

Using Raw Earth Construction Systems on Contemporary Buildings: Reflections on Sustainability and Thermal Efficiency

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Abstract. Although the existence of building energy efficiency policies for several years, studies show that up to 74% of the participant consider their house uncomfortable. European policies favored construction solutions focused on insulating materials rather than other solutions which traditionally were used and proved to be effective. Construction system that uses earth as construction material showed for centuries that it can offer high levels of thermal comfort in a passive way, with a highly sustainable and quasi-neutral environmental impact. With this paper, a study on the thermal performance of three contemporary rammed earth buildings is presented. The aim is to analyze thermal comfort over a critical period of time. It is expected that earth construction proves to be a good choice, creating a sustainable and better integration with the local environment, with almost zero energy incorporation, promoting the local work craftsmen and with a construction range price below the common construction systems.

1 Introduction

It is estimated at European level that up to 97% (i.e. all buildings built before 2010) require partial or total intervention to improve their energy performance by 2050 [1].

In 2012, Portugal (as a European member) presented a building refurbishment production of only 8%, compared to an European average of 26% in the total construction sector, although estimated that almost 1 million buildings (about 30% of the total existing buildings) were already in need of renewal works (Euro-construct, FIEC and AECOPS) [2].

In this context, Portugal is presented as one of the countries where the buildings are less prepared to ensure the housing thermal comfort. It is estimated that about 23% of the houses have this problem, comparing to the European average of only 8.7% (2016, Eurostat).

Furthermore, although the existence of building energy efficiency policies for several years, recent studies show that 23% of the Portuguese are unable to achieve thermal comfort in their houses (2016, Eurostat), and 74% of the participant in a thermal comfort inquire consider their

house to be uncomfortably cold in the winter and 25% to hot in the summer, situations in which 80% of the users declare having to resort to active systems to ensure adequate thermal comfort levels [3], with the environmental and economic costs becoming increasingly costly and unbearable.

Thus, the need to develop specially adapted retrofit solutions becomes evident, in order to achieve constructions that are well adapted to the local conditions and that make use of the passive conditioning processes, at the same time reducing the energy housing needs.

History shows that, throughout centuries, vernacular architecture, in which earth-based constructions were of wide application in southern European countries, has evolved in order to achieve those goals, using the material's thermal inertia and the building passive strategies.

Nevertheless, the emergence of the reinforced concrete (RC) structures, the baked bricks industrialization and the low energy prices in the end of second half XXth century caused the general abandonment of those traditional construction techniques for the more modern, free form and quicker solutions, that ultimately revealed non-adapted and, in time, more costly to the user in energy and wealth.

Nowadays, given the new construction systems available and the technical knowledge, the study of the passive

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Fig. 1. Odemira and Serpa location in Alentejo, South of Portugal map. (West side of Europe) – Image of Alentejo adapted from Google Maps and Mapa Mundi image Designed by Freepik.

processes and of the traditional construction methods and materials, on how to promote the same principles to achieve similar results in the different components might prove to be a sound effort, looking for a mix in solutions that also provide answer to the users modern expectations.

Given the context and constraints previously exposed, this study goal is to access the current suitability of earth as a building material in different climate conditions, starting from a previous research that has been carried out about this subject, making use of the information already produced, seeking to validate it in a more comprehensive way.

To this end, it is proposed the comparison between three buildings with different functions (an office building, a kindergarten and a rural hotel), two of which are located in the same village, Serpa, and another in Odemira, with somewhat different climate conditions.

Digital modulation of these buildings will be developed in order to conduct several comparative studies using Autodesk Ecotect in order to reinforce and complement data logger results.

In this way, we intend to validate the applied methodology to different regions and conditions, as well as to evaluate specific needs, and the possibility to use software modulation in order to incorporate adaptations to the construction system. The control parameter should be the users thermal comfort.

An economic and environmental study is also developed, in order to access the actual expected cost difference between these construction solutions as well as their impacts during the life time of the building.

It is expected that earth construction proves to be a good choice in present days, even more when it can create a better integration with the local environment – both past architecture and local climate as well.

Furthermore, the fact that these constructions were built with a construction range price below the prices of more common systems of construction (concrete and light steel frame) at present time in Portugal will be demonstrated.

Earth construction is also much more sustainable, by using local earth material, and therefore with almost zero energy transport and production/extraction incorporation, and also because of the use of local workcraftmen.

As a final goal, it is expected to show the possible adaptation and suitability of this kind of construction material, with all its advantages, in order to achieve more sustainable and thermal efficient dwellings with low environmental impact.

2 Case study

Based on the analysis carried out on the two buildings located in Serpa, that were modeled and analyzed with Autodesk Ecotect while simultaneously recording the actual temperature and humidity values with data loggers, serving as control elements, it is intended to understand how these digital modeling tools and results can be extracted and applied to other situations, as a way to improve passive strategies development and planning.

Serpa and Odemira (Fig. 1) are both placed in Europés highest annual solar radiation area (Fig. 2). On what relates to the thermal comfort, it is immediately perceptible that, if solar radiation is so high, that will probably translate in the main problem.

The first two buildings are located in Serpa, a southern interior village in Alentejo, about 130 kilometers from the Atlantic coast in the West and South, placing it in the small Bsk region. In the winter conditions, lasting for about 3.8 months, average temperatures register values between a minimum of 5 °C and a maximum of 18 °C. On the other extreme, the summer conditions here lasts for 3 months, with daily average maximum temperatures above 30 °C and minimum temperatures about 18 °C. Therefore, it is perceptible that summer conditions are particularly harsh while the winter is quite soft.

The third case study is located in Odemira village. Although also belonging to the same region and located at the same latitude, is much closer to the Western Atlantic Coast, with the kindergarten buildings just 15 km from the sea. The summer conditions in Odemira last for 3.1 months, from July to September, with the average maximum temperature above 27 °C. The winter conditions here lasts for 3.7 months from November to March, achieving a daily maximum temperature below 18 °C. It is possible to understand that, although in the same region, the

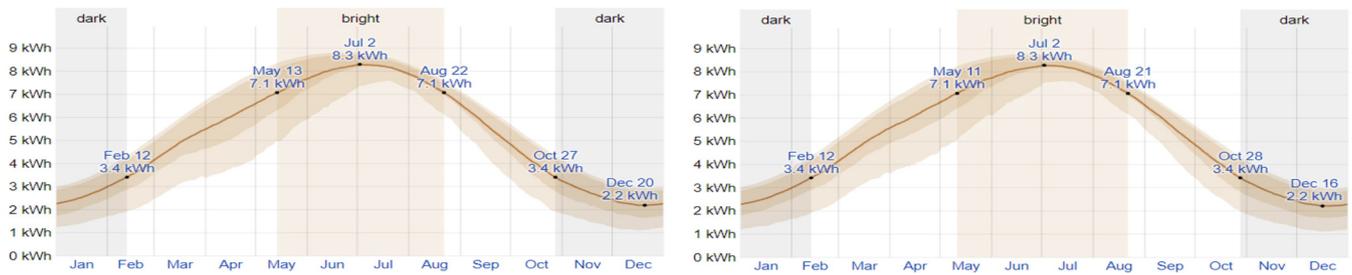


Fig. 2. The average daily shortwave solar energy reaching the ground per square meter in Serpa and Odemira through the year. Image adapted from pt.weatherspark.com.

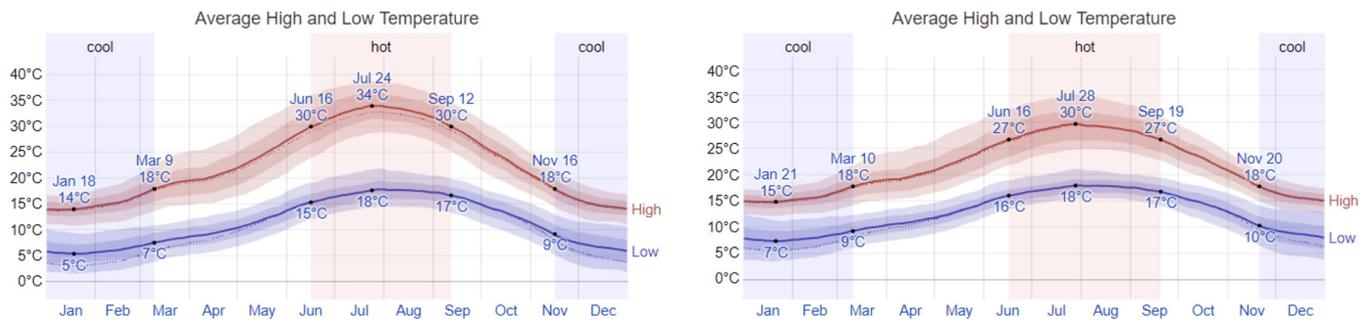


Fig. 3. Annual average high and low temperatures in Serpa and Odemira through the year. Image adapted from pt.weatherspark.com.



Fig. 4. General images from the three-case study. (a) The architectural office “Betão e Taipa”, (b) The rural hotel “Cantar dos Grilos”, (c) The Odemira kindergarten.

proximity to the sea positively affects the building thermal behavior and, therefore the thermal comfort of the users, since daily temperatures are consistently lower in the hottest months. The humidity from the sea also helps to lower the heat thermal impact from the user’s point of view, besides contributing to cool down the materials and dissipate some of the energy stored in them during the day, preparing them to perform well in the next heating period (Fig. 3).

Throughout time, Alentejo vernacular housing evolved to adapt to this situation, presenting rammed earth buildings prepared to perform in this climate. With the massive application of reinforced concrete (RC) structures in the XXth century, becoming the dominant construction system worldwide, many of these vernacular principles

were abandoned, leading to a kind of construction that was not adapted to these conditions. However, in the last years there has been an effort to recover and adapt these techniques and principles, recognizing their advantages, resulting in good contemporary buildings that use earth as a primary construction material.

This study aims to analyze the info gathered from the three case studies, measuring the hygrothermal performance of them. The first building is named “Betão e Taipa” (Fig. 4a), a contemporary building with steel structure that incorporates 50 cm thick rammed earth wall (REW) and large glazed windows, serving as an Architectural Office. The second building, “Cantar do Grilo” (Fig. 4b), serves as a rural hotel presenting a traditional architectural language, although it is in fact a modern RC structure

with 50 cm thick REW. It is very convincing to realize that this building has no air conditioning devices, being able to ensure thermal comfort to its users throughout the year, although located in a very hot climate area.

The last case study is related to two buildings that serve as a kindergarten (Fig. 4c), both also built in RC structures with REW. In the newest building, about 10 years old, there is an active acclimatization system, since it was a mandatory condition in the building licensing to this kind of functions. However, this has been kept permanently off, since the building passive performance has been proving enough to ensure the user's thermal comfort throughout the year. Therefore, this kind of construction has resulted in a significant saving in the energy consumption that the use of the active conditioning system would require.

In order to evaluate the validity of digital modulation software, both Serpa buildings were modeled in Ecotect, properly oriented and replicating the construction systems, wall thickness, roof insulation and glazing.

At the same time, several data loggers were installed in all buildings (relative humidity and temperature recorders, plus thermo-hygrometers), all previously calibrated. Four sensors were placed in the first building and three in the second and third buildings.

3 Measurements, results and performance models

The measurement devices recorded readings every 30 min in the months that are considered the warmest in the region, between August and October 2016. The measured values were then compared to the data gathered from official local sources, in order to validate them. To each case, a representative week was then selected for a detailed analysis (Fig. 5).

As expected, during this hot period, outdoor registered temperatures were very hard, in what concerns thermal comfort conditions. Even so, acceptable thermal comfort conditions were achieved inside the buildings, wherever sun exposure was minimized (like at the rural hotel lobby, in inner zones of the kindergarten, or even in the architectural office hall and warehouse).

On the other hand, as shown above, spaces that were directly exposed to the sun presented harsh uncomfortable conditions, like in the situation recorded in the outside hotel porch, on the kindergarten patio, on the office entrance or even in the office area of the architectural building with big glazing windows, many times registering temperatures outside the comfort conditions, even with the use of air conditioning in this last case. These situations highlight the importance of providing an efficient solar protection, not only to the glazed windows but also to the outdoor places intended for usage.

In the outdoor areas extra care should be taken to provide solar protection to the spaces, but also to opt for adequate coating of the materials exposed surfaces. The failure to provide these can create uncomfortable situations for the users, for example, by the emission of the stored

excess energy in the form of heat, at a time of the day that, in order to achieve comfort conditions, would require a lower use temperature.

Taking into account this information and in order to propose an improvement of solar protection, Ecotect building models were then produced for simulation (Fig. 6), aiming to recreate the office building conditions and thermal response, besides the usage type taking into account the number of users. The analyses scope was focused on a single summer week.

During the visits and inquiries to the Serpa architectural office, the possible thermal uncomfortable situation that the big exposed glazing windows could cause in the working area immediately caught the authors' attention, as the monitoring came to confirm. Solutions were then tested that would provide some kind of solar protection to these elements.

With Ecotec, it was possible to test, evaluate and present a solution of shading, that was then applied to the building, that lead to a better thermal and working environment, as well as to energy savings since the air conditioning needs were reduced (Fig. 7).

4 Economic and environmental components

Actually, the most commonly used construction system in Portugal, especially in small and medium-sized buildings, corresponds to the use of RC frame structures, or RC wall structures, with lightweight slabs systems, or solid RC slabs, and double-leaf masonry walls with thermal insulation.

However, in the studied buildings that are presented in this article, the structural solutions vary between metallic structure frames built outside the walls, in the office case, and the use of RC structure, in the rural hotel and kindergarten buildings. All three solutions present REW.

In the office building, which also houses a company construction yard, the choice for a metal structure solution, over the more common RC, was merely formal/conceptual. Therefore, in this paper we will only address the structural and construction solution that is common to both the rural hotel and the kindergarten, since this combination is the closest to the cost-controlled choices for the current/common constructions.

4.1 Economic component

Since one of the goals is to gauge the relationship between the construction cost versus the environmental and sustainability impact of each construction solution, we present a comparison between the estimate construction costs from solution 1—current construction with a RC structure and hollow brick baked wall masonry; solution 2—RC structure with REW; and a third solution, with the same RC structure and walls made out of compressed earth blocks (CEB), considering a similar construction of 91 m² at the date of 2001. Thus, the values are related concerning a small construction of 91 m², initially developed by Lourenço, P.I. in 2002 [4].

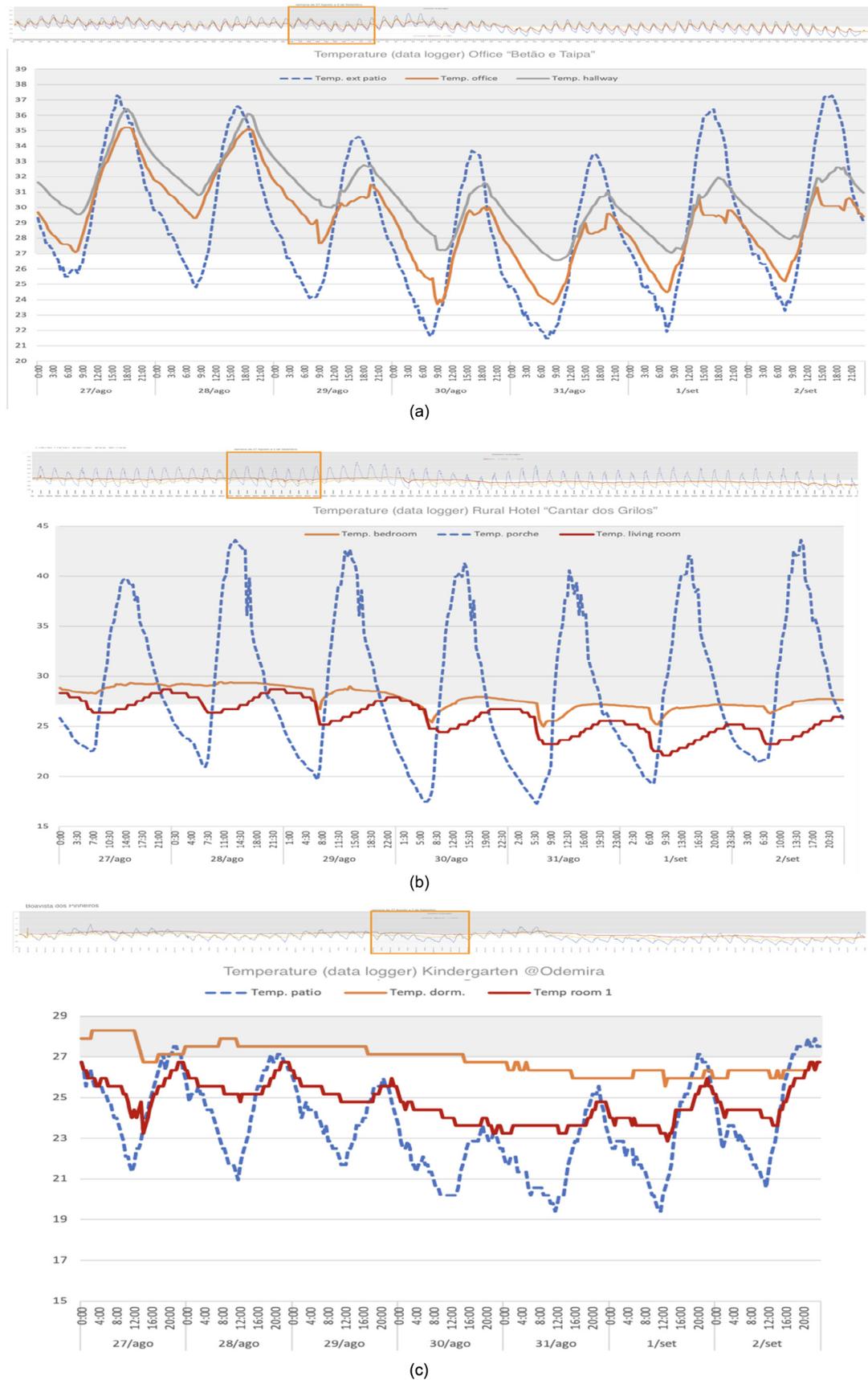


Fig. 5. Measurement recorded by data logger devices, with representative week analysis. (a) The architectural office “Betão e Taipa”, (b) The rural hotel “Cantar dos Grilos”, (c) Odemira Kindergarten buildings.

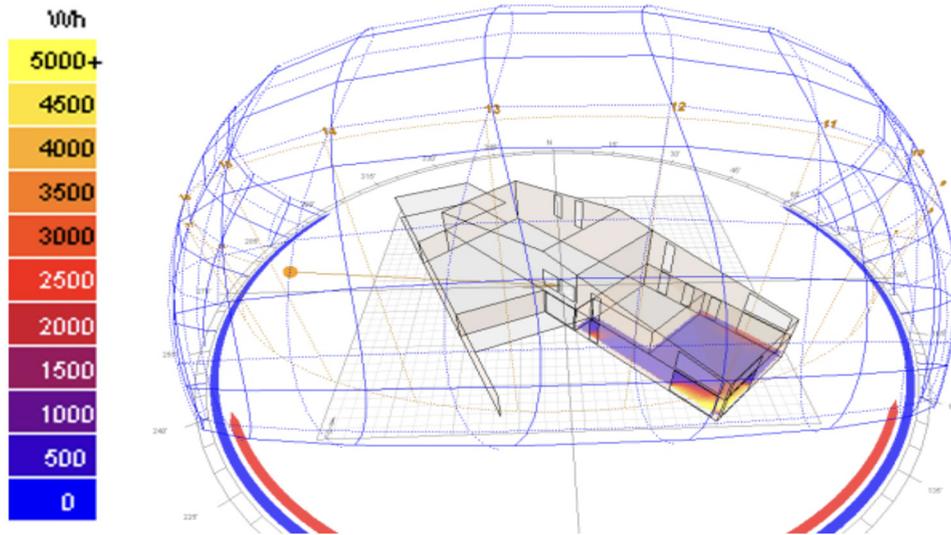


Fig. 6. Ecotec Architectural Office “Betão e Taipa” Simulation with incoming solar radiation.



Fig. 7. Serpa architectural office “Betão e Taipa” west glazing exposure. (a) Glazing with the original solar exposure. (b) The same glazing with a natural shading solution.

In the table below (Tab. 1) we removed the information that was common to all 3 construction solutions and that presented similar costs. These components were integrated in the item “other activities/specialties on site” with a global value.

In the table above, the following points must be highlighted:

- In relation to the original solution (1), solution 3 (RC with CEB) shows that the overall labor cost is almost equal (variation of 1%) and the work duration should only be higher by three weeks.
- The advantage of the near-zero local production cost of CEB (excluding labor), when compared to the acquisition of solution 1 commonly manufactured bricks, is almost canceled out because of the time / man hours spent for the CEB production.

- The resource to CEB, in relation to adobe blocks, must be taken into account since CEB production requires less experience and technical knowledge, proving much easier in the technician’s production training, since it can be achieved by mechanical processes which normalizes the production process. When compared, adobe production requires greater mastery and knowledge because it is a totally manual process and, as such, its quality is totally influenced by its producer. Besides that, CEB production process can also be industrialized, furthering increasing the production quality and cadence, equating it to cast bricks production in efficiency and cadence.
- The construction system using CEB in self-supporting structural walls (without RC frames) can be more economical than solution 1, considered to be the most

Table 1. Cost construction studies, according to 3 different constructive solutions for same 91m2 house prototype.

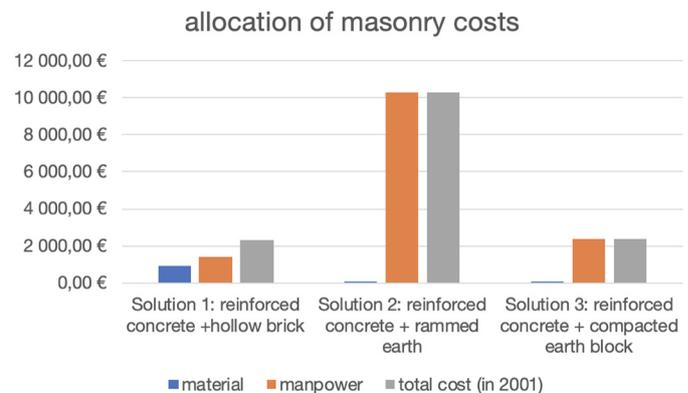
estimated costs of activities in EUR (in 2001) for a construction of 91m2	Solution 1: reinforced concrete +hollow brick		Solution 2: reinforced concrete + rammed earth		Solution 3: reinforced concrete + compacted earth block	
	price	work days	price	work days	price	work days
earthmoving	439,85 €	3	439,85 €	3	439,85 €	3
foundations	3 201,18 €	15	3 201,18 €	15	3 201,18 €	15
structure	3 088,10 €	15	3 088,10 €	15	3 088,10 €	15
masonry	2 328,49 €	22	10 299,60 €	104	2 368,05 €	57
stonework	1 143,33 €	9	1 143,33 €	9	1 143,33 €	9
exterior plasters	1 352,71 €	13	0,00 €	0	1 229,86 €	13
final coating of walls and ceilings	847,48 €	29	791,00 €	29	518,99 €	29
other activities / specialties on site	24 663,68 €	99	25 457,14 €	99	25 457,14 €	81
total cost (in 2001)	37 064,82 €		44 420,20 €		37 446,50 €	
percentage variation between solution 1 and solutions 2 and 3			19,8%		1,0%	
total days of work		205		274		222
variation of work duration between solution 1 and solutions 2 and 3				69		17

common in Portugal, by a difference of 8%, with the total estimated value of 34,068.61€ versus the 37,064.82€ predicted in solution 1.

- The REW production requires much more preparation, construction and drying time than those of masonry blocks (either CEB or cast brick), so the costs associated are well above other solutions in both price and execution time, doubling or even tripling it.
- It should also be borne in mind that an experienced CEB masons' team should be able to reduce the blocks production and settling time to 45 days or less, instead of the originally planned 57 days.
- Solution 1 does not assure the same thermal performance as those built with earth. Therefore, the adding of thermal insulation solutions would result in higher construction costs and, above all, greater environmental impact due to the insulation material type.

This comparative analysis reveals that the most significant influence over the other variables is the required labor since, in the hollow brick masonry system, the cost is mainly incorporated into the raw material and transport cost but, in the other situations, the costs are practically all in the labor force (Fig. 8).

From the economic view point, solution 1 divides the costs between hand labor and the material production and transport, with greater dynamics of the industrial sector, as opposed to the rammed earth solutions that places almost all the economic dynamics on the local hand labor, with a local job increase. The CEB industrialization process can also be developed to reach an intermediate production level, assuring a greater production efficiency and cadence, and access to the local and regional markets, thus directing more workers to the block's settlement and, in this way,

**Fig. 8.** Allocation of masonry costs.

allowing to reduce global costs, production and in-site application time. On the other hand, this would also translate in the energy incorporation and respective environmental impact in the CEB production and transport from the shipyard to the work site.

The use of REW allows an exceptional plastic image, similar to a concrete on sight solution and, as such, can and should be treated as a finishing solution, that justifies its superior cost against the CEB solution.

Given the local climate characteristics, registering the most extreme temperature situation in the summer, solution 2 or 3 (either in REW or in CEB) reconcile the global costs (better in the CEB situation) with the thermal inertia and insulation advantages, in a way to better protect users from the climate aggressiveness, when compared to the conventional construction of leaked brick

Table 2. Table of embodied energy coefficients of materials considered in Table 1. Center for Building Performance. WELLINGTON, U. of (2005).

Materials	Mj/kg	Mj/m ³
Aggregate, general	0.1	150
Aggregate river	0.02	36
Cement, average	7.8	15.210
Cement mortar	2	3.200
Concrete 30Mpa	1.3	3.180
Concrete, block	0.94	–
Ceramic brick	2.5	5.170
Ceramic clay	0.81	–
Adobe brick (added cement)	0.42	–
Compacted earth block	0.42	–
Taipa (added cement)	0.8	–
Local stone	0.79	1.890
Imported stone	6.8	1.890
Timber, air dried	0.3	165

at a similar cost. Besides, these solutions also present enormous benefits to the indoor air quality and, as we shall see below, in the defense of the environment.

4.2 Environmental component

In the current century, mankind is surpassing the planet's population growth, raw materials extraction and residues production goals, hitherto considered to be distant, both from overpopulation and from the planet environmental impact, mainly by human action. Still, it is expected that humanity reach the 10 billion human beings in this century. In a globalized economy, this population increase phenomenon will imply an exponential growth of the natural resources consumption, of the short-term use and discard policies, and of the subsequent pollution, with ever more serious consequences for life on earth.

The construction is one of the largest resource exploration activities in the world, consuming about 3000 Mt/y in raw materials, almost 50% in mass, more than any other economic activity [5]. It has been estimated that this sector is accountable for about a 40% share in the use of natural resources taken away from nature, for 40% of the primary energy consumption [6], as well as for the production of about 40% of each country waste in the European Union [7].

Therefore, the careful selection of building materials is essential, either due to their extraction or production impact, and work application, but mainly because of their environmental impact throughout the useful life of the building. In this context, compressed earth construction plays a preponderant role, making it extremely competitive, low cost and highly accessible, with practically null environmental impact, good thermal inertia characteristics and proven hygroscopic permeability.

The earth extraction, intended for the REW or the CEB production, is a fully reversible process. Locally extracted, although it cannot be considered a renewable resource, it is however the most abundant, reusable and, as such, lower environmental impact construction material. In comparison, the baked brick has an incorporated environmental load associated with the energy incorporation, either by the industrial extraction, production and transport processes, as well as by the fact that it is usually not reused at the end of its life cycle.

The energy expended in the building materials transport is one of the points that most contributes to the poor environmental performance [8]. For example, the transportation of building materials by a diesel truck has an energy expenditure between 0.8 and 2.2 MJ/ton km. When by railroad, moved with a diesel engine, is about 0.6 to 0.9, and from 0.2 to 0.4 MJ/ton km if driven with electricity.

As this impact implies and is shown in Table 2, one should opt for the local materials use, in which the present compressed earth solutions are good examples.

As an example, [5] concludes that for a 92 m² dwelling, the resource to interior CEB walls allows a CO₂ reduction in about 7 tons, when compared to the same walls in cooked brick, or even of 14 tons when compared to the use of autoclaved concrete blocks. The hypothetical 5% replacement of all concrete blocks used in the UK by adobe blocks would save about 100,000 tons of CO₂ [9].

In the table above, the incorporated energy in each type of construction material is presented, revealing a clear advantage in the choice of locally extracted natural materials such as adobe brick, CEB and REW, with values between 0.42 and 0.8 MJ/kg for earth constructions, comparing to the ceramic bricks with values in the order of 2.5 MJ/kg.

Also, from the environmental view point, raw earth buildings present water absorption levels between 40% and 60%, values that guarantees the more indicated humidity levels and that are close to the human's ideal comfort and health conditions.

5 Conclusion

The rammed earth building tradition in the south of Portugal is still alive. The technicians and builders have been able to adapt the use of this material to the current demands, with new functional programs, new architectural solutions and new ways of working the material, in line with the best climate adaptation passive solutions. The adaptation to new structural systems allowed to release the architecture from the self-supporting walls, and in this way permitting to evolve in the form.

All the buildings of the case studies had in common the use of rammed earth walls (REW), with the high thermal inertia given by the thickness of the walls, developed together with other passive solutions, in tune to better adapt them to the local climate. It was demonstrated that during a summer week with climate extremes, the buildings performance was mostly adequate, wherever there was an efficient solar protection (which is the case of the rural hotel and the kindergarten), without using active temperature control solutions, validating this choice against the common solutions in cast brick. It was also showed, from the office building performance, that regardless of the used construction system, building orientation and solar exposure is a critical condition in achieving a good thermal behavior.

Also, from the economic view point, it was evident that the option for a compressed earth solution does not necessarily have to increase the construction cost, adjusting the option of compressed earth walls by compressed earth blocks, with the similar thermal and hygrometric characteristics, both superior to the current brick construction that presents worse performance in both comfort parameters.

From the environmental view point, the choice for earth as a construction material versus the brick becomes evident, given its low energy incorporation, enormous ease of access and, although not being unlimited, is usually of enormous abundance in the site or in its proximity.

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