local development means also preserving the cultural heritage of construction knowledge that is characteristic of a certain region.

Nowadays, the interest in vernacular materials is rising in the construction sector, and slowly they are being reintroduced again in the design of buildings, through an optimised combination between the knowledge of the past with the current scientific and technological developments. In this sense, this study presents an environmental LCA of two earthen building techniques: the rammed earth, a technique that was widely used in the past in Southern Portugal; and the compressed earth block (CEB), which can be considered a technical evolution of the vernacular construction material adobe. The LCA is based on specific life cycle inventory data of the product stage of these two building materials. The specific data is from a company located in Alentejo, a region in the South of Portugal.

Use of Rammed Earth and Compressed Earth Block in Portuguese Building Construction

In the past, in Portugal, the materials used for building construction were obtained from the geographical area of the construction site. The industrialisation promoted the use of industrially-produced materials, which are normally produced very far away from the construction site, implying the transportation for long distances and the related potential environmental impacts. Due to the industrialisation, from the beginning of the XX century to a recent past, the use of traditional materials and techniques was very limited and an important part of the associated knowledge was lost.

Portugal is a small country, but it is full of contrasts in climate, with significant variations in air temperature and precipitation and in lithology. In Portuguese vernacular architecture, it is particularly evident that there is an almost perfect correlation between the distribution of the building materials used and the lithological characteristics of Portuguese territory (Fernandes *et al.*, 2015b) and one of these materials is earth.

The rammed earth is a building technique that consists of infilling a formwork with soil with a wet consistency that is then compacted in layers. Rammed earth is still now the most prevalent construction technique in existing buildings of the Alentejo region. In this region, the good quality of soil for this type of construction technique is the main justification for its wide use (Fernandes *et al.*, 2015a). Buildings with rammed earth walls have high thermal inertia, which allows them to respond appropriately to the scorching summer heat of Alentejo.

The compressed earth block (CEB) is a technical evolution of the adobe blocks and is obtained by manually or mechanically compressing the earth within a formwork. These blocks can be done only with earth or contain additives to achieve better mechanical performance. Since the earth is compacted directly in the formwork, the blocks can have different shapes, ranging from massive to perforated. The use of earth in architecture continues to make sense in the Portuguese context, due to its several advantages (Fernandes *et al.*, 2015b): strong thermal inertia; ability to influence the quality of indoor air; hygroscopic inertia, contributing to regulate the indoor relative humidity; low embodied energy; low potential cradle-to-grave environmental impact; low-cost material; and at the end of the lifetime it can be recycled and used again in a new life cycle. Buildings made with earth have great durability, since there are a lot of examples with hundreds of years old, and some with a lifetime over than one thousand years, which are still in operation. Although this construction system needs some periodic maintenance, the interventions are normally low cost. Despite these materials have some advantages compared to conventionally used building materials, some of their functional properties, as for instance the thermal insulation, can still be improved. Pereira and Correia da Silva (2012) reported the possibility of improving the thermal insulation of rammed earth walls, in order to comply with the Portuguese regulation on thermal performance, without changing their environmental characteristics, by adding granulated cork in the soil mixture.

Materials and Methods

The Life Cycle Assessment (LCA) of rammed earth and compressed earth blocks (CEB) is based on the specific life cycle inventory data provided by a Portuguese company located in the south of the country. The used method complies with the standards ISO 14040, ISO 14044 and EN 15804.

Functional Unit and System Boundaries

In this study, the objects of analysis are rammed earth and CEB. The declared functional unit is dependent on the goal of the life cycle analysis and in this case the impacts resulting from the production of 1 m^3 of rammed earth and 1 block of compressed earth

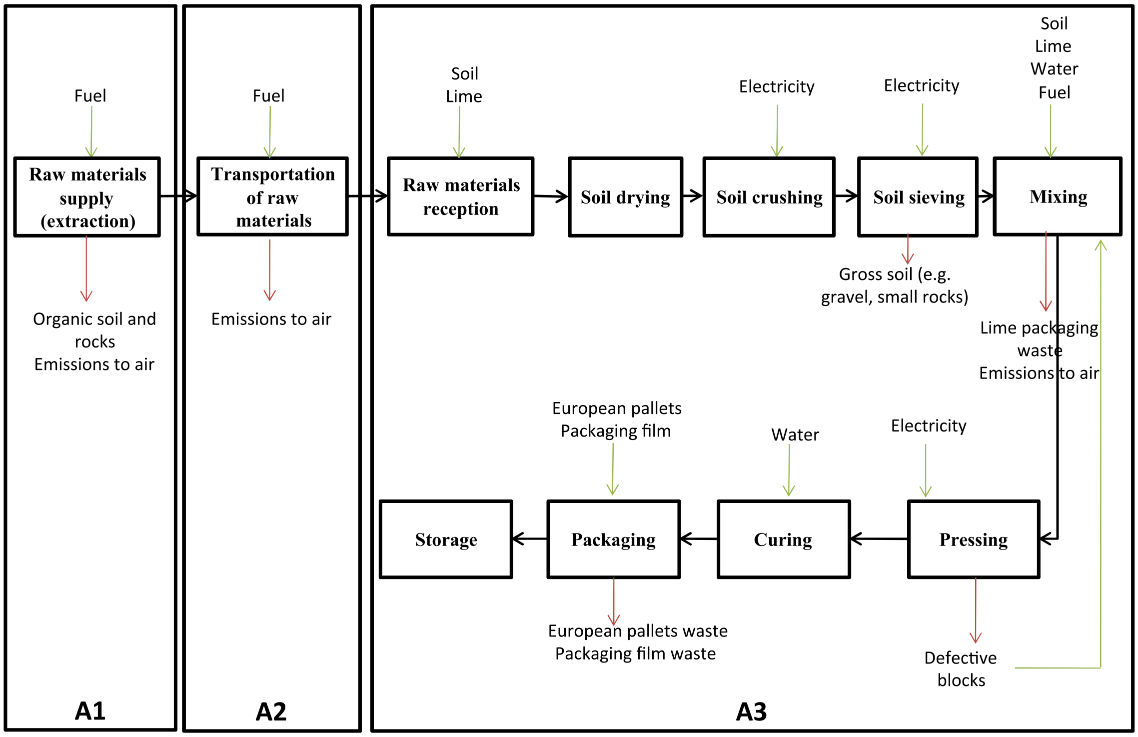

Fig. 1 Diagram of the manufacturing processes of compressed earth block (CEB).

blocks are estimated. This will allow comparisons with other building materials. The boundaries of this work consider the embodied (cradle-to-gate) environmental impacts of the two studied materials. This means that the study takes into account the impacts resulting from the extraction of raw materials, production of secondary products produced by other companies, transportation of the materials to the facility and manufacturing processes. Figs. 1 and 2 present, in a simplified way, the processes that were included in the LCA analysis and the boundaries of the study.

Inventory Analysis

To quantify the environmental indicators it is necessary to first develop the inventory analysis (Teixeira *et al.*, 2016). The inventory is used to quantify the inputs (e.g., energy, raw materials and chemicals) and the outputs (e.g., emissions and wastes) of the product system.

Data used for the modulation of input and output flows of energy and mass is based on a quantitative and qualitative analysis of information received from the manufacturer and of technical documentation of the mechanical and electric equipment used. Generic data was used for the processes in which the manufacturer does not have direct influence or specific information. Therefore, generic data from the Ecoinvent v3.3 database were used for the production of fuels, electricity, tap water, hydrated lime, packaging plastic, wooden pallets and transportation processes. The following processes are excluded from this study: (i) environmental loads resulting from the construction of industrial infrastructures and production of used equipment; and (ii) environmental loads related to the transportation infrastructures of pre-products (e.g., production and maintenance of vehicles and production and maintenance of roads).

The life cycle of the two products was modulated using the SimaPro v.8.4.0 software. Since this study is focused on the analysis of two environmental indicators (Global Warming Potential – GWP and the Total Embodied Energy – EE, tot), the following two lifecycle impact assessment methods were used, respectively: CML-IA v.3.4 method and Cumulative Energy Demand v.1.9 method.

Results and Discussion

Table 1 presents the results from the quantification of the potential environmental impacts related to the production of 1 block of CEB and 1 m^3 of rammed earth and the contribution of different information modules of the product life cycle stage: A1 – raw materials supply; A2 – transportation; and A3 – manufacturing. Since the rammed earth is only materialized in the construction site, the construction process stage was also included. Therefore, the transportation of materials and equipment (information module A4) and the construction process (A5) were considered in the life cycle analysis of rammed earth.

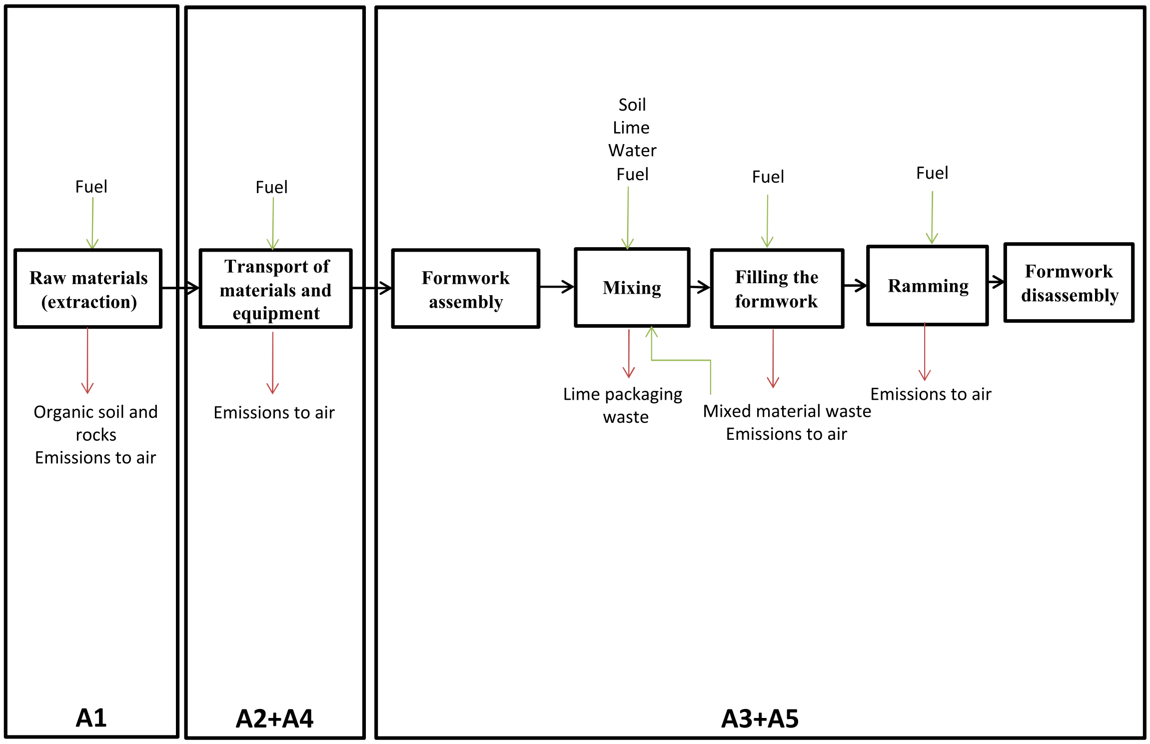

Fig. 2 Diagram of the manufacturing processes of rammed earth.

Table 1 *GWP* and *EE, tot* related to the product life cycle stage of 1 m^3 of rammed earth and 1 block of CEB

Information modules of the product stage	*Rammed earth (1 m^3)*		*CEB (1 block)*	
	GWP (kg CO_2 eq)	*EE, tot (MJ)*	*GWP (kg CO_2 eq)*	*EE, tot (MJ)*
A1	3.14	48.84	0.02	0.26
A2/(A2 + A4, in the case of rammed earth)	2.89	48.30	0.11	1.74
A3/(A3 + A5, in the case of rammed earth)	44.26	529.04	0.26	1.93
Total	50.28	626.18	0.39	3.94

Analysing the results it is possible to conclude that the manufacturing stage is the one that most contributes to the environmental impacts of both materials. Additionally, the production of CEB has higher potential environmental impacts than the production of 1 m^3 of rammed earth. This is mainly due to the higher impacts resulting from the transportation and manufacturing stages of this material and could be minimised if the production of CEB was done in the same place of earth extraction/ preparation, which is the case in the rammed earth.

In order to understand if these two materials have a good environmental performance, it is also necessary to compare these results with the ones of conventionally used building materials. In this case, the results were compared with the ones of the ceramic brick, the most used material in Portugal to build walls and the declared functional unit is 1 kg. In the calculation of the potential environmental impacts of the ceramic brick, the generic LCI data from Ecoinvent v3.3 database and the transportation distance from the nearest brick manufacturer were considered.

Fig. 3 presents the cradle-to-gate environmental impacts resulting from the production of 1 kg of each material. The differences between the three materials are similar for the two environmental impact parameters, being the rammed earth the one that presented the lowest values. Additionally, both earthen materials have substantially lower potential environmental impacts than brick.

Nevertheless, it is important to highlight that the comparison presented in Fig. 3 is based on the same amount (1 kg) of material, but when they are used in the construction, different kilograms of each material are necessary to satisfy the same function. Therefore, it is necessary to compare these three materials when they are used to fulfil the same function. In the case of this study, the comparison is made considering the amount of material that is needed to build 1 m^2 of common walls. Six alternatives for walls were considered: 15 cm thick CEB wall with and without plaster since CEB does not need plaster to be finished; 60 cm thick rammed earth wall without plaster; 22 cm thick hollow brick wall finished with plaster in both surfaces; and

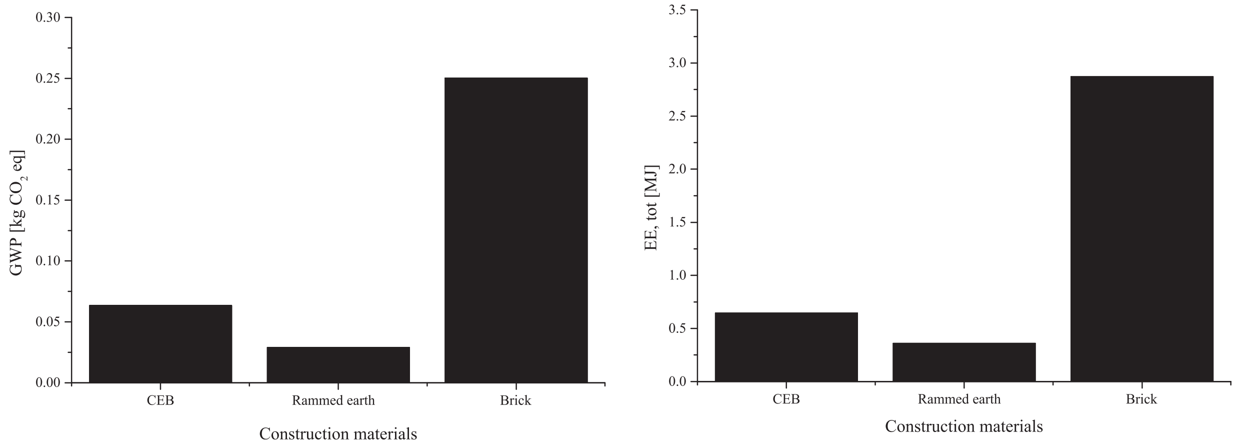

Fig. 3 *GWP* and *EE*, tot related to the product life cycle stage of 1 kg of CEB, rammed earth and ceramic brick.

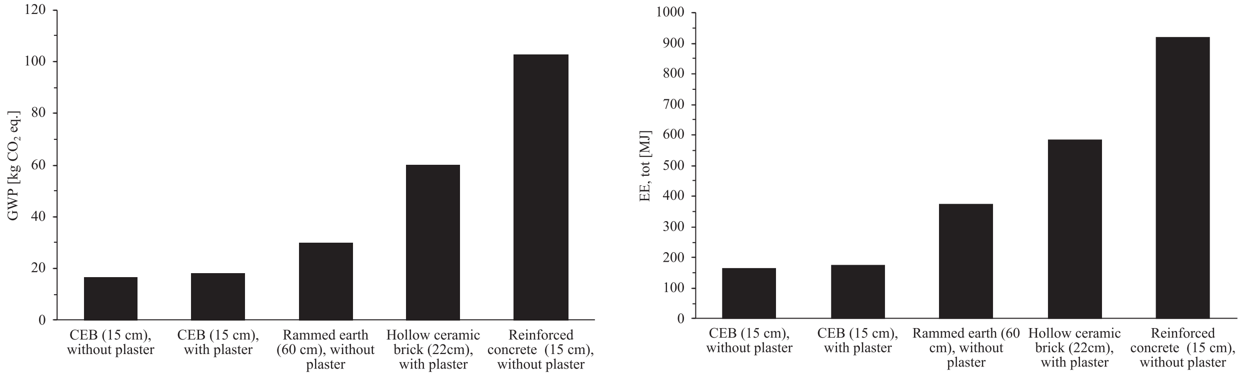

Fig. 4 *GWP* and *EE, tot* for 1 m^2 of each alternative wall.

15 cm thick reinforced concrete wall. The considered plaster is the same for the different walls and is made with Portland cement. In the calculation of the potential environmental impacts of the ceramic brick, cement mortar, concrete and reinforced steel, generic LCI data from Ecoinvent v3.3 database and the transportation distances from the nearest producers were considered.

Fig. 4 presents for the six alternative walls mentioned before the values of the two impact categories. It can be observed that the CEB wall without plaster presented the lowest values for both impact categories. One interesting observation is that when the comparison is made at the scale of the building element, CEB is the material with the lowest potential environmental impact, but when comparing 1 kg of each material, the best material is the rammed earth. This is because the weight of CEB needed to build 1 m^2 of wall is much lower than the weight of a rammed earth wall.

Conclusions

The life cycle assessment results presented in this study are based on specific data from a Portuguese manufacturer of earthen materials (compressed earth blocks – CEB and rammed earth) and showed the substantial environmental savings resulting from the use of these materials in comparison to the use of ceramic brick and reinforced concrete. The comparisons are made at the level of 1 kg of material and also for 1 m^2 of an equivalent wall, considering the cradle-to-gate life cycle stages. Although the end-of-life impacts are not considered in this study, it is necessary to highlight that earthen materials would also have lower potential environmental impact in that stage, compared to ceramic bricks and concrete, since they can be easily recycled to be used in the production of new earthen materials or they can be simply disaggregated and returned to the natural environment at an insignificant environmental impact.

In the case of the compressed earth block there are two major contributors to the value of the analysed environmental parameters: (i) the transportation of raw materials (soil mixture from the extraction site to the manufacturing site and hydraulic lime from the producer to the manufacturing site); (ii) and the manufacturing process of the block, mainly due to the electricity and fuel consumption in the soil sieving, mixing and pressing processes. For the rammed earth, the major contributor is the manufacturing process, mainly due to the fuel consumed in the mechanical ramming process. The potential impacts of the CEB would be lower if the production facility was closer to the place where the extraction of soil is made.

Results of this study show that the two studied vernacular materials have substantially lower environmental impacts when compared to the equivalent materials that are currently used today in the construction sector. Vernacular materials are locally available and therefore they do not need to be transported for long distances. Additionally, they need very low intensive energy manufacturing processes and therefore they have lower embodied energy than conventional building materials. From the analysis of the results, it is evident that the use of the two earthen materials can contribute to decreasing the embodied impacts of a building, but further studies are needed in order to consider other life cycle stages, such as the use stage.

Thus, to achieve the goals for a more sustainable built environment, architecture and construction industry should seek an optimised integration between tradition and modernity, using the best of both at the level of know-how, techniques and materials. Beyond the environmental issues, promoting the use of local materials may have a positive impact on the local social and economic developments. It is up to designers to use their creativity to improve and adapt these vernacular techniques to the new functional requirements. Nevertheless, internationally there is still a lack of quantitative information of most of vernacular materials and techniques. Therefore, more studies are needed to analyse and identify the best vernacular techniques and materials so that they can be improved and scientifically validated in light of the actual technological and scientific knowledge. This will give credibility to those materials and will promote their use by the different stakeholders of the building sector.

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