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Contemporary Earth Architecture

Extended Abstract

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1) INTRODUCTION

This dissertation is about contemporary earth architecture and its role in modern construction industry.

The idea for this investigation arose from the observation that, despite being one of the oldest and more widely used sustainable building materials in the world, earth is not usually seen as a building alternative in the construction industry of developed societies. The goal of this dissertation is to contribute to an understanding of how earth as a building material can respond to contemporary living and building demands and become a common alternative in the industry.

This dissertation focuses on earth as a massive form of construction, capable of being applied without any coating, in order to maximize its aesthetic potential and hygrothermal properties. For this reason, light construction solutions and coating techniques, such as prefabricated light earth panels and plasters, were not included, despite recent developments in technology.

An investigation was undertaken to understand the advantages and limitations of earth as a building material, its properties and testing procedures, how it can be improved through stabilisation, the main design and building requirements and the most relevant constructions techniques that are used in the industry today. In the final part of the investigation, five contemporary case studies were analyzed against a group of parameters identified during research. These allowed benchmarking and criticizing the investigation and contributing to the advancement of its conclusions, by determining the main factors that influence the design and condition an earth building.

Based on this analysis, a synthesis of the premises for the development of earth as a building material was made, as a solution to the question on how earth could respond to contemporary demands in order to become an alternative in the construction industry.

2) CONTEMPORARY EARTH ARCHITECTURE OUTLOOK

Despite being one of the oldest and most extensively used forms of construction (Fig. 1), earth architecture is seldom seen as an alternative in the modern construction industry of developed societies.

Figure 1 – Technical standard of mud block building in ancient Egypt 1.500 BC (Schroeder, 2012)

Taking Portugal as an example (Census 2001), new buildings in earth blocks, rammed earth and stone masonry represents only 3.09% of new construction between 1996 and 2001. Even though this percentage has slightly increased in the past three decades (Table 1), it is far from the reality of the beginning of the century, when it represented more than 50% of the total amount of existing buildings.

Table 1 – Number of buildings built in earth blocks, rammed earth or loose stone masonry in Portugal, compared to the total amount of buildings, by period of construction (adaptation based on the Census 2001 data)

Period	**Total (2001)**	**Before 1919**	**1919 – 1945**	**1946 – 1960**	**1961 – 1970**	**1971 – 1980**	**1981 – 1985**	**1986 – 1990**	**1991 – 1995**	**1996 – 2001**
Number of buildings (total)	3,160,043	253,880	344,936	357,042	395,262	553,349	359,579	289,351	279,146	327,498
Number of buildings with walls in earth blocks, rammed earth or loose stone masonry	352,466	131,679	96,442	54,734	22,380	15,079	7,827	6,495	7,716	10,114
Fraction of buildings with walls in earth blocks, rammed earth or loose stone masonry compared to the total number of buildings	11.15%	51.87%	27.96%	15.33%	5.66%	2.73%	2.18%	2.24%	2.76%	3.09%

Although building with earth was a widespread form of construction until the late XIX century, it grew out of fashion with the advent of the Industrial Revolution and the development of new materials and construction techniques. Eventually, new earth constructions almost ceased during the XX century in developed societies, whilst the majority of new earth buildings were confined to poor settings in developing regions.

The oil crisis in the 1980s led many to revisit sustainable construction. Since then, an increasing number of investigation and research works on earth have been developed, helping it to regain momentum in the industry as an alternative to contemporary building techniques. Yet, there is a long way before it is again a common building alternative.

2.1) ADVANTAGES AND LIMITATIONS

As a building material generally available in the construction site and that does not require high energy consumption for processing, earth is easily perceived as an ecological material with a low environmental impact (Hall *et al*., 2012). Earth's sustainable nature (Table 2), allied to its strong aesthetic capacity, good hygrothermal and acoustic properties (Hall and Casey, 2012), fire resistance (Minke, 2012) and recyclability (Fig. 2) (Minke, 2012), support the investment in its development and diffusion.

On the other hand, there is still little systemic knowledge regarding the behaviour of earth as a building material (Easton and Easton, 2012). Earth's weak mechanical and tensile resistance and susceptibility to water make its application difficult and imply extensive precautions in order to protect the material from these shortcomings (Augarde, 2012; Minke, 2012). The reduced industrialization of earth construction (Hall *et al.*, 2012; Schroeder, 2012), lack of specific legal context (Cid *et al.*, 2011; Schroeder, 2012) and high cost in developed societies, due to its traditionally intensive labour requirements (Lourenço, 2002; Easton and Easton, 2012), along with the prejudice that it refers to a poor construction technique (Blondet *et al.,* 2008), hinder its establishment as a common building material.

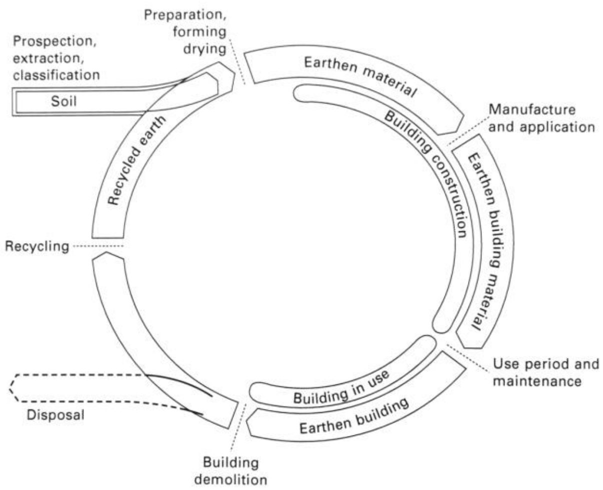

Figure 2 – Building with earth presented as self-sustaining life cycle (Schroeder, 2012)

Table 2 – Primary energy impact values (PEI) of typical building materials comparing with earth building materials (Schroeder, 2012)

Building material	PEI [kWh/m^3]
Earth	0-30
Straw insulation panels	5
Timber materials	800-1,500
Fired bricks	500-900
Cement	1,700
Concrete	450-500
Lime sandstone	350
Glass panes	15,000
Steel	63,000
Aluminium	195,000
Polyethylene (PE)	7,600-13,100
Polyvinylchloride (PVC)	13,000

2.2) LEGAL FRAMEWORK

The global contemporary legal framework of earth construction is still not sufficiently conclusive, as laws tend to be scarce, non-comparable and do not take in consideration sustainability (Cid *et al.*, 2011; Schroeder, 2012).

Earth construction is traditionally associated with non-engineered and non-industrialized techniques. It was observed that the technical data available in different norms and legal documents often differs from one another, as well as the used terminology, testing procedures and production methods (Schroeder, 2012). This complicates implementation, despite the increasing introduction of norms on earth construction in the past decade.

In order to facilitate data comparison, there is a need for standard and internationally accepted criteria for earth materials and construction systems (Cid *et al.*, 2011; Schroeder, 2012). Two guidelines for the production of regulations that can improve the legal framework of earth construction worldwide and the implementation of earth in the building industry were identified: i) the production of new construction norms for building materials and construction techniques that take in consideration the environmental impacts and ii) new production techniques of earth materials that allow for better performance and systematized behaviour.

2.3) EARTH AS A NON-INDUSTRIALIZED MATERIAL – ANALYSIS, PROPERTIES AND STABILIZATION

As a traditionally non-standardized and non-industrialized material, the search for quality control, homogeneity and accuracy of the constructed elements in earth can only be achieved through constant quality analysis in accordance with increasingly precise criteria. This can be achieved in two ways: i) careful analysis of the quality of soil available in order to support the decision of which construction strategy to adopt and whether specific stabilization to improve quality is required; ii) and stressing the need to implement quality control procedures throughout construction to guarantee homogeneity and compliance with building specifications.

The strength of any earth material is defined by the quality of the soil that is used. It depends on its compressibility, which varies according to the type of earth used, its particle size distribution and the humidity of the mix during compaction (Burroughs, 2001; Reddi *et al*., 2012; Reddy, 2012; Schroeder, 2011). Even though chemical stabilisation can be used to improve the resistance of a soil (for instance, adding cement to the soil), the result of this technique is proportional to the quality of the mixture used (Table 3) (Hall, 2004). On the other hand, to control the plastic index of a soil and its drying shrinkage, chemical stabilisation can be extremely efficient in soils that are more subject to shrinkage, such as clayey soils, by adding, for example, lime to the mix (Burroughs, 2001). It is thus concluded that the quality of a soil is a key determinant in establishing the required properties of a building element, in particular its resistance, and that the means of stabilisation available can help improve specific properties of a mix for specific uses.

Table 3 – Strength and density for compacted stabilised soil blocks (Prasanna Kumar, 2010)

Dry density	**Wet compressive strength (MPa)**	
(kg/m^3)	**5 % cement**	**8 % cement**
1.600	0,66	0,96
1.800	1,37	3,00
2.000	2,71	4,52

This stresses the need for pre-construction testing, in order to define the suitability of a local soil to be used for construction purposes and the need to correct it.

Stabilising local soil is not necessarily cheaper or has a lower environmental impact than factory-premixed soil or to artificially correct it by adding aggregates from a quarry (Easton and Easton, 2012). This decision has to be made according to each specific situation, considering the quality of local soil, type of equipment and available workforce. Only taking these elements together one can maximize the characteristics of earth and reduce costs without jeopardizing its sustainability.

2.4) DESIGNING PRINCIPLES

Due to earth's low mechanical strength, high weight, susceptibility to water and low tensile strength, it requires a careful design prior to building. As in all non-industrialized construction techniques, strong implementation is crucial to guaranteeing the quality of the building elements. Among the many factors to take in consideration while conceiving an earth project, one stresses the need to adapt the building to its context, to protect the construction against the effect of water, to carefully choose the structural system and guarantee the implementation of strict building criteria, in accordance with the best practices on earth construction. Among these best practices are: i) the need to control the natural tendency of earth to shrink and crack, ii) the precautions needed when making openings in walls and iii) the need to reinforce the construction by interconnecting multiple elements and contribute to its ductility and resistance to horizontal stresses.

The reinforcement principles of earth construction in seismic zones and areas that are subject to extreme weather can be as well generalized to common earth design as they promote an increase in the strength of the constructive systems (Morris, 2012). As stated by Minke (2012), it is not earth as a building material that is responsible for structural failure, but its structural system, layout and type of openings.

2.5) MODERN CONSTRUCTION TECHNIQUES

Four massive, solid earth construction techniques are addressed in this dissertation. They are: rammed earth, earth blocks, pneumatically impacted stabilized earth (PISE) and cob.

Of all techniques analyzed, rammed earth and earth blocks have been the most commonly researched and applied in new buildings in developed societies.

Of the two, rammed earth is the one that demonstrates increased capabilities to be used as a finishing material with no need for further coating. It is also the technique that seems to respond more effectively as a structural element in new construction. New research includes conformation procedures and alternative ways of production, such as pre-fabrication. The main challenge to the use of rammed earth is technical: how to improve its efficiency and be able to progressively respond to more standardized construction criteria, while controlling the tendency to increase its environmental impact.

Earth blocks have the advantage of being easily industrialized, even though they are not usually used as structural elements. They can compete in the masonry industry and its use as a technique has a lot to gain from future legislation that will benefit the production and application of ecological materials, instead of more pollutant ones. This may increase demand and lead to an increased production capacity and subsequent cost reduction, which would make the technique progressively more competitive.

The other two techniques have different characteristics. PISE is showing a great potential as a modern building technique due to its fast application, anti-seismic capabilities, adaptability to complex structures and capacity to repair damaged structures in rehabilitation works. However, it is technically demanding and requires specialized workmanship and complex projection gear, which tends to make its use more expensive. Its development will require cost control and improved compatibility with internal reinforcement structures, especially when made of steel.

Cob is the most rudimentary of all four techniques. The reason why it was selected is its recent application in some interesting projects. From a technical point of view, it has the advantage of being the least demanding technique of all four and not requiring a specialized workmanship. However, it tends to use a lot of material and subsequent labour due to its great thickness. Its lower strength requires further reinforcement, if it is to be used as a structural element. For that reason, the most conservative solution is to use it as a complementary material to other structures.

On a smaller scale, coating systems based on light earth techniques have become more sophisticated and extensively used in some developed markets. Among these materials are earth plasters and light pre-fabricated earth panels. As factory prepared materials, their production can respond effectively to standardized parameters and quality control procedures in a way that *in situ* building techniques cannot. This makes them good examples of techniques that can be developed in the future.

3) CASE STUDIES

This chapter reviews five contemporary earth projects, chosen based on a group of parameters extrapolated from this investigation on earth construction. The goal is to understand the spectrum of applications that earth construction can have and the parameters that particularly influence the adoption of a construction strategy from an architectural point of view.

3.1) SELECTION CRITERIA

The number of projects included in this analysis has been limited to five. The purpose was to use contemporary projects that seek to reinterpret the premises of earth construction from a singular perspective. The option was to select projects in which earth had a prevalent role as a massive monolithic structure for their greater analysis potential, in opposition to light earth constructions techniques.

The five selected projects have similar size and are all relatively recent, from the past sixteen years. They are located in different economical and climatic contexts and possess different functions within their societal context. Their choice reflects a desire to demonstrate the wide spectrum of applicability and adaptability of earth as a construction technique in different contexts and local conditions.

The option was to use projects whose architecture expression is mainly contemporary, even though this classification is naturally subjective.

3.2) METHODOLOGY

For each case study there is a factsheet, a brief project description and an architectonic and constructive analysis. The purpose of the factsheet is to use criteria comparable across each project drawn from specific, quantifiable data. The project description provides a brief characterization of the building. Both were supported in the literature review and examination of building elements, such as technical drawings, photographs and constructive details. The architectonic and construction analysis reflects the author’s view. It tries to identify the techniques that were used, highlighting the most interesting construction strategies, the main risks and, if applicable, possible solutions to mitigate them. The focus was on earth and the way the buildings adapted to its characteristics and demands.

Then, a comparative analysis was made between the collected data in the five case studies. The analysis was based on a group of factors extrapolated from the investigation which stood out in the case studies. They were divided in external parameters (climate, seismicity of the region and economic context) and internal parameters, associated with specific project decisions (function of the building, earth construction technique, type of structure, specific use of reinforcements, use of stabilizations, layout, water protections, use of complementary materials, coatings, wall openings and infrastructural integration).

Finally the main parameters that influence the design of the earth buildings reviewed in this study were identified.

3.3) LIST OF CASE STUDIES

01_CHAPEL OF RECONCILIATION, BERLIM, GERMANY, 2000

REITERMANN, SASSENROTH

RAMMED EARTH

02_RAUCH HOUSE, SCHLINS, AUSTRIA, 2008

M. RAUCH, R. BOLTSHAUSER

RAMMED EARTH

03_FLURY HOUSE, DEITINGEN, SWITZERLAND, 2009

SPACESHOP ARCHITEKTEN

COB

04_METI – SCHOOL, RUDRAPUR, BANGLADESH, 2005

A. HERINGER, E. ROSWAG

COB

05_PALMER-ROSE HOUSE, TUCSON, ARIZONA, USA, 1998

RICK JOY

RAMMED EARTH

3.4) SUMMARY OF THE MAIN CASE STUDIES CONCLUSIONS

Due to their characteristics, earth buildings tend to be influenced and conditioned by the context in which they are inserted. The natural restrictions that affect its design principles – fragility, weight, low mechanical and tensile strength and susceptibility to the effect of water – imply precautions and adaptations to keep the walls stable, safe and healthy.

However, the case studies have revealed great capacity to adapt the constructive guidelines that have been identified in this investigation. The different approaches undertaken for each project tended to enrich each project individually. Nevertheless, constructive precautions were constant throughout all projects. Among the parameters that were included in the analysis of the case studies, those that most influenced the development of the projects were:

a) The economic context and availability of resources;

b) The climate and, in particular, the effect of rain and temperature;

c) The function of the building;

d) Whether earth elements had a structural function.

All four factors were determinant to define the feasibility, construction strategy, image of the buildings and the type of projects that were built.

The availability of resources, such as equipment, workmanship and raw materials, facilitates earth construction in developed societies but tends to increase its cost. On the other hand, while the availability and low cost of the workmanship in developing countries helps to control the cost of construction, it requires the use of less sophisticated construction solutions.

Due to earths' instability in the presence of water, regions with higher precipitation imply thorough precautions with the design and construction of walls. The same applies to temperature control, particularly in cold climates, due to compacted earth high thermal conductivity. This affects the minimum thickness of the walls and may require the use of internal thermal insulation, which will influence its appearance and constructiveness. Still, both factors (rain and temperature) can be used in favour of the construction. As observed in the case studies, they may serve to enhance the aesthetics of the buildings.

Function is, by definition, a determinant factor in any construction. This determinism is stronger in the case of earth, as it may require extensive variations in the way it is used. In all five cases, function conditioned the constructive strategy and the techniques that were used, as well as the shape of the buildings. Nevertheless, it is worth mentioning the diversity of functional typologies to which earth can respond and to which its physical and aesthetic properties can contribute – from houses to religious buildings, schools and other sort of public equipments and working places.

The use of earth as a structural material gives relevance to its application. Nonetheless, it implies a further precaution with the structural system and the mitigation of its specific fragilities. On the other hand, the use of earth as a complementary material in a combined or autonomous structural system minimizes some of its natural restraints, in particular its weak tensile strength. This will avoid the use of a significant reinforcement ratio that can increase its environmental impact. Overall, it allows earth's application in construction to be seen in a broader way.

The influence of the remaining parameters included in the analysis was considered secondary to these first four.

This is the case of the decision on the type of earth construction technique to use. On one hand, this decision stems from i) whether earth has a structural role in the building, ii) the availability of resources to build in a more efficient way and iii) its climatic response. On the other hand, once the construction technique is selected, it has an impact on the plasticity of the building and on the type of reinforcement and stabilisation that it may require.

Decisions such as the number and size of openings depend on the function of the building, but also of the technique that is used. On the other hand, the number of openings and their size will condition the strategy used during construction. They can either be integrated in the earth walls or be positioned in-between wall segments. The first choice will result in smaller openings or more complex forms of reinforcement. The second one will allow greater size but require a ceiling slab whose support is independent from the walls or the use of specific reinforcements in its interior.

The selection of the type of stabilisation depends on the construction technique, the characteristics of the soil and whether earth is being used in structural elements. Stabilisation helps to improve the properties of a soil but may have a direct impact on the carbon dioxide incorporated in the building, which has an impact on its sustainability.

Other factors, such as the materials to use as complements to earth or the need for coating of the surfaces, are typically defined by transversal earth construction principles. Nonetheless, its use is always dependent on the constructive strategy that is adopted, which is conditioned by the previous parameters.

The analysis of the case studies was not conclusive regarding the influence of the seismicity of a given region on the development of each project. It was also not conclusive about the influence of each specific legal framework. Nevertheless, it is believed that they are determinant factors for the development of any earth project.

The case studies showed that earth's natural constraints can be responded by a variety of solutions. Still, many state of the art construction techniques with earth are not frequently used. Whereas some are very widely used, in particular those related to water protection, others, such as complex reinforcement and stabilization techniques, are not commonly found.

On the other hand, the case studies have exemplified how the use of earth's advantages as a building material can add value to buildings. Its sustainability, strong aesthetical capacity, hygrothermal and acoustic properties have contributed to the quality of these projects. They thus help promote earth as a building material.

From this analysis it can be concluded that the limitations of earth as a building material do not necessarily mean limitations to architectural expression, sophistication and its modernity. They are more dependent on the quality of the projects than the characteristics of the material.

It can, however, be inferred that earth's limitations as a material can promote the development of alternative constructive solutions which, if well used, add value to projects.

4) CONCLUSION – SYNTHESIS OF THE PREMISES FOR THE FUTURE DEVELOPMENT OF EARTH CONSTRUCTION

The increasing quality and variety of typologies of recent earth buildings indicate that there is a growing integration of earth in modern construction industry. However, if this integration is to be more efficient several key issues need to be addressed.

As Hall *et al*. (2012) refer, the guarantee of comfort in line with the expectations of a common user in a developed society has to be obtained without compromising the low environmental impact and the sustainability of the construction. These need to be achieved through the emissions that stem from processing the material, which should tend to zero, as well as the carbon dioxide incorporated in the construction and the estimated energy of its future demolition or alienation. The first challenge for earth construction in developed societies is technical: to increase its efficiency and construction safety without jeopardizing its sustainability.

The second challenge is for earth to be comparable with the other current building materials. Earth construction is usually seen as a non-industrialized form of construction, associated with traditional building techniques and non-engineered materials. As Schroeder (2012) refers, in order for earth to be accepted as a current alternative in the construction industry, its various materials and construction systems have to be technically recognized. To be so, they have to be able to respond to standard parameters and precise criteria which require the use of regular laboratorial testing and, inevitably, more industrialized forms of production.

Even though the diffusion of earth construction is easier in regions whose construction culture is founded on the use of massive solid walls, it is also essential to develop the capacity to implement these techniques globally. For that purpose, it is equally important to move towards cost reduction in the production of earth as a building material in developed societies, without compromising sustainability, and to expand the pool of qualified trainers, in order to reach a broader demand and to guarantee quality (Easton and Easton, 2012).

5) REFERENCES

Augarde, C. - *Soil mechanics and earthen construction: strength and mechanical behaviour*. Modern earth buildings - Materials, engineering, construction and applications. Ed. Woodhead Publishing Limited, United Kingdom, 2012.

Blondet, M.; Vargas Neumann, J.; Tarque, N. - *Low-cost reinforcement of earthen houses in seismic areas*. The 14th World Conference on Earthquake Engineering, Peking, 2008.

Burroughs, V - *Quantitative criteria for the selection and stabilization of soils for rammed earth wall construction*. PhD Thesis, University of New South Wales, Australia, 2001.

Cid, J; Mazarrón, F. R.; Cañas, I. - *Las normativas de construcción con tierra en el mundo*. Informes de la Construcción, Vol. 63, n.º 523, 2011, pp. 159-169.

Easton, D.; Easton, T - *Modern rammed earth construction techniques*. Modern earth buildings - Materials, engineering, construction and applications. Ed. Woodhead Publishing Limited, United Kingdom, 2012.

Hall, M.; Casey, S. - *Hygrothermal behaviour and occupant comfort in modern earth building*. Modern earth buildings - Materials, engineering, construction and applications. Ed Woodhead Publishing Limited, United Kingdom, 2012.

Hall, M. - *The mechanisms of moisture ingress and migration in rammed earth walls*. PhD thesis, Sheffield Hallam University, United Kingdom, 2004.

Hall, M.; Lindsay, R.; Krayenhoff, M. - *Overview of modern earth building*. Modern earth buildings - Materials, engineering, construction and applications. Ed Woodhead Publishing Limited, United Kingdom, 2012

Lourenço, Patrícia - *Construções em terra - Os materiais naturais como contributo à sustentabilidade na construção*. Instituto Superior Técnico. Dissertação de Mestrado em Construção, Lisboa, 2002.

Minke, Gernot - *Building with earth. Design and technology of a sustainable architecture*. Birkhäuser, Basel-Berlin-Boston, 2012.

Morris, H.W. - *Natural disasters and earth buildings: resistant design and construction*. Modern earth buildings - Materials, engineering, construction and applications. Ed Woodhead Publishing Limited, United Kingdom, 2012.

Prasanna Kumar, P - *Stabilised rammed earth for walls: materials, compressive strength and elastic properties*. PhD thesis, Dept. of Civil Engineering, Indian Institute of Science, Bangalore, India, 2010.

Reddi, L.N.; Jain, A.K.; Yun, H-B. - *Soil materials for earth construction: properties, classification and suitability testing*. Modern earth buildings - Materials, engineering, construction and applications. Ed Woodhead Publishing Limited, United Kingdom, 2012.

Reddy, B.V. Ventakarama - *Stabilised soil blocks for structural masonry in earth construction*. Modern earth buildings - Materials, engineering, construction and applications. Ed Woodhead Publishing Limited, United Kingdom, 2012.

Schroeder, H. - *Moisture transfer and change in strength during the construction of earthen buildings*. Informes de la Construcción, Vol. 63, n.º 523, 2011, pp. 107-116.

Schroeder, H. - *Modern earth building codes, standards and normative development*. Modern earth buildings - Materials, engineering, construction and applications. Ed Woodhead Publishing Limited, United Kingdom, 2012.

Other resources:

Census 2001, Instituto Nacional de Estatísticas, Lisboa, Portugal.