Raw earth and natural stone in contemporary Portuguese architecture

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Abstract

The increasingly tangible effects of climate change have given rise to a growing concern about the environmental impact of the construction industry. It is therefore necessary to find alternative building materials with lower embodied energy to contribute to a more sustainable built environment.

The main objective of this dissertation is to examine the current architectural and socioeconomic context for the use of earth and stone in Portugal and explore their future potentials as well as limitations to providing a relevant alternative to the widespread use of industrial materials. The topic is contextualized by examining the state-of-the-art of related academic education, research and architectural practice in Europe.

The methodology of the study combines qualitative and quantitative data collection. A set of architectural examples are identified in Portugal and the different aspects of construction and operation of the buildings are explored through the experience of the architects and clients involved. Specific case studies are selected for further quantitative analysis to examine the hygrothermal performance of earth and stone constructions.

The study reveals the main difficulties to the use of earth and stone which are of an economic, legislational and social nature. It also outlines potential solutions to overcome these problems. To facilitate a widespread and reasonable use of these materials, it is necessary to introduce structural changes in the academic educational offer, to sensitize the public about alternative solutions and to standardize the processes related to earth and stone construction.

Key words: raw earth, natural stone, sustainability, contemporary architecture, viability

Resumo

Os efeitos cada vez mais tangíveis das alterações climáticas têm dado origem a uma preocupação crescente com o impacto ambiental da indústria da construção. Por isso, é necessário encontrar materiais de construção alternativos com menor energia incorporada para contribuir para um ambiente construído mais sustentável.

O principal objetivo deste trabalho de investigação é examinar o contexto arquitetónico e socioeconómico atual para a utilização da terra e da pedra em Portugal e explorar as suas potencialidades futuras, bem como limitações para fornecer uma alternativa relevante à utilização generalizada de materiais industriais. O tema é contextualizado examinando o estado da arte da educação académica relacionada, investigação e prática arquitectónica na Europa.

A metodologia do estudo combina recolha de dados qualitativa e quantitativa. Um conjunto de exemplos arquitetónicos são identificados em Portugal e os diferentes aspetos da construção e operação dos edifícios são explorados através da experiência dos arquitetos e clientes envolvidos. São selecionados estudos de caso específicos para análise quantitativa mais aprofundada para examinar o desempenho higrotérmico das construções da terra e da pedra.

O estudo revela as principais dificuldades para o uso da terra e da pedra que são de natureza económica, legislativa e social. Também descreve potenciais soluções para ultrapassar estes problemas. Para facilitar uma utilização generalizada e razoável destes materiais, é necessário introduzir mudanças estruturais na oferta educativa académica, sensibilizar o público sobre soluções alternativas e uniformizar os processos relacionados com a construção da terra e da pedra.

Palavras chave: terra crua, pedra natural, sustentabilidade, arquitetura contemporânea, viabilidade

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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List of acronyms

AAP – Associação dos Arquitectos Portugueses (Portuguese Architects Association)
ACL – Advanced Ceramics Lab
AECC – Architecture, Environment and Constructive Cultures
AM – Additive Manufacturing
amáco – Atelier Matières à Construire (Building Material Workshop)
BIØN – Building Impact Zero Network
BIT – Burkina Institute of Technology
BRG – Block Research Group
CAS – Certificate of Advanced Studies
CdT – Centro da Terra
CEB – Compressed Earth Blocks
CNC – Computer Numerical Control
CNN – Cable News Network
CO_2 – carbon dioxide
CRAterre – Centre international de la construction en terre (International Center for Earthen Architecture)
dB – decibel
DICAR – Dipartimento di Scienza dell'Ingegneria Civile e dell'Architettura (Department of Civil Engineering and Architecture Sciences)
DSA – Diplôme National de Spécialisation et d'Approfondissement en Architecture (National Diploma of Specialization and Advanced Study in Architecture)
EE_{tot} – total embodied energy
ENSAG – École Nationale Supérieur d'Architecture de Grenoble (National School of Architecture of Grenoble)
EPDRS – Escola Profissional de Desenvolvimento Rural de Serpa (Technical Training School of Rural Development of Serpa)
ESAP – Escola Superior Artística do Porto
ESG – Escola Superior Gallaecia
ETH – Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology)
GWP – Global Warming Potential
IAAC – Institute for Advanced Architecture of Catalonia
INE – Instituto Nacional de Estatística (National Statistics Institute)
K – Kelvin
λ – thermal conductivity value
LNEC – Laboratório Nacional de Engenharia Civil (National Laboratory for Civil Engineering)
MJ – megajoule
MPa – megapascal

NFRG – New Fundamentals Research Group
OA – Ordem dos Arquitectos (Order of Architects)
OC – Oficinas do Convento
OCT – Oficinas da Cerâmica e da Terra (Ceramics and Earth Workshops)
R&D – Research and Development
RH – relative humidity
RPBW – Renzo Piano Building Workshop
Rw – sound insulation coefficient
TUM – Technical University of Munich
U – thermal transmission value
UNCTAD – United Nations Conference on Trade and Development
UNESCO – United Nations Educational, Scientific and Cultural Organization
UPT – Universidade Portucalense
UV – ultraviolet
WASP – World's Advanced Saving Project

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1. INTRODUCTION

1.1. Contextualization of the research

"There is always a connection between the materials with which we choose to build and the responsibility all of us share toward each other and the planet." (Heringer et al., 2019)

Even though the world has seen rapid urbanization and population growth over the last 30 years (UNCTAD, 2021), especially in developing countries, paradoxically, there is a reverse trend in industrialized regions – a growing number of people are beginning to leave the urban for the rural, prioritizing settings closer to nature with lower population density (Casa Iberia, 2021). A shift in consumer behavior is reflected in the Portuguese real estate market as well (Casa Ibéria, 2021).

Can this phenomenon be seen as a "countercultural return to the countryside, emerging as an antithesis of urban life"? (García-Masedo, Ramírez-Blanco; 2021) If so, what kind of culture have some decided to turn away from? The architectural culture of today is strongly affected by globalization, in which the unvarying application of industrialized materials and structures are ruling. "In a globalized chain of construction processes, local inflections and social values are suppressed" (Heringer et al., 2019). This has led to a breaking of continuity with the architectural roots, the abandonment of traditional, natural building materials predominantly found in local vernacular architectures. As Paul Ricoeur puts it in History and Truth, "The phenomenon of universalization, while being an advancement of mankind, at the same time constitutes a sort of subtle destruction, not only of traditional cultures [...] but also of [...] the creative nucleus of great cultures, that nucleus on the basis of which we interpret life." (Paul Ricoeur cited in Kenneth Frampton's Towards a Critical Regionalism, 1983)

At the same time, and despite the above-mentioned trend of counterurbanization, it is impossible to question the role of cities and urban settlements that have been vital for civilizations to emerge throughout history. As opposed to dispersed rural settlements with limited capacity of organizing societal structures, economic, political and cultural systems, cities provide complex infrastructure, interconnection and collaboration that allow for diversified societies and economies to appear (Time Maps, 2022).

"Cities have always reflected the civilizations that built them", although this relationship, today, is characterized by a "position of domination" (IAAC, 2022a). Under such conditions, urban populations are losing their sense of connection with the natural world. A question, therefore, is how to reconnect humans and natural systems in the urban context (BioCities, 2022) as well and transform cities into resilient organisms and urban ecosystems. In this process, natural construction materials could have a crucial role to play.

Fortunately, a new ecological sensitivity has begun to take shape, and there is a growing concern about the environmental impact of human activities. More and more people have started to realize the ever more serious effects of climate change and have chosen to approximate their lifestyle towards that of a harmony with nature, regarding sustainability more as a principle to practically incorporate in their lives through specific action rather than a mere concept of fashion. Likewise, architects, developers, international organizations as well as local communities have been seeking more ecological approaches to design and construction (Heringer et al., 2019). This is especially urgent as cement, a key input into concrete, the most widely used construction material in the world, is a major contributor to climate change (Chatham House, 2018). A recent report by the Royal Institute of International Affairs estimated that 8% of global CO_2 emissions can solely be attributed to the production of cement (Chatham House, 2018). From a broader perspective, the construction industry accounts for 38% of energy-related CO_2 emissions according to a report published by the United Nations Environment Programme in 2019 (Environment Journal, 2020). At the same time, "decarbonising the buildings and construction sector is critical to achieve the Paris Agreement commitment and the United Nations Sustainable Developments Goals" (International Energy Agency, 2019). This is a responsibility all parties involved – from architects, contractors and manufacturers to decision-makers and public and private institutions – need to share.

Consequently, over the past decades the potential of natural materials has been recognized again. In a historical perspective, their use has undergone different patterns of priority from being a consequence rather than a choice, the technology of the majority in vernacular contexts to the option of the few in contemporary ones (Jorge, 2015). Building with what is available used to be the most basic condition of architecture up until the industrialization and the following Modern Movement. Before the 20th century, natural building materials were adopted widely throughout Europe and the world. In Portugal, the most common locally available materials for structural application were stone in the mountainous north, and earth in the central and southern areas (Simões et al., 2019).

The gradual abandonment of the use of vernacular materials came about with the industrial revolution in the 19th century and the appearance of concrete and steel positioned as the materials of future and progress. Modernism set out to create a new architectural language based on novel materials and paradigms from the beginning of the 20th century. Along with it came the desire to improve the life of, or to create a new standard of life for the human. As a result and ever since, "vernacular architecture suffers from archaism because it conveys the image of an outdated way of life." (Moriset et al., 2021)

The widespread use of standardized materials resulted in an exponential increase in energy consumption. It was not until the first oil crisis in the 1970’s, however, that a growing awareness of the finity of resources and a concern about the unsustainability of current energy consumption rates was given rise to (Easton, 2007). The crisis was a push for the rediscovery of alternative materials and techniques including those used in vernacular architectures. Their readoption, especially that of raw earth, began in the 1980’s. It was given a boost by the 1981/82 exhibition organized by Centre George Pompidou in Paris, France, called "Des Architectures de Terre - ou L'avenir d'une tradition millénaire" (On Earthen Architectures - or The future of a millennial tradition). It contributed to the dissemination and promotion of raw earth as a building material on an international level. As a result, the next decades have seen pioneering projects using earth as their primary construction material.

Times of crisis often boost the emergence of alternative solutions as has been proven throughout history. This has special relevance in the 21st century context of climate change and inherent social crisis, which requires changes in the foundations of contemporary building culture. It is important to establish new relationships between the man-made and the natural and also between tradition and technology. Vernacular materials can have the potential of this connection while providing several advantages compared to their industrialized counterparts. The low embodied energy and CO_2 emission associated with their production and use make up one of their most valuable characteristics in the contemporary context. As they can be sourced locally, there is minimal associated transportation to their use. They are recyclable and adapt better to local climatic conditions while creating a healthier indoor environment. Further economic and social benefits include reduced costs in the production of materials, the creation of jobs and the conservation of traditional construction know-how rooted in local cultures (Mateus et al., 2019).

There could be a rich palette of environmentally friendly building materials existing on the market that respond to the assets mentioned above. However, there is a set of problems that makes it close to impossible to have a relevant choice of alternative when conceiving the materiality of a design. These problems are principally rooted in economic, legislational and social grounds, making it very difficult to conventionalize these construction materials.

Firstly, there is no lobby for natural materials – primarily because the profit associated with them is significantly lower (Heringer et al., 2019) and the profit cycle is showing different patterns than that of conventionally used materials. Namely, the financial gain will not go directly back into the company/manufacturer but instead, remain within the area of influence (be it a project of national, regional or local importance). Or, as the report of the Royal Institute of International Affairs puts it: "The [construction] sector is dominated by a handful of major producers, which are cautious about pioneering new products that challenge their existing business models" (Chatham House, 2018).

Secondly, on a legislational level, very few countries have managed to establish building codes for the application of natural building materials including raw earth and natural stone. In the case of Portugal – though intention has been formulated several times (see e.g. 3ª Mesa Redonda organized by Centro da Terra (Associação Centro da Terra, 2020a)) –, it is only a recent change in the regulations of the thermal performance of buildings that considers earth constructions and establishes different requirements for them. Apart from that, there are no applicable standards or building codes. The lack of legal framework is discouraging both for the architect/contractor and for the client itself. This is a question of responsibility that few are willing to take.

Lastly, the social perception of earth and stone (and of vernacular materials in general) is still not favorable and often associated with poverty, backwardness and insecurity. Unfortunately, the dissemination of knowledge on these materials in architecture education is considerably stepped back both in Europe and in Portugal. It is even so, despite the fact that the training of young architects would be the key for a shift in what we consider contemporary design today.

Generally speaking, at the level of university education the themes related to natural materials and construction techniques are little explored. Technical subjects as well as design studios are almost exclusively centered around the use of reinforced concrete and other industrial materials. Raw earth and natural stone only appear in a historical perspective as vernacular construction materials without any reference to their contemporary potential. More often than not, architecture students are not presented with alternative material or constructive solutions which gives them a limited range of tools and knowledge to work with. In light of the current environmental uncertainties, it is especially important to train competent professionals who are responsive to the present-day climatic and social challenges. As architects and other experts in the field argue, changes need to start on an academic level to achieve relevant results and shift the current practice of architecture.

It is in relation to the aforementioned problems that this dissertation set out the goal to study raw earth and natural stone constructions – as the most widely used materials for structural application in local vernacular building cultures in Portugal – and examine their suitability in contemporary Portuguese architecture. The assets and potentials of these materials might well be the answers to the challenges highlighted before. Currently, there is no other material like earth that "completely aligns with fully sustainable building principles, such as the cradle-to-cradle concept" (Heringer et al., 2019), that is to say, the ability to be recycled multiple times without loosing quality. Acting as a thermal mass, earth and stone structures provide good indoor comfort and control humidity. The materials are widely available depending on the geographical regions of Portugal. Earth and stone constructions have a high adaptability to a range of contexts considering the technology - human labor gradient, thus contributing to creating employment. Additionally, a variety of design possibilities and a modern architectonic appearance can be achieved resulting in an aesthetics that has the full potential of becoming the contemporary counterpart of industrialized constructions.

Reinventing earth and stone architecture in Portugal can reinforce the reconnection to vernacular roots, resulting in a rich architectural landscape and strengthening local cultural and social identity.

1.2. Objectives of study

The principal objective of this dissertation is to explore the use of raw earth and natural stone in the context of contemporary architecture in Portugal and outline their potentials as well as limitations to satisfy contemporary needs, with regard to the notion of functional requirements, comfort and performance, economy, sustainability and architectural language.

This dissertation aims to investigate if the above-mentioned materials are able to provide a relevant alternative to the popular use of industrialized materials in today's construction, often referred to as 'conventional'. Revealing the recent evolution of earth and stone techniques in Europe, it will be possible to see how the current Portuguese status quo could be changed towards a wider acceptance and use of these materials. The current situation concerning natural materials and techniques will also be explored in the context of education in architecture schools in Portugal.

In this sense, the dissertation presents a comparative overview of material characteristics with regard to their physical properties and applicability depending, among other things, on climate and geographical conditions as well as the construction processes and the architectural language that can be achieved taking into account also the limitations of the materials. It will also present examples built both in natural and industrialized materials to be able to see the interoperability of constructions in order to reach a similar (or even better) architectural solution.

Finally, the dissertation explores in more detail the hygrothermal performance of earth and stone constructions. Through specific case studies, the level of comfort in indoor environments can be defined and the properties of each material illustrated.

1.3. Methodology

This dissertation is based on a mixed research method combining qualitative and quantitative data collection to be able to grasp the complexity of the subject and to present its various aspects. As Bogdan and Biklen say in Qualitative Research for Education (2006), "research questions are formulated to investigate topics in all their complexity, in context. [...] [Researchers] try to analyze the data with all of their richness [of description] as closely as possible to the form in which they were recorded." They do not hold a specific hypothesis to prove or disprove, "rather, the abstractions are built as the particulars that have been gathered are grouped together." (Bogdan, Biklen; 2006)

Having this in mind and in order to fulfill the objectives mentioned previously, two main approaches are defined.

One is based on fieldwork and includes the performance of a set of measurements on two representative case studies, each one structurally built in one of the materials in focus. An analysis is done concerning the hygrothermal performance of both buildings and the results are compared with one another.

The other approach is of a sociological character. It includes conducting a series of interviews with previously established contacts i.e. architects, residents and professors at universities as the main actors involved (or not) in natural building processes, be it design and realization, use or dissemination of knowledge. On one hand, it aims to gather and systematize findings related to the participants' experience in building with earth and stone including the principal reasons of material choice and all the inherent details to the construction and life cycle of the buildings. On the other hand, reaching out to contacts at university level contributes to establishing an overview of the evolution of the education of architecture in Portugal up until the present day. This way it will be possible to see how the role and importance of teaching about natural materials and techniques has changed and what effect it has had on the current practices and the ruling architectural style.

The method of performing qualitative interviews allows for the collection of extensive responses that better suit the goals of this research as the aspects of the topic are numerous and the chosen architectural examples differ widely. Analyzing the collected data it will be possible to draw conclusions about the suitability of such constructions in the 21st century from the point of view of the very people inhabiting them as well as their social perception today.

The interviews were based mainly on open-ended questions to explore the subject in a comprehensive way and allow for a free expression of the participants. Nevertheless, closed-ended questions were also included in the interviews. Three different sets of questions were invented to target the different groups of participants – architects, clients and professors at universities. The discussions took more or less an hour during which each participant was given the same set of questions so that a cross-comparison of the answers can be performed at the end of the process. All the interviews were recorded and transcribed. The questions of the interviews are included in the annex of this dissertation.

A set of architectural examples are identified, out of which two case studies are selected for further analysis. These will be the subjects of quantitative measurements.

The adoption of case studies as a research method to complement the study was decided on because, relying on multiple sources of information, case studies can provide an elaborate picture of the subject investigated. They are "applicable to real-life, [...] human situations" (Soy, 1997) thus being an adequate method to explore and describe contemporary phenomena in all its complexity.

The criteria for choosing the examples and the case studies are as follows:

- Time of construction. The main focus is put on the works done in the 21st century, especially the 2nd decade, in the case of earth constructions. This is the period after the active presence of the first pioneer generation of architects who reintroduced earth in modern Portuguese architecture in the turn of the century (end of 20th and beginning of 21st), including Alexandre Bastos, Teresa Beirão, Bartolomeu Costa Cabral and Henrique Schreck to mention a few. One rammed earth building is also included from this period in order to see how today's architects and practitioners have benefited from this legacy and how they have adapted it to the changing social, environmental and economic needs of the present day. In the case of stone, emphasis is put on contemporary applications as well in a similar time period as was defined for earth constructions.
- The project location. Examples are collected from all over mainland Portugal, from different geographical and climatic conditions.
- Existing typologies. The aim is to present examples incorporating a wide variety of programmes and functions to show the diversity of typologies that can be achieved using earth and stone structures, ranging from private housing and public holiday resorts to mixed use functions such as wineries.
- Constructive system. A heterogeneous sample of examples in terms of construction techniques were chosen in order to show the richness of viable solutions and adaptations to different climatic, geographical and social conditions. It is, obviously, to show the pattern of material availability as well.

Criteria of comparison

In order to systematize the guidelines for the comparative analysis of the identified architectural examples, a set of criteria is defined. It ranges from the measurable/visible to the personal, trying to embrace all the aspects associated with the construction project.

For the definition of the criteria, consideration was given to the following descriptive elements:

- Functionality and typology. The aim is to identify which functional requirements are currently fulfilled by earth or stone constructions and to establish the relationship between the programme of the building and its spatial characteristics.
- Structural solutions. It is important to identify the different constructive systems applied in each case with regard to the foundation, structural and filling walls (interior-exterior), roof and floor structure and renderings.
- Volumetry and geometrical constraints. Special focus is put on understanding the interior space dimensions including heights and spans and the position of openings taking into account the limitations resulting from the characteristics of the applied construction materials. This will help to describe the overall architectural aesthetics of the building as well.

- Durability and maintenance. Aspects of maintenance are also explored based on the personal experience of residents and builders of the selected buildings. This allows for conclusions to be drawn as for the durability of the construction materials.
- Time and cost of construction. It is important to outline a comparison between the building costs of different projects which will be put in the context of conventional constructions as well. The duration of the building process and time constraints are also identified.
- Initiative and personal motivation behind the project. Being the most subjective element of the criteria, it aims to explore the reason for the material choice in each example and the drive to build with natural building materials. It reveals a diversity of opinions, attitudes and personalities laying behind each architectural project.

1.4. Structure

This dissertation is organized in six main chapters.

The first introductory part aims to contextualize the topic of investigation. It briefly presents the current situation of architecture and the construction industry considering the related environmental, cultural and social aspects. It provides a framing of the use of natural and industrial materials in building practices over time highlighting the associated challenges to each. The next subchapters outline the objectives and methodology of the study as well as describing its structure.

The second chapter provides an overview of the current European tendencies of academic education, applied research and practice concerning the use of raw earth and stone as construction materials.

The third chapter presents a comparative overview of the characteristics of earth and stone as construction materials, including physical and mechanical properties and environmental and economic aspects.

The fourth chapter has a similar objective to the second one but focuses on the contemporary trends in Portugal. It outlines the present-day state of academic education and research regarding natural materials and presents a set of contemporary architectural examples using raw earth and stone.

The fifth chapter provides a more detailed overview of case studies that were selected from the examples introduced in the previous chapter. It includes a set of measurements concerning the hygrothermal performance of buildings made of earth and stone, and the comparison of results.

The sixth and last chapter contains the final conclusions and considerations drawn from the findings of the investigation.

2. RAW EARTH AND NATURAL STONE – STATE-OF-THE-ART IN EUROPE

"There is no such thing as an ancient material or a new material – it is the way we use them that creates a new architecture or an ancient architecture." (Giuseppe Fallacara)

The present chapter of this work aims to outline the current European tendencies as for the recent innovations of earth and stone construction in contemporary architecture as well as the direction of research and academic education in this field.

Although the potential of the use of natural building materials such as earth and stone has been recognized by many countries since the second half of the past century, it is the most recent progressive technology that made the development of innovative ways possible for their use. While there definitely is a contrast between the vernacular nature of earth and stone and the highly digitalized processes now available for their application, this very fusion might be the key for a shift in their social perception as alternative solutions to use in new construction. This chapter therefore is focusing on the present day tendencies that are outlining ways for a sustainable future for architecture.

2.1. Academic education and applied research

Technological development in the past decades has enabled the automation of production and distribution processes and new innovation opportunities. This phenomenon is referred to as the third industrial revolution or Digital Revolution (Manufacturing Data Summit, 2019). It has led to a significant progress in digital fabrication tools which are now being applied together with traditional building materials with compelling results. Leading institutions of research and training in the field of architecture like the Institute for Advanced Architecture of Catalonia (IAAC) in Spain are taking a principal role to foster "a widest use of digital fabrication technologies amongst European creatives" (IAAC, 2022b) and the dissemination of knowledge connected to it. It has been realized that the changing circumstances in the environment require a shift in current construction practices and methodologies. The European Commission has been working on "Scenarios for a transition pathway for a resilient, greener and more digital construction ecosystem" (European Commission, 2021) which foster the use of nature-based solutions "to achieve more sustainable and resilient societies" (European Commission, 2022). The document states:

"The use of biobased materials and natural resources such as rammed earth and wood, can help to mitigate [environmental] impacts while reducing greenhouse gas emissions. [...] The proper use of these [nature-based] solutions will require enhancing the skills of architects, engineers and construction workers."

Consequently, the existing educational systems are challenged and, many argue, "must fundamentally change both in terms of goals and methods" (Heringer, 2018).
The aim of this part of the chapter is to provide an overview of how current educational and research methodologies are responding to these challenges and what direction they are taking in architecture with natural building materials and techniques, specifically with raw earth and stone. The primary focus is put on European higher education institutes with wide outreach and international renown and active, ongoing research.

Universities have always had a key function in the development of society. As research institutions, they are centers of new, advanced knowledge and skills (Steele, Rickards; 2021) as well as catalysts for changing paradigms. A range of distinguished institutions have already set the goal to change the conventional construction industry and train a new generation of young architects as the key future players in this process. They are focusing on sustainable, ecological design and development and offer interdisciplinary skills and understanding.

One such institution is CRAterre - ENSAG, the Center for Research and Application of Earth Architecture created in 1979 by a group of students of the École Nationale Supérieur d'Architecture de Grenoble (National School of Architecture of Grenoble), France. CRAterre is "the world's main research center specialized in earth construction" (IAAC, 2018). Obtaining its accreditation as a research laboratory in 1986 (CRAterre, 2022a), it fully dedicates a research line to the understanding of the nature and behavior of earth itself to encourage innovation. One of the main objectives of the research is to "standardize construction techniques in earth and other non-industrialized materials" including the "characterization of simplified test procedures" and contribution to the "development of normative documents". This way researchers are addressing the major legislational obstacle concerning earth construction, namely the lack of regulatory framework for the use of the material. To enhance the feasibility and to facilitate the application of earth constructions, CRAterre aims to define methods for the identification and utilization of the resources of a territory. It includes the recognition of "construction techniques with high potential for use" (CRAterre, 2022a) in the given context and the adaptation of local know-how to contemporary construction. This objective responds to the need of strengthening local constructive cultures and acknowledging different identities to balance the effects of cultural homogenization and globalization (Getty, 2022).

Research and education is conducted within the framework of several programmes that CRAterre has developed in partnership with other national institutions in France. Atelier Matières à Construire (amáco - Building Material Workshop) is an educational research center that has a broad profile of activities ranging from consulting, design and production to training, organizing workshops and disseminating knowledge on a "scientific and eco-friendly technical building culture" (amáco, 2022). Amáco's pedagogy is based on the experimentation with the material where aesthetics, senses and emotions have an important role in the cognition process (BASEhabitat, 2020). The trial and error method of the training enables participants "to think and build with the material" while "developing a spirit of research". The training courses are fostered by applied research on natural materials providing "content based on new knowledge in order to share the latest innovations and technical advances".

Among the latest innovations about the material is the poured earth technique which consists of casting earth in a liquid state similarly to cement concrete to produce wall structures. Emerging nanosciences have made it possible to better understand the material's mechanical, thermal, hygrometric and rheological behavior (Moevus, 2016). Researchers from the laboratories of CRAterre-ENSAG and the National Institute of Applied Sciences of Lyon together with material producers and builders in France have been investigating deeper into material cohesion which is fundamental for the development of clay concrete. They are looking into the possibilities of creating more efficient clay binders, in particular, of increasing cohesion by the addition of natural biopolymers (amáco, 2016a). The outcome of the research was published in 2016 under the name "Béton d'argile environnemental" (Environmental Clay Concrete) (amáco, 2016a). As a follow-up, between 2018 and 2020, amáco produced several experimental prototype walls made of cementless poured earth. Different aggregates were combined with the raw material to improve its strength and cohesion. In Paris, the soil used for the prefabricated prototype wall of the future Jean-Quarré media library and refugee house was supplemented by natural fibers (see Figure X). "This prototype was stripped after only two weeks of drying in winter" (amáco, 2020) due to the very fine and cohesive silt the soil contained. Results showed that poured earth technique, when further improved, can possibly "reduce the cost of implementation of the earth material and promote its deployment on the scale of the city" (amáco, 2020). It also has the potential to make the process of earth construction faster and less labor intensive.

The amáco educational center also provides students with the opportunity to develop ideas and implement projects of their own. "By offering to teach about materials that are little or not regulated today, amàco brings a complementary point of view to academic programs" (amáco, 2022b). Future professionals get the chance to work very closely to the material and develop 1:1 scale prototypes of their ideas. Learning by doing enables them to think in an open-minded way and become more flexible in developing strategies and responses to emerging challenges. New layers of the cultural, social and technical background associated with the materials give a broader perspective on how contemporary architecture can be shaped.

Along with research activities, with its Unesco chair "Earthen architecture, constructive cultures and sustainable development", CRAterre-ENSAG supports the development of "specialized education in universities and professional training centers at an international level. [...] It has developed new teaching methods ranging from the manipulation of materials to the training site." It offers Master's and postgraduate degree courses and doctoral thesis supervision in earthen architecture.

The Master’s Degree "Architecture, Environment and Constructive Cultures" (AECC) offered by ENSAG aims to train professionals in eco-responsible design that takes into consideration the specificities of a territory. As an important basis for the project, knowledge on materials and construction techniques is shared in theoretical and practical components to "apprehend the links between design logic and construction logic" (CRAterre, 2022c). This approach is mirrored in the pedagogy behind the project of a community center designed and realized by students within the framework of the first-year studio ‘designbuildLAB’ in the AECC Master’s. "This pedagogy, unique in France, considers the profession of the architect as inseparable from the act of building". (Timur Ersen, 2018) The experience of the realization of a conceptual work allows for developing a better insight to design itself, and a better estimation of limitations and future consequences of decisions. The Maison pour tous (House for all) project was built in 2018 in Four, in the Auvergne-Rhône-Alpes region of France. The walls of the building are made of load-bearing unstabilized rammed earth despite the absence of legal standards (Figure 1). The material used for the construction had been tested and validated in the laboratories of CRAterre (Timur Ersen, 2018). The qualities of the project were recognized by the American Architecture Award and the Architizer A+ Award in 2020.

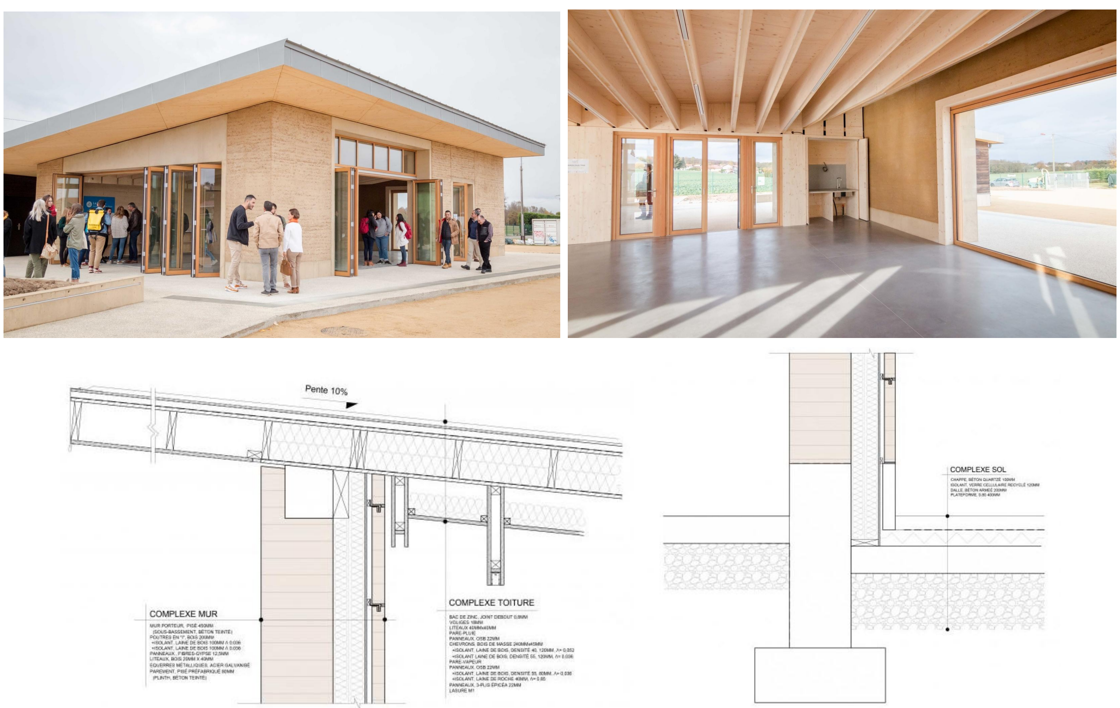

Figure 1 - Maison pour tous (source:Timur Ersen, 2018; World-architects, 2018)

Besides the Master’s Degree, CRAterre provides the most comprehensive post-degree course specialized in earth architecture in Europe. The DSA "Earth Architecture” is a 2-year long post-master's course that is part of the activities of the UNESCO chair "Earth architecture, constructive cultures and sustainable development". Its aim is "to disseminate scientific knowledge and techniques on earthen architecture"

(CRAterre, 2022d) in partnership with other existing training organizations. Besides theoretical components on earthen constructive cultures and heritage, scientific, technical and methodological bases, emphasis is put on "fundamental material research and development in constructive innovation" (CRAterre, 2022d). Recognized international experts together with teachers and researchers from CRAterre are providing theoretical and practical courses and an inherent networking environment where students can connect with specialized practices.

BASEhabitat, a studio within the Department of Architecture at the University of Art and Design Linz, Austria is advocating similar educational values and methodologies to the above-mentioned. Being a member of the UNESCO Chair “Earthen Architecture, Building Cultures and Sustainable Development”, it is focusing on education, research, design and construction in a sustainable and socially responsible manner. Its pedagogy is centered around "thorough analysis, high-quality design and a realization with one’s own hands" (BASEhabitat, 2022a). For fifteen years, BASEhabitat has been offering Master’s and post-graduate degree courses in architecture in an international and collaborative environment with the aim to train a new generation of architects, responsive to new global challenges.

In line with this goal, the post-graduate course, Master of Advanced Studies – Architecture "explores the practice of architecture in a different way" (BASEhabitat, 2022a), based on new methods and tools. The program combines theoretical knowledge with hands-on experience and real-scale projects. Learning by doing allows for a deeper "understanding of the implications of design decisions" (BASEhabitat, 2022a) and emphasizes the need to focus on the whole design process instead of the result only. The opportunity to work on real building sites enables developing a sensitivity to local environmental and social conditions while providing insights to participatory approaches in architecture. Making decisions on-site and together with future residents is widening the role of the architect. The deep understanding gained this way allows for making strong connections between the complexities of design and reality. The importance of focusing on the choice of materials and construction methods when conceiving a project is emphasized throughout the course accordingly, together with a constant exploration of "the possibilities that natural building materials offer for contemporary architecture" (BASEhabitat, 2022a).

In Germany, the Technical University of Munich (TUM) is fostering a change in the conventional architectural approach to achieve a more sustainable building culture. To achieve this goal, the scope of its training offers and methodologies are being widened accordingly. The Chair of Architectural Design and Participation in the Department of Architecture in TUM was created in 2017 with the professorship of architect Diébédo Francis Kéré, winner of the 2022 Pritzker Architecture Prize. His appointment is considered as an important step in a new direction in the field of architectural education. As TU Munich President Wolfgang A. Herrmann puts it: "From now on, Professor Kéré, the internationally highly renowned protagonist of sustainable architecture will work in Munich making our university the epicenter of a new philosophy of architecture." His works and professional practice are elaborated on later in this chapter.

The Chair of Architectural Design and Participation provides project courses for both Bachelor and Master students. Its main educational approach is to teach how to "connect the thinking and the making" (TUM, 2022) in an environment where real conditions and needs are addressed. The aim of the courses is to "explore the social role of architecture" (TUM, 2022) with special focus on "participatory processes in the design for the community"(TUM, 2022). Aspects of bioclimatic design principles and the design strategies of emergency architecture are also explored (TUM, 2022). Most of the project themes are directed at non-European contexts, primarily in the African region. This requires an open-minded and flexible approach to design and construction as well as developing the use of different architectural tools instead of already learnt fixed templates. Within the framework of the course, a 1:1 scale construction project is realized on site in order to explore if a "high degree of architectural and spatial quality can be achieved through simple solutions" (TUM, 2022) and through the use of local resources.

According to the European Commission, "the construction ecosystem has been considered to be lagging in the adoption of digital technologies. At the same time, digitalisation is a means, an enabler to achieve a better built environment for the planet and people. Digitalisation is transformative to the whole ecosystem, resulting in process efficiency; support for circularity; certification and traceability." It is precisely these questions that the already mentioned Institute for Advanced Architecture of Catalonia in Spain is targeting in its educational programme while "revolutionizing current architectural approaches" (IAAC, 2022c). The focus of its multidisciplinary educational approach is the combination of "technology, biology, computational design and digital and robotic fabrication" (IAAC, 2022c). The principal methodologies supporting this approach are learning-by-doing and design-by-research. IAAC offers Master’s and post-graduate courses which provide tools to respond to the environmental, social and economic challenges in today’s architecture and to create self-sufficient, ecological environments.

The Master in Advanced Ecological Buildings and Biocities is focusing on designing and building a new generation of buildings and cities with the use of the most advanced technologies and design techniques. It provides a unique and innovative educational format – the programme is carried out in Valldaura Labs, a self-sufficient habitat research center in Barcelona, located in a natural environment (IAAC, 2022d). As observed by one of the participants, studying in Valldaura Lab implies constantly "pushing the limits of co-creating and also of existing educational methodologies." (IAAC, 2022f) The programme consists of theoretical components followed by the conception and fabrication of a full scale building prototype. Design is conceived as a "comprehensive applied project" where the role of the architect is emphasized as a "hands-on applied maker" (IAAC, 2022d). Central to IAAC’s pedagogy is the question of reciprocity between nature and the built environment and the different scales in which a building is interconnected with its broad surrounding. The programme is thus addressing all the scales of a project from material to territory. The Lab's fabrication infrastructure allows for the tracing, sourcing and processing of locally available material – wood and earth primarily – and its transformation to building elements.

Other than that, IAAC offers the first programme on 3D printing construction in the world (IAAC, 2022f), the Postgraduate in 3D Printing Architecture. The programme explores the potential of "additive manufacturing of sustainable architecture" (IAAC, 2022f), applying state-of-the-art technology to develop new construction methods. It is a programme of applied research focusing on areas such as "robotic manufacturing, eco-friendly material research and performance-based design" (IAAC, 2022f). Projects such as the Building Architecture Continuity and Digital Adobe incorporate in a full scale the outcomes of research in the faculty (Figure 2). The projects demonstrate "the language of large-scale 3D printing" and the potential of using "advanced construction technology in combination with materials from the past" (IAAC, 2022g). By developing efficient on-site construction methods for local, natural materials (IAAC, 2022h), the projects are addressing the obstacle of labor-intensity and scarcity of know-how related to the use of traditional techniques of vernacular materials.

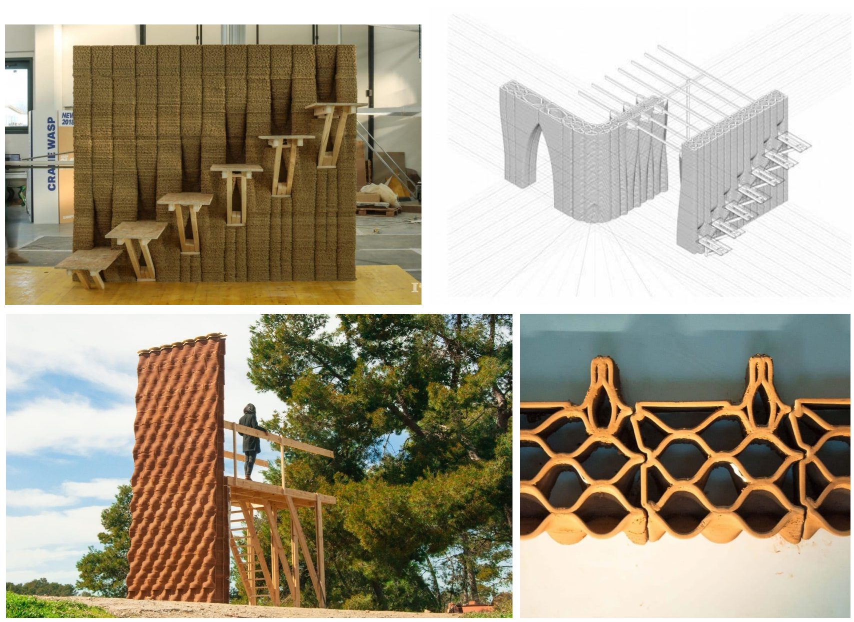

Figure 2 - Building Architecture Continuity and Digital Adobe projects (source: IAAC, 2022g, 2022h)

One of the most significant, tangible outcomes of the research so far is a 3D printed housing prototype (Figure 3). Together with World's Advanced Saving Project (WASP), an Italian 3D printing company, IAAC completed Spain's first 3D printed earthen construction in 2022 during 7 weeks of construction. The prototype was researched and tested in terms of CO_2 footprint and full material life cycle (3D Printing Media Network, 2022).

Figure 3 - 3D printed housing prototype (source: IAAC, 2022i)

Recognizing the necessity for an ecological and social turn in the building industry, the Chair of Sustainable Construction at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) "aims to ground sustainability in all disciplines involved in the built environment" (ETH, 2022a). As a result, the Certificate of Advanced Studies (CAS) in Regenerative Materials, a new, part-time continuing education programme was launched in 2022, addressing project managers, building contractors, architects and engineers. The programme is responding to the problem of scarcity of information available for decision makers and practitioners about the potential of local resources, preventing the widespread use of environmentally conscious construction solutions. It offers "knowledge and skills to question conventional construction techniques and to promote regenerative materials" (ETH, 2022b) such as earth and other bio-based and reused building materials.

Research into the physics of regenerative materials and construction processes ensures that they can be upscaled to meet contemporary demands in architecture. Similarly to the previously mentioned amáco's investigation into environmental clay concrete, researchers at ETH Zurich are also experimenting with new technologies for the use of earth, namely the poured earth technique and cementless clay-based concrete. Studies are conducted with the intention to find solutions for low-carbon earth stabilization methods. Combining geopolymers derived from agricultural wastes with the poured earth technology is one of the ongoing research projects of this focus. Most notably, the work of Gnanli Landrou and Prof. Dr. Guillaume Habert – holder of the Chair of Sustainable Construction at ETH Zurich – about the development of self-compacting clay concrete is an outstanding initiative. It aims to promote the use of material earth by inventing a process similar to concrete construction, that is, fast and easy-to-use but still eco-friendly and cheap (Landrou, 2018). According to the cost and environmental assessment, "the final product reduces 2.5 times the cost and 20 times the carbon footprint" compared to concrete products (Landrou, 2018).

Optimizing the construction process is a key in the conventionalization of bio-based materials and an important field of research at ETH Zurich. The resulting projects represent different approaches to the material, among which are combining prefabrication with form-finding processes or integrating the traditional raw material with computational design techniques.

Within the framework of an elective design-build workshop in the Department of Architecture led by Prof. Annette Spiro and Gian Salis, and in collaboration with Martin Rauch’s Lehm Ton Erde GmbH, the first-ever load-bearing rammed earth vault was created using prefabricated elements and unstabilized raw material (Figure 4). Although earth can only function as a funicular, that is, compression-only structure, the project is challenging the general notion of the architectonic expressions related to earthen construction and is showing the possibility of creating a contemporary architectural language of its own (Rauch, 2019).

Figure 4 - Rammed earth vault (source: ETH, 2014)

The use of digital fabrication tools, as illustrated before in the case of IAAC, is opening new potentials in the use of natural building materials. The Robotic Clay Rotunda, designed by Gramazio Kohler Research from ETH Zurich is a free-standing, unstabilized earth-based music auditorium (Figure 5). The quick in-situ realization of its complex structure was made possible due to computational design and robotic fabrication (Insight Architecture, 2022). The production process represents an alternative to traditional construction techniques in terms of labor-intensity and cost, thus proving more suitable for contemporary applications. Also, the project "has acted as a catalyst for knowledge transfer between research and industry" (Gramazio Kohler Research, 2022). By involving multiple different stakeholders and actors of the construction industry in the research project it becomes possible to disseminate knowledge to relevant decision-makers about alternative options for a regenerative architecture.

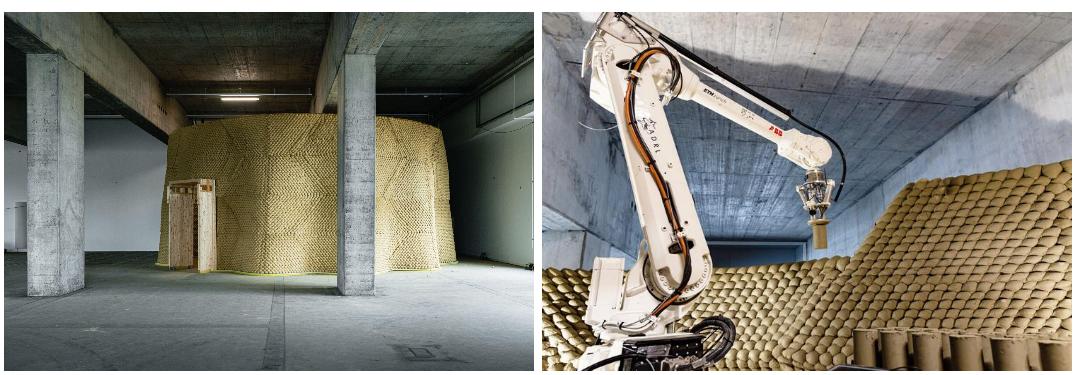

Figure 5 - Robotic clay rotunda (source: Insight Architecture, 2022)

Research bodies at ETH Zurich such as the Block Research Group (BRG) are also working towards the redefinition of current construction approaches and paradigms. BRG is led by Prof. Dr. Philippe Block, a full-time professor at the Institute of Technology in Architecture at ETH Zurich together with Dr. Tom Van Mele (ETH, 2022d). With the aim of responding to the challenges of climate change, it is advocating resource-and structural form-efficiency through prefabrication strategies and the combination of traditional principles with advanced technology. More precisely, the research is built, among other things, on the principles of classic stereotomy. Stereotomy is "the art of cutting three dimensional solids into shapes to be assembled, [...] more specifically the art of stone carving for the purpose of constructing vaults, squinches or cupolas" (Sakarovitch, 2003). Achieving structural strength through the geometry of the construction is the main focus of the research. The use of computational form-finding tools allows for generating self-supporting modular structures constituting stereotomic parts (BRG, 2022a). Compression-only forms make it possible to use materials with limited tensile capacity such as stone while reducing both cost, time and material needed for construction. The Armadillo Vault was created for the 15th International Architecture Exhibition - Venice Architecture Biennale in 2016 and represents, in a full scale project, the above-mentioned concepts. Computational design and optimization as well as historic construction principles allowed for the creation of its complex form within a tight timeframe and budget. The structure consists of individually cut thin limestone pieces and stands without any reinforcement or use of mortar (BRG, 2022b) (Figure 6). The simplified building process and increased quality of the result, illustrated by the project, are opening possibilities for a new use of stone in contemporary construction.

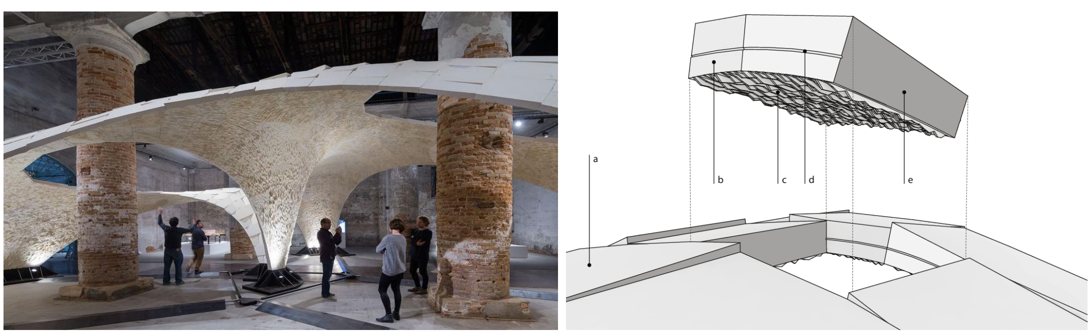

Figure 6 - Armadillo vault (source: BRG, 2022b; Rippmann et al., 2016)

The Department of Civil Engineering and Architecture Sciences (DICAR) of the Polytechnic University of Bari, Italy carries out significant research activities on a similar topic. Researchers are exploring "innovative approaches on new uses of traditional construction materials" (Politecnico di Bari, 2022), with special focus on stone. The most active, notable actor of the department is the New Fundamentals Research Group (NFRG). The team is led by Prof. Giuseppe Fallacara, architect and associate professor at DICAR where he teaches Architectural Design and Stereotomy (Monash University, 2022). The aim of the group is to explore "the relationship between innovation and tradition in architecture" (NFRG, 2022). Building on knowledge from the architecture of the past while taking advantage of advanced digital modeling and fabrication tools, Prof. Fallacara advocates the creation of a new stone architecture. As a basis of this, he emphasizes the importance of education on stereotomy: "I firmly support [...] introducing the study of stereotomic culture among the main basic teaching within the architecture and engineering degree courses all over the world" (YouTube, 2018). He argues that the discipline establishes the rediscovery of historical stone heritage while demonstrating a holistic approach to design. To put it in his words: "The architect fluent in stereotomy has the tools to conceive a covered space where form, material and structural performance are integrated in the design act." (Stone-Ideas, 2020) The revival of the discipline can be related, on one hand, to the development of advanced design and manufacturing tools which makes it possible to exploit the potential of stereotomic principles to create complex structures. On the other hand, pressing environmental concerns foster the need to turn to alternative building materials. Stereotomy offers new uses for structural, natural stone in the construction industry.

The research activities of the NFRG thus seek to "close the distance between practice and theory through the realization of demonstrational projects" (YouTube, 2018). Such projects include the Italian pavilion for the 2021 Venice Architecture Biennale called Section of Infinity or the Hyparvault-and gate (Figure 7). Their aim is to create self-supporting vaults with the use of parametric analysis and design. The projects are based on additive manufacturing using modular stone blocks in compression-only structures. The stone modules are prefabricated by Computer Numerical Control (CNC) machines and wire saws which allows for minimizing the amount of waste material. The shape of the stone blocks are optimized in order to use the least amount of pieces possible while still having the most variety of configurations to achieve different shapes based on the same geometry (YouTube, 2018). The vaults are prestressed by steel cables which hold the structure together. Prefabrication and modular construction ensures a quick and easy assembly while using robotic fabrication makes it possible to achieve high precision at a low cost (Stone-Ideas, 2020).

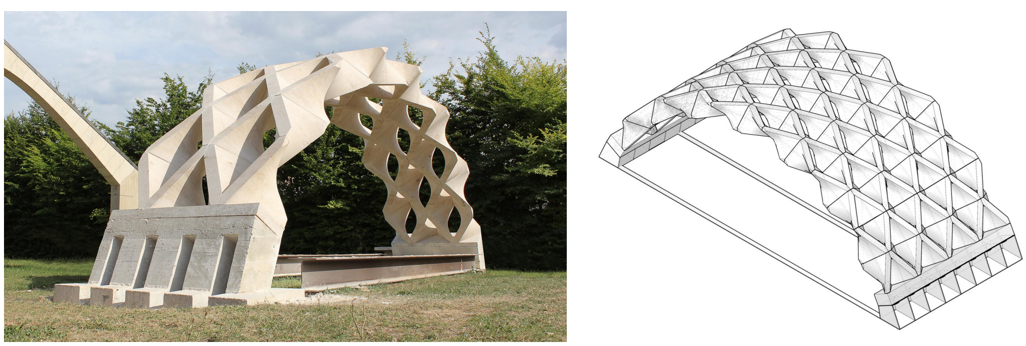

Figure 7 - Hyparvault (source: archdaily, 2017; Parametric Architecture, 2021)

Further research on the contemporary application of stone has been carried out by United Kingdom-based office Groupwork and structural engineering firm Webb Yates. The research project formed part of the New Stone Age exhibition at the Building Centre in London in 2020. The exhibition advocates the use of structural stone and demonstrates its potential to create large-scale contemporary buildings (dezeen, 2020a). The research team conceived a conceptual 30-storey skyscraper with load-bearing stone structure and compared it to one built with concrete or steel (dezeen, 2020b). The main aspects of the investigation and the comparison were environmental impact and cost. The project also aimed to demonstrate what the limitations of height and scale are when building with stone. The results showed that using stone in both the outer skeleton, slabs and core would reduce the embodied CO_2 of the project by up to 95% compared to steel or concrete structures, if stone is quarried in the same country where the project is erected (Eight Associates, 2020). As the report states, "inherently stone has zero carbon footprint. It is the energy used in quarrying, preparing and lifting the stone into place where CO_2 builds up." Typically, the carbon reduction would be approximately 60% when compared to a concrete frame and around 80% when compared to steel frame structure (Eight Associates, 2020). The research found that the use of granite or basalt would be the most appropriate due to their ability to withstand fire. While the cost of a stone superstructure would be somewhat higher than the use of steel or concrete equivalents, it doesn't need to be fireproofed, weatherproofed, insulated or clad which overall results in a lower construction cost (Coles, 2020). Research of this kind constitutes an impetus to making the use of stone more widespread and to create legal norms for its application. Industrializing the material would also imply a reduction of global costs related to stone construction (Webb, 2020).

As far as educational institutions are concerned, it is very important to provide adequate responses to the changes in current circumstances concerning architecture, among which one of the most pressing is environmental issues. While the process of adapting the educational offer to respond to contemporary challenges is relatively slow, the previously mentioned universities have succeeded to achieve this goal through innovative academic methodologies. The above-mentioned institutions have developed and applied state-of-the-art scientific results and tools in research and education challenging "the discipline of traditionally conceived architecture" (BASEhabitat, 2022b). Their knowledge transfer is based on the combination of theoretical and practical components. This way students get the opportunity to learn based on their own experience and gain a deeper understanding of the different stages of the design and construction process. As architect Timur Ersen puts it: "Learning to love building is one of the strongest ways for architects to become aware of everything that is at stake with each of their features or each of their decisions." (Timur Ersen, 2018) Such an integrated approach should be an essential feature of academic education to train competent professionals, though it is still not commonplace. Most often, students are not presented with the wide range of alternative solutions concerning ecological materials, construction techniques and the different approaches to design. Progressive universities such as those presented before, provide a more flexible and comprehensive way of learning by focusing on the process rather than the outcome of design. It implies a new perspective on architecture enabling young professionals to target the real needs in a specific project. By applying theoretical knowledge in practice, they learn to effectively take into consideration the client/community, the available resources, material characteristics and the environmental and social impact of different solutions. Having access to a broad range of tools and a variety of alternative options encourages experimentation which is a key for further development.

2.2. Practice

This chapter aims to outline selected examples of contemporary architectural works made of earth and stone in the past two decades that are challenging the way these materials are perceived today. The chosen projects represent a shift in how natural materials can be applied in the architecture of today. They present buildings of a wide range of scales in different climatic conditions as well as innovative techniques used in the construction process. They illustrate buildings with contemporary aesthetics which fully satisfy the needs and requirements associated with their function, socioeconomic and climatic context. Prominent, Pritzker-prize winner architects' works are also included in the selection. The influence they represent puts them in a special situation. Their related work potentially has a great international impact in changing the image of earth and stone. They show that the architectural mainstream is moving to a new direction of ecological sensitivity and environmental consciousness. The projects are "regarded as trend-setting and constituting a new style for contemporary architecture" (TUM, 2017).

The Pritzker Architecture Prize is awarded annually to an architect who consistently and significantly contributes to humanity and the built environment through the art of architecture (The Pritzker Architecture Prize, 2022a). In the year of 2022, the prize was received by Diébédo Francis Kéré, as mentioned in the previous chapter. Born in Gando, he is transplanting into his professional practice the experience he derived from growing up in Burkina Faso. It translates to a transformative and socially engaged architecture, sensitive to local socioeconomic and environmental conditions. As the 2022 Jury Citation states, "He knows, from within, that architecture is not about the object but the objective; not the product, but the process. Francis Kéré's entire body of work shows us the power of materiality rooted in place." (The Pritzker Architecture Prize, 2022b) His works are primarily addressing the context of developing countries but they can be found in Europe and the United States as well. His studio, Kéré Architecture is based in Berlin, Germany which means that the principles he is advocating through his projects and his educational activities carried out at TU Munich are likely to have a broad influence on European creatives.

Two representative works of Kéré Architecture are presented in this chapter, both public buildings of educational function made of earth and stone, respectively. The Burkina Institute of Technology (BIT) campus in Koudougou, Burkina Faso was completed in 2020 and allows local high school graduates to continue their studies without having to leave their hometowns. The simple rectangular volumes are built with locally available clay using the innovative technique of poured earth mixed with cement and aggregates (Kéré Architecture, 2020) (Figure 8). This construction method of in-situ cast walls resulted in a significantly faster building process than that of clay bricks or rammed earth. The thick walls have considerable thermal mass thus contributing to good indoor comfort. Extensive roof overhangs provide protection for the walls against rain and direct sunlight and enable natural ventilation.

The merit of the project is described by the architect: "By showcasing the potential of clay as a desirable and contemporary building material, our projects also play a political role in the reappropriation of vernacular building practices." (Kéré Architecture, 2022)

Figure 8 - Burkina Institute of Technology (source: Kéré architecture, 2020)

The use of earth in the projects of Kéré Architecture is based on a current trend of stabilization. It means that the raw material is complemented by 5-10% of chemical additives, most often cement to reinforce its structural stability and achieve better water resistance. While this process can increase the durability of the structure, it decreases its breathability i.e. moisture exchange which is an important factor influencing indoor comfort. Besides that, it affects the recyclability of the material. This method might prove arguable for the above mentioned reasons, and there are several different solutions to address the problem of weathering while still maintaining the ecological characteristics of raw earth. These solutions are mainly structural and include the protection of the top and bottom of the walls from direct water contact or applying the principle of calculated erosion which will be discussed later in this chapter.

The Startup Lions Campus in Kenya is an information and communication technologies campus completed in 2021 (Figure 9). It serves the purpose of providing high-level training to young people in order to fight unemployment in the region (Kéré Architecture, 2021).

Figure 9 - Startup Lions Campus (source: Kéré architecture, 2021)

It takes inspiration from local conditions and specificities at different levels. The multistorey building features tall towers to allow for natural ventilation through stack effect similar to the towering mounds built by local termite colonies (Kéré Architecture, 2021). The project employs locally available resources and strongly relies on local construction know-how. The structure is made of natural stone quarried close to the building site and built with the help and expertise of the local community in a participative process.

Recognizing Kéré's ecologically and socially sensitive work with such a prestigious international award as the Pritzker Prize implies a shift in values – "a shift from spectacular architecture to vernacular architecture" (Insight Architecture, 2021). It has become necessary to reconsider the importance of authorship and artistic freedom often placed over social purpose. As architect Anna Heringer puts it: "I believe that the time of starchitects is over but I still believe that we need iconic buildings [of sustainable architectural solutions] that give directions and show some visions." She argues that politics have an important role in boosting the implementation of good quality landmark projects (Heringer, 2018) which are also convincing with their aesthetics. It is through making these kinds of projects visible that relevant changes can be achieved on a larger scale.

The 1998 laureate of the Pritzker Prize, Renzo Piano is the author of many internationally renowned buildings from which stands out the Centre George Pompidou in Paris, France. Although the following two projects of his studio, the Renzo Piano Building Workshop (RPBW) might potentially be less known, it is important to highlight them because they reveal the versatility of his work, his sensitivity for the material as well as his concern with sustainable architecture. As J. Carter Brown, 1998 Pritzker Prize jury chairman put it: "Deeply imbued with a sense of materials and a craftsman's intuitive feel for what they can do, his architecture embodies a rare humanism." (The Pritzker Architecture Prize, 2022c) The following projects demonstrate his ability to enhance the value of local resources with technological innovations and bioclimatic design principles (Architettura di Pietra Journal, 2009).

The Padre Pio Pilgrimage Church in San Giovanni Rotondo, Italy was built between 1991 and 2004 with the purpose of receiving an increasing number of pilgrims visiting the town. Piano's concept was to create "a church that is open to all" and blends in with its mountainous landscape (RPBW, 2022a). As an experiment with new possibilities for the use of an ancient building material, the complete structure of the church is made of locally quarried stone (Figure 10). It consists of massive arches, spanning a length of up to 50 meters. Located in a seismically active area, it was necessary to apply innovative techniques to support the structure against horizontal loads. The use of fiber reinforced mortar and reinforced stone technology provide for structural stability (Architettura di Pietra Journal, 2009). The latter means complementing the stone structure with internal post-tensioned steel cables that keep the blocks together in case of a movement generated by seismic actions. Exploring the potential of stone with technologies that were new at the time resulted in a project that proved the applicability of the material in large constructions and in earthquake-prone regions, in a European context.

Figure 10 - Padre Pio Pilgrimage Church (source: archdaily, 2004)

The Children's Surgical Hospital in Uganda, completed in 2020 by the RPBW has a symbolic importance as explained by the studio: "The challenge of this new project is to combine the practical requirements of a [...] hospital in Africa with the desire to create a model piece of architecture: rational, tangible, modern, beautiful, but firmly linked to tradition." (RPBW, 2022b) The hospital provides free medical care for African children and functions as a training center at the same time. Its walls are made of raw earth using the rammed earth technique (Figure 11). The choice of material responded to the aim of the studio to deconstruct the image of poverty connected to the material in the region. Besides that, it was locally available in high quantities and there was no need for highly skilled labor for its execution. The hygrothermal properties of earth provide a constant good indoor comfort in terms of temperature and humidity. The roofs of the building are elevated to provide shade and host photovoltaic panels which cover the electricity needs of the health center.

Figure 11 - Children's Surgical Hospital (source: archdaily, 2020)

The next projects feature large scale public and residential buildings executed in France, with the use of structural stone or non load-bearing earth walls. Realizing public buildings using natural resources contributes to changing the status of the material. It shows its ability to meet the strict requirements posed by specific building functions in the public sector. To illustrate the applicability of earth and stone, different aspects are examined from structure and comfort to legislation and environmental impact.

The Miriam Makéba School Group in Nanterre was completed in 2019 by toa architectes associés. It is the first public building to use raw earth in the Île-de-France region (Architecture Terre Bois, 2018) demonstrating the possible use of the material in a dense urban situation, as toa architectes associées (2019) state. The building employs self-supporting rammed earth walls within a concrete frame on the ground level with stainless steel façade cladding on the upper floor (Figure 12).

Figure 12 - Miriam Makéba School Group (source: toa architectes associés, 2019)

The decision not to use earth as a load-bearing structure resulted from a lacking regulatory framework. This condition posed a certain risk for the architects which they chose not to take. In the absence of standards, a technical assessment of experimentation (Atex) was requested to provide a proof for the reliability of the material and the rammed earth technique. A characterization of the material was carried out by CRAterre and amáco (amáco, 2016b). The carbon footprint of the construction was reduced both in terms of embodied and operational energy. The raw material came from a quarry nearby, minimizing transportation needs. Earth was used in its natural raw condition without being further processed or manufactured. The thick walls allow for a balanced indoor temperature and humidity without the use of an air conditioning system that cuts the energy needs of the building throughout its life cycle.

French architecture studio, Atelier d'Architecture Perraudin has been experimenting with massive stone as a construction material for 25 years (Building Centre, 2022). In 2013, the studio completed a social housing project near Toulouse, built entirely in structural stone (Figure 13). The building was regarded as a case study of contemporary stone architecture to explore the potential of the material in a context of strict economic and energetic restrictions and a tight schedule (dezeen, 2013). As architect Gilles Perraudin explains, every decision in the project was dictated by the material. The design is of extreme simplicity to meet the budget of 1150 eur/m^2. The 3-storey building is made of load-bearing unreinforced limestone blocks. For the architect, this is a key question in the future of stone: "it must absolutely be able to be used without reinforcement" (Perraudin, 2020). The studio’s main reason behind working with stone is to reduce the embedded CO_2 of new construction (Building Centre, 2022). The blocks constituting the social housing unit were cut in a nearby quarry and assembled on site with the use of lime mortar to provide airtightness. The floor slabs are made of reinforced concrete. The thick stone walls provide high thermal inertia and regulate indoor temperature and humidity without the need of mechanical air conditioning. The architect believes that "there is an absolute necessity to construct in stone in order to diminish the energy expenses" during the life cycle of a building (Building Centre, 2022).

Figure 13 - Social housing in Toulouse (source: dezeen, 2013)

The next group of projects presents new technologies and principles for the use of material earth in contemporary architectural practices. These technologies are targeting the mechanization of the construction process by means of prefabrication. They build on traditional techniques such as rammed earth or adobe but replace on-site manual work by industrialized or semi-industrialized processes. It results in the standardization of the final product by guaranteeing controllable geometrical and physical properties. The industrial prefabrication of rammed earth developed by Martin Rauch contributes significantly to the affordability of earth constructions in developed countries. Rauch is an Honorary Professor of the UNESCO Chair “Earthen Architecture” since 2010. Together with Lehm Ton Erde GmbH, he has been working on creating a contemporary language for earth construction by developing traditional techniques. He has been refining the prefabrication process of rammed earth wall elements since the foundation of his company in 1999 (Lehm Ton Erde, 2022a). In the context of developed countries where labor is expensive and construction times need to be estimated precisely, prefabrication proves to be a feasible option. The process takes place in a warehouse which ensures its independence from weather phenomena and other building site constraints. In order to protect the modules from the effects of weathering, a passive measure, namely the method of calculated erosion can be used. It means designing the earthen walls 2-3 cms thicker than it would initially be necessary (Heringer et al., 2019). In the first years, this additional layer, the outermost fine proportions of the wall get washed out. Later, the bigger stone particles in the material prevent water from further protruding the wall and weathering stops. Consequently, earthen construction can be applied in a wide range of different climatic conditions.

The next two projects illustrate the use of prefabricated compressed earth blocks (CEB) and complete rammed earth wall panels. The value of both was recognized by the TERRAFIBRA Award in 2021. It is the first international prize for contemporary earthen and plant fiber architecture (TERRAFIBRA Award, 2022a). Its goal is to raise awareness of projects remarkable in their environmental approach, constructive solutions and aesthetics while underlining the merits of the different stakeholders involved in their realization.

The MIBI Yoga Center in the Metropolitan Area of Barcelona, Spain was completed in 2019 by Italian architect Elisabetta Carnevale. She is founder of Barcelona-based Arquitectura de Terra, a consultancy and design studio specialized in earthen architecture (Arquitectura de Terra, 2022). The project was a finalist of the TERRAFIBRA Award in the category of interior architecture (TERRAFIBRA Award, 2022b). It is a pioneer in Barcelona using prefabricated earth blocks (Carnevale, 2020). The blocks were used for the construction of the partition walls of the center and were manufactured by Spanish company Fetdeterra (Figure 14). Earth was chosen as a building material to reflect on the architectural heritage of the region and because of its optimal properties for creating a healthy indoor environment in terms of temperature and humidity. As the architect states: "[earth] is a material of the future: it is a low-carbon material, it is a natural and locally available resource and it is completely recyclable." (archdaily, 2019)

Figure 14 - MIBI Yoga Center (source: Fetdeterra, 2022)

The Alnatura Campus office building, completed in 2019 in Darmstadt, Germany, was one of the laureates of the 2021 TERRAFIBRA Award in the category of commercial buildings (TERRAFIBRA Award, 2022c). It was designed by haascookzemmrich STUDIO2050 and realized by Martin Rauch's Lehm Ton Erde GmbH. It is using prefabricated rammed earth elements with an integrated core insulation to create the 3-storey high self-supporting outer walls (archello, 2022) (Figure 15). The additional insulation was necessary to comply with the German regulations for thermal performance. The walls are equipped with geothermal heating as well. The building is a pioneer in the latter technology and also in being the largest office building in Europe with an earthen façade. A specialized ramming machine was developed for the execution of the wall panels which posed further challenges in the project. Obtaining the certification for the machine required considerable financial investment from all stakeholders in advance which posed a risk to all parties involved (Heringer et al., 2019). This process showed that sometimes legislative regulations are counter-effective, making earth construction even more difficult rather than facilitating it.


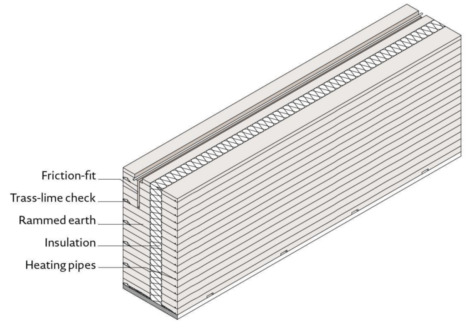

Figure 15 - Alnatura Campus (source: Lehm Ton Erde, 2022c; Kapfinger & Sauer, 2022)

Having worked together with the client before, Portuguese architect Henrique Schreck has a personal insight in the project. The decision to make the façade of the office in prefabricated rammed earth, realized by a machine developed for this single project, increased the price of construction by around 1 million euros as opposed to the use of a current building method (Schreck). Besides the financial aspects of the project, the architect also has a concern about the structural safety of the façade walls. In principle, earth works as a monolithic system and the separation of the wall elements makes the structure vulnerable to horizontal forces generated by seismic action. To counteract this, a strong foundation and connecting elements alongside the wall were required. As remarked by Schreck, the "problem is the junction of knowledge and costs" – to increase the prices so significantly by a construction that is not perfectly sound seems to be art for art's sake. It is therefore important to find the ways for the reasonable use of earth that make it possible to exploit the potentials of the material to the greatest degree.

The following projects were conceived and constructed in recent years using advanced digital tools in combination with natural materials. Automated fabrication and industrial manufacturing have been transforming conventional building processes related to the use of earth and stone in the past decades. They are capable of providing what is most often missing in traditional methods, that is a controlled process of construction. It means that the quality and liability of the result will improve and at the same time, it will be more cost and resource efficient. The different aspects of the next projects include the technology and tools used in their design and execution, the duration and environmental impact of the construction and the gradient between industrial manufacturing and craftsmanship in which each project is positioned. The latter characteristic can also be translated into each building's capacity to engage the vanishing local know-how concerning natural building materials and to address different social and cultural levels in the building practice.

In 2021, TECLA, the first fully 3D printed housing prototype made of local raw earth was completed in Massa Lombarda, Italy in collaboration with studio Mario Cucinella Architects and 3D printing specialist company WASP (Figure 16). The prototype aims to provide a sustainable response to increasing housing needs by offering a fast, energy-and material-efficient construction with locally available resources. The extrusion material for 3D printing consisted of locally sourced earth, water, natural fibers and around 5% of binder (CNN, 2021). The use of chemical additives, however, limits the recyclability of the construction.

A double dome system provides the structure, the roof and the cladding of the housing unit at the same time where each dome is naturally lit through big circular skylights (WASP, 2022). Thanks to its parametric design, the architect remarks, the geometry of the module is adaptable to different climatic conditions and to the use of different types of earth (dezeen, 2021). The housing unit was conceived by modular, multi-level 3D printers on site. It was the first time in 3D printing construction that two printers were applied simultaneously on the same project, resulting in a fast execution (WASP, 2022) – the construction took 200 hours in total, although the complete drying of the clay took several more weeks. As WASP founder Massimo Moretti said: "TECLA shows that a beautiful, healthy, and sustainable home can be built by a machine." Nevertheless, fully mechanizing the building process implies completely diminishing human labor from construction. The decline of mass labor is already a problem in Europe (Spiegel International, 2005) which is going to have impacts on local economies and thus poses itself as an important factor to consider.

Figure 16 - TECLA (source: dezeen, 2021; archello, 2021)

The next project presents an example where digital manufacturing and human expertise complement each other in the creation of a contemporary project with the use of massive stone as a building material. The Delas Frères Winery in the Rhône Valley in France was completed in 2020 by Carl Fredrik Svenstedt Architects and was included at the New Stone Age Exhibition in London. It features a seven-meter high curved façade made of structural sandstone (dezeen, 2020c) (Figure 17). Reducing embodied energy and the need of transportation, the material was quarried on a nearby site. The wall panels were then cut with a wire saw and carved by a robotic arm individually (Svenstedt, 2020). The use of robotic manufacturing helped minimize waste material and achieve a standard quality and geometry with a high degree of precision in execution. The assembly of the thick prefabricated blocks was done by a group of stonemasons using traditional techniques (dezeen, 2020c). For further stability, the wall was post-stressed by steel cables (Svenstedt, 2020). The high thermal inertia of the stone wall creates an ideal condition for the production and storage of wine. As for the client's perception of structural stone, the architect explains that the idea was initially not well received but the novelty of the construction in terms of material use and structure proved to be a convincing asset (Svenstedt, 2020). This experience is much in line with what Schulz (2020) underlines in the Manual of Natural Stone: the use of advanced digital design and fabrication tools in a specific project depends largely on the individual stakeholders and project participants and not only on the technological state of the art.

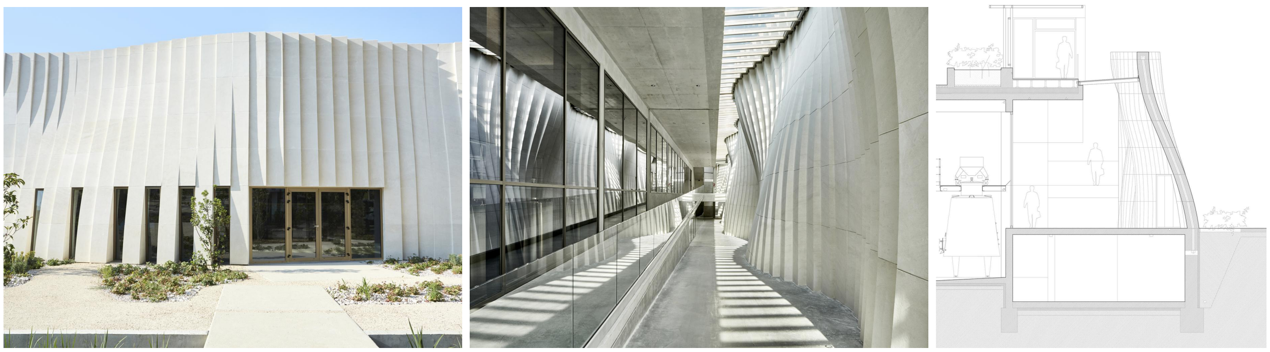

Figure 17 - Delas Frères Winery (source: dezeen, 2020c; archello, 2019)

As it can be seen from the previous examples, the challenges connected to building with earth or stone lie more in their perception characterized by a lack of trust and knowledge rather than in the lack of available technology for their use. Overcoming the outdated image inherent in such constructions could be possible, according to Rauch, by widely publishing example projects that demonstrate their viability. As opposed to man-made materials such as concrete and steel, there is a limited quality-control in the case of earth and stone. Although, even in the absence of building codes, Steve Webb argues, tools exist to analyze how the materials work (Webb, 2020). Repeatedly testing their performance is a crucial aspect in regaining trust as well as in creating new norms. The current lack of legislation, however, poses key questions of liability. The risks involved when constructing in such a context can discourage further development, as some projects revealed. Economically speaking, as earth and stone construction is still a niche in the industry, it inherently has higher costs. This is mainly because there are only a few specialized companies to supply products and technology, and labor is expensive. At the same time, for both earth and stone to be an economically competitive material, the cost of building should be "calculated on a whole-life cycle basis" (Moriset et al., 2021). In the long term, these materials can help to cut comfort-related energy expenses and often have a lower maintenance need than their industrial counterparts (Building Centre, 2022). When outlining the future of earthen architecture, both architect Anna Heringer and Martin Rauch refer to the importance of introducing stricter carbon taxes to change the common practice of the construction industry and make earth a more competitive player on the market.

3. TECHNICAL ASPECTS OF THE MATERIALS

"For me, earth and stone are the same material. They are both made of mineral substrates that cover the earth." (Gilles Perraudin)

Earth and stone are non-standardized building materials. They can both be readily found in nature with different proportions of components and substrates that build them up. It means that their performance in terms of thermal and structural behavior varies accordingly. To characterize earth, factors such as grain size, clay, moisture content and plasticity needs to be taken into account (Neves, 2005). In the case of stone, the characteristics of each type are defined by the rock-forming minerals (Siegesmund & Snethlage, 2011). The minerals affect porosity, heat-conductivity and moisture absorption capacity.

The present chapter provides a brief comparative overview of the material characteristics of earth and stone with regard to environmental impact, hygrothermal characteristics, mechanical properties, seismic resistance and economic viability. Their features are compared to those of industrialized materials as well.

3.1. Environmental impact

The environmental impact of building materials lie primarily in the related processes of extraction and production, transportation and assembly, in the maintenance and operation during the building's life cycle as well as in recyclability at the end of useful life. Various papers exist that studied the environmental impact of building materials to illustrate the differences between the use of industrialized and natural resources. Figure 18 below shows the values of total embodied energy of different building materials.

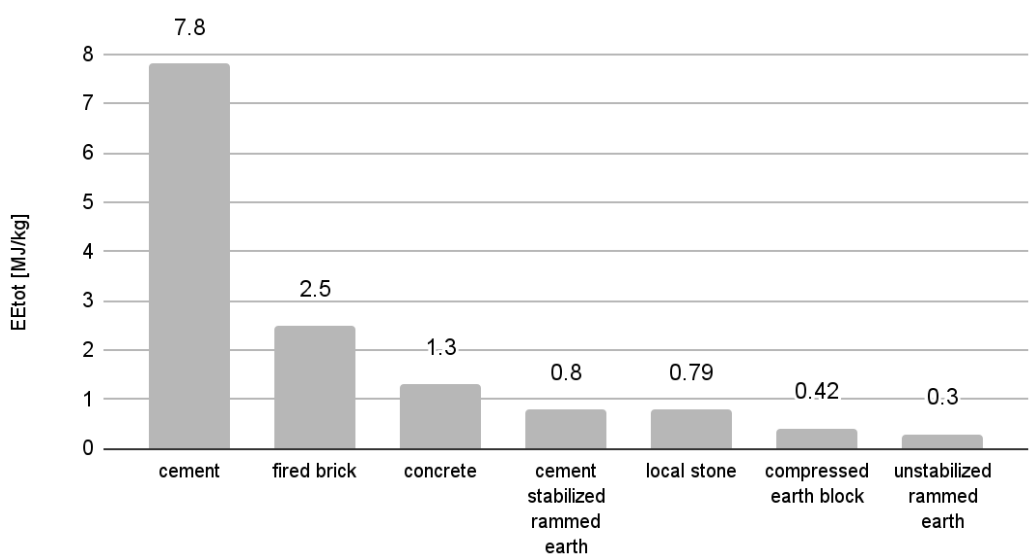

Figure 18 - Total embodied energy of building materials (MJ/kg) (adapted from: Mateus et al., 2019; Marques et al., 2021)

It is based on two studies from recent years (Mateus et al., 2019; Marques et al., 2021). The energy needed for the extraction and production of each material and its transport is included in the figures.

The values above illustrate that locally extracted resources account for a much lower energy need compared to industrially manufactured products. It is partly because natural materials are usually available locally, reducing transportation needs to a minimum which otherwise is a considerable factor of energy use and pollution. A low environmental performance of industrial materials also results from the related energy-intensive extraction and production processes.

As for stone, today's highly mechanized quarries and the existing legislation to control the process make it relatively easy to extract and shape the material, as Pierre Bidaud, director at The Stonemasonry Company Ltd. points out (Building Centre, 2022). At the same time, the quarrying of stone has a significant impact on the surrounding landscape. It alters natural sceneries including local flora and fauna as well as human living conditions. Quarries also increase noise and dust pollution in the area (Schulz, 2020). These factors need to be considered especially in the light of the amount of waste generated during extraction. The proportion of the finished product is very small compared to the sand, gravel and broken stone produced at the same time (Schulz, 2020). To be exact, according to Estremoz quarry workers, 80% of extracted stone in the Estremoz marble quarry in Portugal is a waste due to different reasons of imperfection concerning cracks or color (Figure 19). This fact, at the same time, implies an enormous potential for the (re)use of natural stone in Portuguese architecture. Besides extraction, transportation can constitute a large part of negative environmental impact in case stone needs to be imported. As a comparison, the Global Warming Potential (GWP) of locally sourced stone in European countries is less than half of that quarried and imported from Asia (Schulz, 2020).

Figure 19 - Waste material in Estremoz marble quarry (source: photo of the author)

At the same time, one of the reasons why earth proves to be an environmentally competitive option is because it does not require considerable energy to be extracted, manufactured and transported over long distances – the related energy needs is roughly 1% of those of fired bricks or concrete (Minke, 2009). Although a finite resource, earth has a recyclability of 100% – given it is unstabilized – as opposed to 50-60% in the case of concrete (Heringer et al., 2019). It means that the material has a practically unlimited lifespan while also being available in abundance. Stone possesses similar qualities. Being a very durable construction material, it can be reused multiple times without losing quality (Bergeron, 2020) while it is also a widely available resource. The use of earth implies further environmental benefits when it comes to the useful life of a building. Due to its good hygrothermal properties – described in more detail in the next chapter – and given a good design, it is able to reduce operational energy needs used to run heating and cooling systems to provide good indoor thermal comfort.

3.2. Hygrothermal and acoustic performance

The thermal capacity of construction materials has a major effect on the indoor climate of a building. The specific requirements of thermal comfort depend on the location and the function of the building and can be differentiated to winter and summer thermal comfort (Ramos de Freitas, 2001). In general, indoor comfort depends on the temperature, humidity, velocity, and pollution content of the air in a given room (Minke, 2009). In this chapter, the first two aspects are addressed from a material point of view.

As referred before, the thermal conductivity and thermal capacity of earthen and stone structures may vary widely depending on several material composition factors.

In the case of earth, its capacity of heat transfer and storage depends significantly on water content, material density as well as the construction technique applied at work. In general, earth can be characterized by a high thermal absorption and low thermal diffusion capacity, making it a good insulator against external temperature variations (Lourenço, 2002). Still, it needs to be noted that the high thermal inertia of earth can be best exploited in climates "with high diurnal temperature differences" (Minke, 2009). The way earth is used in construction has an impact on its thermal behavior. By compacting earth (rammed earth, CEB techniques), a higher material density can be achieved than using it in a malleable form (adobe). A greater density and thickness of the structure consequently translate to higher thermal capacity. This means that by adjusting the weight/density of the material through the construction technique or thickness of the wall, it is possible to respond to different thermal requirements (Lourenço, 2002). Besides that, earth can maintain a balanced indoor climate through entirely passive means by regulating indoor air humidity. Being a porous material, it has an equilibrium moisture content, a state when the material is not gaining, nor losing moisture. It depends on the relative humidity (RH) and temperature of the surrounding air. An increase in RH enhances the water adsorption of earth from the air, while a decrease makes the material release it, until a balance is reached. According to Minke (2009), for a building material to balance indoor humidity effectively, the speed of these processes is a key and earth "is able to absorb and desorb humidity faster and to a greater extent than any other building material".

As for stone, heat conductivity largely depends on the characteristics of its rock-forming minerals. Density and porosity are two important factors affecting the thermal behavior of stones. "Porous rocks, for example, can delay the heat exchange between the inner and outer environment of a building" but in general, natural stones are "poor heat conductors" (Siegesmund & Snethlage, 2011). Similarly to earth, some porous stones have the capacity to regulate indoor humidity through the adsorption of moisture from the air. The extent and speed of adsorption depends on the porosity of the specific stone but it is generally a slower process than it is in the case of earth. A limestone wall of the same thickness as an adobe one can absorb three times less humidity from the air in the same period of time while this value is ten times less in the case of fired bricks (Minke, 2009).

In Figure 20 below, the thermal conductivity values of a unit thickness of each material and constructive system is shown based on previous studies (Lourenço, 2002; LNEC, 2006; CRATerre, 2022e; Maisons Paysannes, 2018), including also industrial materials for a better comparison.

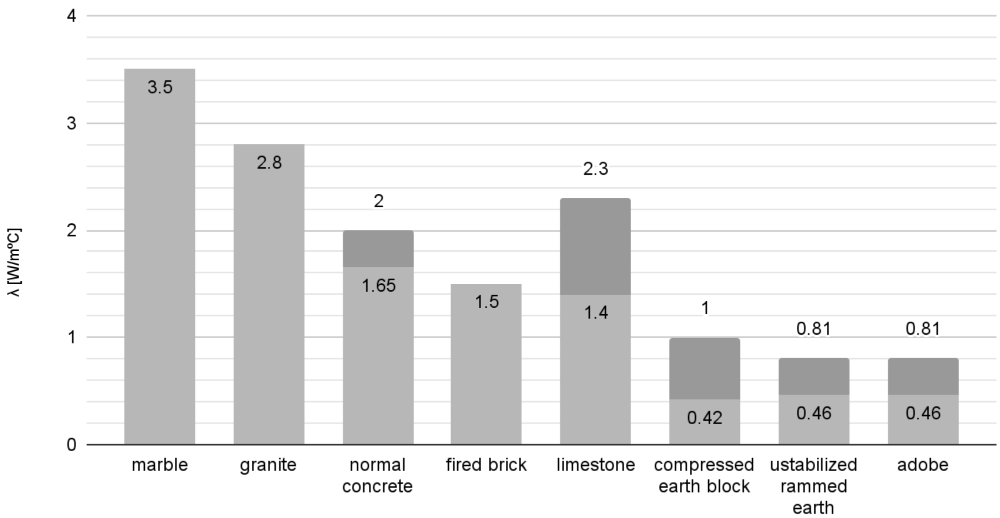

Figure 20 - Thermal conductivity of building materials (W/m°C)
(adapted from: Lourenço, 2002; LNEC, 2006; CRATerre, 2022e; Maisons Paysannes, 2018)

In Portugal, the current legislation in force for the minimum requirements of energy performance of the building envelope (Decreto-Lei n.o 101-D/2020, de 7 de dezembro) allows a maximum thermal transmission value (U) of 0,5 W/m^{2}K for exterior walls in the case of residential buildings and a value of 0,7 W/m^{2}K in the case of commercial ones in I1 winter climatic zones. The novelty of the current law, however, is that it considers exceptions from the regulative values referred to above which is described in paragraph c) of n° 1.2 of Article 3.°. According to this, exterior walls using the construction technique of “rammed earth or similar” need to comply with a maximum thermal transmission value of 1,3 W/m^{2}K.

The values show that it is difficult to achieve satisfactory indoor thermal comfort by the sole use of stone masonry walls. An additional insulation system is necessary to complement the stone structure. Concrete and fired brick structures also need to be insulated to comply with current regulations. In the case of earthen constructions, recent changes in legislation make it possible to conceive rammed earth walls of around 50-60 cm of thickness without insulation and still remain within the regulative values. Widening regulations to include earthen constructive solutions is an important step towards the conventionalization of the material and the promotion of its use in contemporary construction.

Additionally, it should be noted that the choice of material and construction system alone does not guarantee good thermal behavior. Climatic factors, building orientation and solar exposure needs to be taken into consideration from the beginning of the design phase in order to ensure good performance of the building (Marques et al., 2021).

With regard to acoustic performance, material density is one of the most important factors to consider for airborne sound insulation capacity. Due to their high mass per unit area, both earth and stone walls perform well in acoustic attenuation. Their sound absorption qualities are similar to those of widely used industrial materials. Table 1 below illustrates the sound insulation coefficient of different building materials (Lourenço, 2002; Ramos de Freitas, 2001).

Table 1 - Sound insulation coefficient of building materials (dB)

	fired brick	**concrete**	**adobe**	**CEB**	**rammed earth**	**stone**
R_w at 500Hz, 20cm thick wall	55	50	50	50	50	
R_w at 500Hz, 100 kg/m^2 density wall						40

(adapted from: Lourenço, 2002; Ramos de Freitas, 2001)

The Regulation of Acoustic Requirements for Buildings (Decreto-Lei n.º 129/2002, de 11 de Maio) specifies the airborne sound insulation requirements for exterior walls in Portugal. In case of residential and mixed use buildings, the minimum value is $D_{2m,nT,w}$ >=33 dB in mixed zones.

3.3. Mechanical properties, durability and maintenance

Earth and stone are the two most ancient building materials of humankind. Existing prehistoric examples demonstrate the resilience that these structures possess. As Schulz (2020) argues, "current knowledge of historical structures made from natural stone is due entirely to the durability of the material, a characteristic that remains an argument for its use in construction to this day". Still, the durability of the material has a pivotal but not exclusive role in the longevity of a construction and several different factors need to be considered to achieve long lasting buildings, including proper maintenance. Yet durability is also a design question which may either ensure or jeopardize the proper and lasting function of a construction. Design should always be adapted to the physical and mechanical properties of the materials used (Siegesmund & Snethlage, 2011). A construction material can be characterized by its strength parameters, specifically its compressive and bending tensile strengths. In the case of both earth and stone, the tensile strength is insignificant compared to compressive strength, constituting only 10 to 30%.

This characteristic is decisive for the materials' structural application and is also the source for most limitations to arise.

In Table 2 below, the indicative values of compressive, tensile and flexural or bending strengths of different construction materials are shown (CRAterre 2022e; Maisons Paysannes, 2018; Siegesmund & Snethlage, 2011; Eurocode 2).

Table 2 - Mechanical properties of building materials (MPa)

	granite	marble	limestone	concrete	fired brick	CEB	rammed earth
Compressive strength	140 - 160	80 - 140	40 - 160	20 - 38	15 - 21	2-6	0,9 - 1,7
Tensile strength	12 - 16	8 - 16	4 - 12	2 - 5	1 - 3		0,52
Flexural strength	12 - 16	12 - 18	4 - 16			0,2 - 0-6	0,2 - 0,3

(adapted from: CRAterre 2022e; Maisons Paysannes, 2018; Siegesmund & Snethlage, 2011; Eurocode 2)

As the values suggest, earth has a significantly lower compressive strength compared to stone, concrete or fired bricks. Different stabilization processes exist, however, which allow for obtaining a higher resistance. The use of lime or natural fibers contributes to a better mechanical behavior, cohesion and water resistance while maintaining the valuable assets of earth such as its recyclability and good hygrometric properties. The addition of chemical stabilizers such as cement may increase compressive strength more significantly than natural additives but, as referred before, it largely affects the environmental benefits in favor of earth's use. At the same time, numerous examples show that unstabilized load-bearing earthen walls are perfectly capable of satisfying the structural requirements of multi-storey residential and public buildings worldwide. On the contrary, different types of stones have much higher compressive strengths than commonly used industrial building materials. It is an important asset concerning not only sustainability but also economic viability especially when examined from a full life cycle point of view, as is presented in the next chapter.

The limitations arising from low tensile strength require a special structural answer to the application of earth and stone. It means that they can only be used in funicular structures and as such, they are unsuited to span large distances (Schulz, 2020) as a flat structure. When used to cover spaces, they work well in vaulted systems or domes that only allow compressive forces to be transferred. Earth or stone walls can be complemented by other materials, such as timber beams or concrete slabs to create intermediate floors. Exposure to tensile forces can lead to the cracking and failure of the structure and thus should be avoided.

Earth and stone are perceived very differently in terms of durability. While "stone is generally considered one of the most resistant materials" (Siegesmund & Snethlage, 2011), earth is principally regarded as a non-long-lasting one. Nevertheless, both earth and stone constructions need to respond to different requirements of durability which include: resistance to climatic agents (humidity, heat, ultraviolet (UV) radiation etc.), resistance to chemical and biological agents, resistance to erosion, withstanding deformations due to changes in temperature or moisture content and being easily replaceable (Ramos de Freitas, 2001). Environmental factors such as precipitation, UV radiation and chemical or biological pollutants affect earth and various kinds of stones to a different extent.

As far as solar exposure is concerned, earthen walls show a natural aging process because earth pigments are UV resistant (Lehm Ton Erde, 2022b). In the case of stone, although air temperature is not a key factor of deterioration, surfaces exposed to sunlight can show greater thermal deviations which some stones such as granites do not endure well (Siegesmund & Snethlage, 2011).

The effect of biological pollutants on the two materials also varies widely. The hygroscopic activity and dryness of earth prevents the development of microorganisms and fungi on or in a structure (Lehm Ton Erde, 2022b). On the other hand, stone, especially porous types, is prone to biodeterioration due to the microorganisms inhabiting its surface or its pores. They can cause a color modification of the surface which may also involve structural degradation. Besides biological pollutants, chemical agents such as vehicle-generated gases and acid rains pose further challenges to the built environment due to intensified urban air pollution.

The most important thing, however, to prevent most degradation, including biodeterioration, is the protection of earth and stone structures against direct water contact both from the top and bottom of the wall as well as its surface. Being water-soluble, it is especially vital in the case of earth. Good design and execution, however, can ensure that maintenance is not needed for decades for earth constructions (Lehm Ton Erde, 2022b). Even if it becomes necessary, it can easily be done with the same raw material with little cost and effort. Improper maintenance, however, can be the source of additional problems in earth constructions and it is a frequent phenomenon. Misinformation, negligence and other factors may lead to the use of incompatible materials (cement) or techniques when repairing earthen structures which results in further degradation.

In the case of stone, as it is an extremely strong building material, it needs hardly any maintenance during its life cycle (Schulz, 2020). The most important thing, similarly to earthen constructions, is to prevent deterioration through good design and implementation.

3.4. Seismic resistance

As Portugal is situated in an earthquake-prone region, the seismic resistance of existing and new constructions is a particularly relevant subject to address. In case of an earthquake, buildings are mainly affected by the horizontal forces created by the movement of the ground. In general, the quality of a structure in terms of seismic behavior depends on its ductility and resistance (Minke, 2009). In other words, seismic resistance is primarily the question of structural design rather than the question of the material (Rauch, 2021). The behavior of earth and stone walls against seismic action varies a lot and can be improved to a greater or lesser extent by various methods. On a material level, a proper composition and fiber additives can increase the ductility of earth (Lourenço, 2002). On a structural level, earth and stone walls can be complemented by timber or concrete reinforcement systems. As Perraudin underlines, one of the advantages of stone construction is its good compatibility with wood – a combined structure of this kind shows good flexibility and thus satisfactory resistance to seismic actions (Building Centre, 2022). The post-earthquake Pombaline houses in Lisbon represent the application of such an integrated system.

In the following, the main principles to conceive seismic-resistant earth and stone structures will be outlined. In general, "the seismic forces acting on a building are proportionate to its mass" (Minke, 2009), so it is recommended for the roof structure to be as light as possible. The different building elements (foundations, walls, roof) need to be well interconnected. The building should be symmetrical, regular and compact with solid and reinforced foundations. The walls of the building should be reinforced by timber or concrete piers connected to the foundations, placed in the corners, by the openings and regularly across the walls. A concrete or timber ring beam should be placed on the top of the walls, adequately fixed to them. The intermediate floor slabs need to be rigid enough to distribute horizontal loads and act as diaphragms. The openings of the building, proving a weak point in the general stability of the wall, need to be proportioned meticulously (Minke, 2009).

In the case of stone structures, the minimum thickness of a regular, unreinforced stone masonry wall is 30 cm and its height should be less than nine times its thickness. Dry masonry walls and weak binders with irregular stones should be avoided. The minimum area of the floor plan occupied by resistant stone walls in each direction varies between 2 and 7% according to the seismic zone in which the building is situated and the number of floors it has (Ramos de Freitas, 2001). In the case of earth structures, the minimum thickness of a rammed earth wall is 40cm. Its height should be less than seven times its thickness and its length less than ten times its thickness. Openings should be less than 1.2 m wide and altogether less than one third of the length of the wall. The recommended area of the floor plan occupied by resistant earthen walls in each direction is 10% (Lourenço, 2005). It also needs to be noted that the construction technique has a great impact on the seismic resistance of an earth building. The lighter and more flexible the construction is, the less prone it is to damage. Consequently, wattle-and-daub walls, for instance, perform better in seismic action than those of rammed earth or earth blocks due to the ductility of the timber structure and the light infill (Minke, 2009).

3.5. Economic viability

The context of economic, political and social uncertainty of the 2nd decade of the 21st century has been affecting most economic sectors including the construction industry. It is therefore very difficult to provide an up-to-date financial overview of construction activities and it is not in the scope of this study to quantify the different related variables. The aim of this chapter is to focus on the main components of construction costs in relation to the use of natural and industrial building materials taking into account the different factors affecting these figures.

In Portugal, global construction costs have risen considerably over the past years which is mainly due to an increase in the price of raw materials and the cost of labor (INE, 2022). According to EUROSTAT, since the year of 2020 there has been a steady increase in the Construction cost index of Portugal (Trading Economics, 2022). Due to soaring fuel prices, transportation has become ever more expensive while diminishing skilled labor has been posing further challenges in the construction process. Current constructions using reinforced concrete and fired bricks are energy, material and transport intensive which makes them vulnerable to the aforementioned conditions. When compared to traditional earth constructions, however, they are much less labor-intensive. It is mainly the manual production of earthen elements influencing the required labor that constitutes most of the associated costs. Nevertheless, as it was highlighted before, technological innovations have made it possible to adjust the degree of technology and labor to different economic contexts in earthen construction. Industrial methods such as prefabrication allow for a considerable reduction in manpower during the construction process, making it a more viable option in developed countries. When it comes to stone constructions, costs build up largely due to the process of quarrying, transportation and labor but the possibility of large scale industrial production of stone elements reduces the on-site requirements of labor as well.

In the context of a growing ecological concern, it is important to address the environmental impact of construction which translates to environmental costs through energy consumption in the production of materials, as the previous chapters indicate. Industrial materials such as concrete, fired bricks and steel require huge amounts of energy to manufacture and transport. In contrast, the same energy needs in the case of earth constructions are insignificant as the material, ideally, is locally available and does not need to be processed to be used. Stone constructions are more energy intensive, although transportation needs can be minimized if the material is sourced locally.

Despite all this, as referred before, in different parts of Europe both earth and stone construction tends to have a higher global cost. It is mainly due to the scarcity of skilled labor and specialized companies who provide service in the field. The overall duration of the construction is also longer which translates into higher labor costs. To overcome this, the cost of construction should take into account the whole life cycle of a building. As Lourenço (2005) indicates, "it is estimated that in the life cycle of a building about 2 to 4% of energy consumed refers to its planning, 20 to 30% to its construction and 70 to 80% to its management and use". Natural materials have a great potential to adjust energy consumption as well as global costs by creating good indoor thermal comfort through passive means during the useful life of a building. A further relevant aspect of sustainability of stone constructions, when examined from the perspective of the whole life cycle, is its projected lifetime. The longevity of the material can potentially balance the higher initial cost of construction and can make it a more attractive solution to potential clients.

The previous overview shows that, from an environmental point of view, raw earth proves to be the most favorable construction material given its low embodied energy and abundant availability on or near the site. As it does not need a lot of energy to be manufactured nor transported over long distances, the associated environmental impact is insignificant. Stone has a weaker environmental performance than raw earth due to the energy needed for the extraction of the material. However, the energy needs of transportation can be minimized if local resources are used. As the comparison indicated, neither earth nor stone relies on fossil fuels for manufacturing and transportation as much as industrialized materials which makes both of them a more attractive solution in the light of the current climate crisis.

In relation to indoor comfort, earthen components have the best hygrothermal performance when compared to different types of stones and current construction materials. The high thermal inertia of earthen walls, given by their thickness, and their low heat conductivity adapts very well to climates with high daily temperature differences, providing a good indoor thermal comfort. Though stone walls also have a high thermal inertia, their heat conductivity is much higher than that of earth which means that they cannot delay heat exchange between exterior and interior as effectively. Among the different types of stones examined, limestone performs best in this respect, its heat conductivity being lower than that of both concrete and fired bricks.

Taking into account the strength parameters, there are significant differences between the two materials. While both work in compression-only structures, the compressive strength of stone is far greater than that of earth or currently used materials. Stone is extremely durable and the longevity and low maintenance needs of the material make it favorable from both an environmental and economic point of view.

Regarding seismic resistance, both earth and stone need to be complemented by other materials to increase their resistance against earthquakes. There is no specific legal framework for seismic resistant earth and stone structures but there are general regulations to be followed to overcome this constraint.

From an economic point of view, the overall costs of construction using natural or industrialized materials are similar. The prices of each are affected by different factors. The local availability of natural resources such as earth or stone reduces considerably the cost of material and transportation, but increases the required labor due to the duration of construction. Current building materials, on the other hand, require a lot of fossil fuels for manufacture and transport that is reflected in the price of material, though less human labor is required for construction. On a full life cycle basis, however, natural materials can be considered more economic as they reduce operational energy needs during the useful life of a building.

4. EARTH AND STONE CONSTRUCTION IN PORTUGAL

"The dreams must be bigger than the obstacles." (Arq.º Miguel Rocha)

The present chapter is focusing on the applicability of earth and stone in Portuguese contemporary architecture. It is considering socioeconomic, climatic and cultural aspects and is exploring the present-day tendencies of academic education, research and practice in the field. This chapter draws on the knowledge and opinion of architects, consultants, university professors and clients related to earth and stone architecture. Information was gathered through personal interviews which aimed to provide extensive, subjective information about the experience of the participants about the different aspects of construction and operation of buildings as well as about the current state of academic education in architecture concerning the topics of sustainability and natural construction materials. Three different sets of questions were invented to target the different groups of participants – architects, occupants of buildings and professors at universities. Each participant was given the same set of questions so that it is possible to cross-compare the answers. The interviews were based mainly on open-ended questions to explore the subject in its complexity and allow for a free expression of the participants. The result aims to formulate an up-to-date image of current potentials, opportunities and difficulties underlying the topic of constructing with earth and stone, through a diversity of points of view.

4.1. Climate and geography

Mainland Portugal shows great variations of both climate and geography on the north-south and the east-west axis. The influence of this diversity on Portuguese vernacular architecture was recognized already in the 1950's by the National Survey on Regional Architecture led by the Portuguese Architects' Association (AAP) (Simões et al., 2019). Among the aims of the survey was to present the richness of traditional architecture in the different regions of Portugal and to integrate these traditional models in "the recent Modern architecture style" (Simões et al., 2019).

The northern regions (Minho, Trás-os-Montes, Alto Douro) have a temperate climate with high precipitation rates (Simões et al., 2019). It can be characterized by cold winters with the presence of snow and frost, and warm summers. The southern regions (Alentejo, Algarve) have lower precipitation year-round and hot climate in summers (Simões et al., 2019). Rainfalls are more frequent close to the Atlantic coastline and becoming less and less so towards the interior of the country. In the inland areas of Alentejo, high temperature differences can be observed between winter and summer seasons.

According to the Köppen Climate Classification, Portugal has type C, Mediterranean climate with Csa (Hot-summer Mediterranean climate), Csb (Warm-summer Mediterranean climate) and a small area of BSk (Cold semi-arid climate) subtypes.

In the European Union, the territory is divided into winter and summer regions that set out criteria to design buildings taking into account the aspects of energy performance and human comfort. "The winter dimensioning is based on the concept of Heating Degree Days (HDD) adjusted by altitude and summer design conditions are based on external mean temperature (T_{ext}) also adjusted by altitude" (Marques et al., 2016). In Portugal, according to the current legislation in force (Decreto -Lei n.º 118/2013, de 20 de agosto) about climatic zoning, winter regions I1 (HDD<1300), I2 (1300<HDD<1800) and I3 (HDD>1800) and summer regions V1 (T_{ext}<20ºC), V2 (20ºC<T_{ext}<22ºC) and V3 (T_{ext}>22ºC) exist.

The high temperature characterizing the south of the country implies a particular importance of achieving good thermal comfort in buildings in summer. The high thermal inertia of earth due to its material properties and the characterizing thick walls have long proved to be an adequate material solution. The dryness of climate is also favorable for earth construction since it is vulnerable to humidity (Ribeiro, 1961).

The soil types throughout mainland Portugal are as diverse as the climate is. The north, center and part of the south of the country is formed by eruptive, metamorphic and sedimentary rocks (granite, schist, marble) while the south (Alentejo, Algarve) is characterized by clayey rocks, limestones and sandstones (Lourenço, 2002). "Ribeiro (1961) mentions the opposition present between the use of stone and earth in buildings, attributing the first material to the North, where the mountains are predominant and the stones available and the latter to the South, where the climate is drier and the lands flatter. The abundance of the clay is also in the origin of the designation of clay civilization when characterizing the South of Portugal." (Ribeiro (1961) cited in Correia Macedo (2009)). As Lourenço (2002) suggests, the dominance of earth construction in Alentejo results more from historical-cultural influences and economic and climatic reasons rather than from the lack of another raw material (stone). The numerous examples of earthen vernacular heritage located in Lower Alentejo is a testimony itself of the good climatic and geographical conditions of the region (Bicas da Silva, 2009) while the wide availability of stone – most often granite or schist – in the north of the country is illustrated by the rich vernacular heritage of the area.

4.2. Socioeconomic and cultural aspects

The distribution of population in mainland Portugal shows a significant contrast from north to south as well as from coastal to inland areas. The southern and interior regions are scarcely populated as opposed to the dense littoral and northern parts of the country (Simões et al., 2019). About two-third of the population lives in urban areas while there has been a continuing phenomenon of aging and depopulation of rural towns and villages (Simões et al., 2019). It is mainly due to limited employment opportunities for local young people. Simultaneously, rural farmlands are becoming more and more attractive in the eye of a growing number of people such as foreign investors or communities and families representing an alternative way of living (Simões et al., 2019). These trends imply a need and potential in the requalification of rural territories.

On a socioeconomic level, the use of earth and stone in contemporary architecture can contribute to revitalizing rural areas. The application of traditional construction techniques do not rely on external supply – the material and the skills required for its use being, ideally, locally available. Engaging skilled local labor indicates valorizing the traditional construction know-how and creating employment. It also guarantees that the profit remains within the community, giving a boost to local economies. Employing local builders and craftsmen creates job opportunities which can prevent the further abandonment of rural areas and slow down the migration to cities.

On a cultural level, constructing with earth and stone can reinforce connection to local vernacular traditions and create a harmony with the surrounding landscape. Complemented by current construction materials and techniques, new earth and stone constructions can respond to the simplicity of local vernacular architectural cultures as well as the climate while satisfying contemporary needs.

4.3. Current situation

Earth and stone constructions, their perception and favor of use have undergone significant changes in the past century in Portugal. Nowadays, emerging ecological thinking and concern about sustainability and authenticity represents a boost in reevaluating the qualities of these materials. After the resurgence of natural materials, especially of earth, in the beginning of the 21st century among a small elite, they are slowly becoming an alternative to reconsider. There are, however, many factors that make it difficult to implement projects on a wider scale, even if initiative exists. "There are some myths about construction with natural materials that are not real" – as remarked by architect Paula Miranda from ateliermob. It describes accurately the global image characterizing the attitude of the majority of professionals and non-professionals in Portugal today. Misinformation, lack of information and false judgment related to natural construction is present on several levels.

On the client's side, the image of poverty and outdatedness connected to the use of natural materials still prevails. This notion has a lot to do with the absence of national examples that could showcase the potential of earth and stone in contemporary architecture. Realizing example projects presumes the active engagement of local administration as well, yet there are no strategic policies formulated on this level.

According to the experience of some of the architects, the level of education of the client is also determinant in whether they are more open to using natural materials or not. In general, new construction of this kind is still regarded as out of the ordinary. Earth or stone are not part of the mainstream of construction materials nor of any kind of lobby. As a result, they are most often not considered as alternative options in construction by potential clients. Despite the regaining popularity of natural materials, it is a knowledge that is hardly present in practice and in the curricula of educational institutions in

Portugal. This is probably the main reason why a lot of architecture students and young professionals do not tend to consider applying them in projects.

Among architects, opinion on the use of earth or stone in new construction varies a lot. Some consider them as old-fashioned while others underline their good material properties and qualities in creating intense, powerful spaces of a unique character (Domingos).

Difficulties are manifold, among which is the lack of legislation and bibliography that could be a good reference to the design and implementation of projects using earth or stone (Rocha). In the case of earth especially, there is a need for new, comprehensive regulations that facilitate and encourage instead of restrict the use of this material, as architect Miguel Mendes underlines. The lack of information and institutional framework results in a scarcity of craftsmen and companies on the market which are able to carry out such projects. Limited supply implies higher prices which has an impact on the economic aspects of construction. Still, even with the necessary financial means it can be difficult to execute a project given the limited availability of skilled labor.

In spite of all these problems, as the next chapters reveal, there is a growing interest in natural construction materials from students, architects and clients as well. The related academic offer is expanding as a recently launched postgraduate course shows. Legal regulations are slowly following up with the new demands which indicates an intention of embracing alternative construction materials on a bigger scale.

The related themes are also promoted on such major international forums as the 2022 Lisbon Architecture Triennale – *Terra* explores "a more sustainable future where new paradigms reinvent our ways of place-making on a globalized planet". The Triennale is a powerful platform to disseminate knowledge and raise awareness among professionals and the general public about the pressing issues of the ecological impact of the built environment and the consequences of architectural decisions.

It all shows that steps have already been taken to move in a new, sustainable direction but there needs to be a more comprehensive strategy, a strong network of institutions and professionals and an active participation of relevant decision-makers to change the current status quo.

4.3.1. Academic education and research

Despite the renewing interest in sustainable architecture and natural materials, there are few educational institutions today that include the themes of earthen and stone architecture in their syllabus in Portugal. As described by architect Pedro Domingos, the current Portuguese educational system concerning architecture is very traditional and is based on the same curriculum for decades. There is a slow follow-up with the current needs and challenges the profession is facing today. Some topics are completely missing from the courses and the lack of information results in an intuitive decision-making process for students with limited tools, instead of objective, knowledge-based choices. Often, university courses do not provide the possibility for students to explore alternative solutions and understand the qualities of natural materials. In general, it very much depends on the teacher himself and their personal interest if these topics are included in class. Conversely, more and more architecture students and professionals are becoming interested in the subject of sustainable architecture and natural materials. Currently, however, it requires self-study and a strong personal initiative to satisfy this interest. It can most often take place in an informal way through workshops or specialized training courses, though, according to architect Miguel Rocha, there are few institutions in Portugal that provide adequate and satisfactory knowledge in this field. The aim of this chapter is, therefore, to provide an overview of the present-day possibilities students and interested professionals have in order to deepen their understanding on what natural materials can offer in contemporary architecture in Portugal.

One of the schools with the longest tradition of providing specialized technical training in traditional construction including earth and stone masonry building techniques is the Technical Training School of Rural Development of Serpa (Escola Profissional de Desenvolvimento Rural de Serpa - EPDRS). The course of Master Builder of Traditional Civil Construction had an important role in the recuperation of earthen construction techniques both in new builds and in the conservation of old buildings. The principal aim of the course was to provide more skilled craftsmen and experts in the field and to raise global interest in traditional construction techniques. The training consisted of theoretical classes and practical field work that included the implementation of a small scale project as the completion of the course. Providing the necessary infrastructure, students could gain hands-on experience "through constant contact with materials, machinery and tools" (Pereira Santos, 2005). Even though the school is still functioning today, due to the insufficient number of applicants, the above mentioned course is currently not available, according to Rocha. Lack of interest has most to do with the image of traditional craftsmanship as a non-lucrative profession for reasons previously outlined. Most often even students who had completed the course ended up working in current civil construction, as Lourenço (2002) remarks. The sensitization of the general public about alternative constructive solutions and creating a market for it could strongly contribute to making the related professions more attractive.

On the level of university education, the most notable institution in Portugal to include the themes of traditional construction materials and techniques and ecological architecture in its curriculum and research lines is the Universidade Portucalense (UPT) – the formal Escola Superior Gallaecia (ESG) – in Porto. The school is dedicated to disseminating knowledge on earthen architecture, the director of the Department of Architecture and Multimedia Gallaecia, Mariana Correia and some of the professors having been trained at CRAterre. Courses at UPT provide a deeper understanding of the characteristics of vernacular materials such as raw earth, stone and wood in the context of their potential in traditional as well as in current use in architecture (UPT, 2022). They aim to develop a better comprehension of the logic behind the choice of materials and constructive systems. From the first year on, students are presented with a wider range of alternative solutions that extends the scope of architectural tools they can work with. The relationship between architecture and its environment is also explored in terms of sustainable resource management and the environmental impact of construction. Besides the academic offer, the university has held exhibitions, conferences and seminars in cooperation with national and international institutions such as CRAterre, Proterra, Fundação Convento da Orada and Centro da Terra (Cdt) (Correia, 2005).

Through the Architecture and Heritage research line of the ESG research center, the university is investigating the topics of earthen architecture and sustainability, among other fields of study. Together with partner institutions, it has been coordinating various projects and publications which aim to improve scientific and technical knowledge related to earth construction (ESG, 2022).

On a postgraduate level, a novel one-year degree course on sustainable architecture has recently been launched in Porto, being the first of its kind in Portugal. The Sustainable-Sustainable Architecture Postgraduate course has been coordinated by the Escola Superior Artística do Porto (ESAP) and non-profit organization, Critical Concrete since 2020. It aims to provide an innovative learning experience with a focus on sustainability and participatory design in architecture (Critical Concrete, 2022). It questions conventional building practices and offers alternative approaches and methods, focusing on using natural materials and applying vernacular construction techniques in contemporary architecture. The programme has a hybrid format with online theoretical classes and practical hands-on workshops. The theoretical classes cover a wide range of topics from ecological construction principles and natural building materials with special focus on raw earth to vernacular building techniques and strategies for participatory processes. During the workshops, theoretical knowledge is put into practice through the design and construction of a project with local communities. The course offers a "transformative education" with international instructors from various different fields from architecture, urbanism and ethnography to art and social sciences. The formation of such a course in Portugal indicates an increasing demand for alternative educational methodologies which are responsive to current ecological and social challenges.

In Portugal, one of the organizations with the most comprehensive approach to develop earthen architecture is the Associação Centro da Terra (CdT). It is "a non-profit organization with the aim of preserving the existing heritage and promoting contemporary earthen architecture." (Centro da Terra, 2019)

CdT has been engaged in the organization of workshops and seminars, the participation in research programmes and the publication of specialized scientific and technical works. It has also been working on the establishment of legal standards and building codes related to earth construction. In order to "define steps for the elaboration of recommendations (guides) for construction with earth in Portugal" (Associação

Centro da Terra, 2020a), three roundtable discussions were organized with a focus on thermal and structural performance in 2018 (Associação Centro da Terra, 2020b). It involved national and international specialists in the field, including designers, engineers, researchers and builders. The aim of the series of discussion was to better understand the thermal and structural behavior of earth and to highlight strategies for a future improvement of disseminating knowledge to achieve a more widespread use of the material.

According to the president of the Board of Directors of CdT, Ana Perdigão Antunes, interest has been growing significantly about earthen architecture in the year of 2022 in Portugal. It is reflected, among other things, in the approach of the organization by the Ordem dos Arquitectos (OA), the most important national association representing the profession of architecture in Portugal. This inquiry made for courses that target the topic of earth construction is "a big step" indicating an intention for change in the current practice of architecture. As a result, a training cycle is being organized by OA in partnership with CdT starting in 2022. It is called Architecture and Construction with Earth and it is offered to students and professionals alike. The training aims to provide first-hand experience of earth construction and its specific techniques with a practical approach complemented by theoretical components. The educational methodology of the training cycle is based on the principle of learning by doing, encouraging a proactive attitude in the participants. The courses cover the aspects of both rehabilitation and new builds on two levels, taking into account the degree of previous knowledge and skills of the participants (beginner or advanced). The construction techniques of adobe, CEB, rammed earth, tabique and plasters and mortars are included in the training offer together with a general introductory course on the material. Upon successful completion of the course, a Professional Training Certificate is issued.

At the same time, despite the growing interest in earth construction, the organization has been losing members over the recent years, an unfortunate change remarked by Rocha. Cdt has become less active and there is an overall declining participation in what was initially set as the organization's goal. This tendency, however, might change in the future along with the recognition of the importance of a strong networking required to effectively develop earth architecture in Portugal.

Another Portuguese association of reference that is actively involved in the development and investigation of traditional construction techniques related to ceramics and raw earth and the dissemination of knowledge about them is the Oficinas do Convento – Cultural Association of Art and Communication (OC). It is "a non-profit cultural association, with its registered office at Convento de S. Francisco, in Montemor-o-Novo" (Oficinas do Convento, 2022a). It is engaged in activities in a wide range of different fields, among which the most distinct is the Oficinas da Cerâmica e da Terra (OCT - Ceramics and Earth Workshops). OCT is carrying out its activities in three complementary areas: in the Ceramics Research Center, the Castle Hill Pottery and the Earth Laboratory. The latter is "dedicated to the continuous research of traditional construction techniques seeking to preserve the local building culture" (Oficinas do Convento, 2022b). It is developing ways for the adaptation of traditional earth construction techniques to contemporary needs including experimentation with new techniques and methods. The laboratory, also available for the public, provides infrastructure for material testing and analysis and for the production of earth building components (mud bricks). The Earth Laboratory is dedicating a full research line to the production of CEB. Besides this, the Oficinas do Convento offers technical assistance and consultancy for earth construction as well as for research and educational projects.

The Ceramics Research Center aims to "solve gaps on a national level" through the performance of training activities. It offers workshops in an autonomous or guided format including sessions dedicated to the use of clay. Being part of the Building Impact Zero Network (BIØN), the Oficinas do Convento has a wide outreach in sharing knowledge to international collaborators and participants on the principles of bio-construction and participatory processes. BIØN is "a network of organizations active in low impact building techniques" (BIØN, 2022). It aims to share knowledge and practices in alternative ways of building using local materials. The network has eight partners from six different countries. Through LearnBIØN, a series of training programmes, the partner organizations and project participants completed prototype structures in the involved countries, each targeting specific natural materials and related techniques. OC hosted two practical workshops in the years 2017 and 2021 with the themes 'Design and Build with Compressed Earth Blocks' and 'Design and Build with Poured Earth', respectively. The workshops offered hands-on experience of building with local communities and resources and concluded with the realization of a 1:1 prototype. In 2017, a prototype for an artist residence was constructed using locally produced CEB (Figure 21). The building, located at the OCT, has a vaulted structure and stone foundation. The building course aimed to illustrate the potential of CEB to meet contemporary architectural needs and standards. In 2021, a storage space was constructed using the poured earth technique. The workshops were complemented by theoretical lectures and study visits to allow for gaining a deeper understanding of the given topics.

Figure 21 - Prototype for an artist residence in CEB (source: BIØN, 2022)

Due to its diverse activities in research and education, the Oficinas do Convento proves to be a relevant complementary platform of training for students, professionals or interested individuals to develop their knowledge and experience in earth construction techniques.

A progressive Research and Development laboratory in Portugal, the Advanced Ceramics Lab (ACL) has been exploring the integration of ceramic and natural clay-based composite materials in additive manufacturing (AM) processes in the design and production of building envelopes (ACL, 2022). ACL is based in the Design Institute of Guimarães and is working on research projects with international partner institutions such as the Delft University of Technology, the Netherlands and the Darmstadt University of Technology, Germany.

AM, or 3D printing, has a big potential in revolutionizing the building industry. It is a cost and time-effective method that reduces material waste while allowing for customization and geometrical freedom in the design process. When combined with natural materials, AM can contribute to the creation of a more sustainable built environment. For these reasons, ACL started to explore the potential of additive manufacturing for the building industry through a range of research projects. Between 2016, the foundation of the laboratory, and 2018 ACL developed a set of prototypes used for testing and optimizing the ceramic extrusion material for 3D printing and evaluating the formal and structural constraints inherent in the method. In the scope of the KERAMOS R&D project between 2018 and 2019, ACL was focusing on researching and creating multifunctional ceramic and composite architectural elements with a sustainable performance. The prototypes include components for façade cladding, hexagonal blocks for a vaulted shading system and column systems (ACL, 2019) (Figure 22). The wall components offer different ways of assembly resulting in a multifunctional solution that allows for creating opaque or ventilated façades. The thermal and structural performance of the prototypes are optimized by parametric tools. Their design is based on a free-form approach, taking maximum advantage of the AM method. The outcomes of the KERAMOS project were presented in the exhibition SHARE – "Innovative and multifunctional ceramic products" held in the University of Minho in 2019. The exhibition aimed to disseminate the results of the investigation and "boost the commercial and industrial attractiveness" of the products.

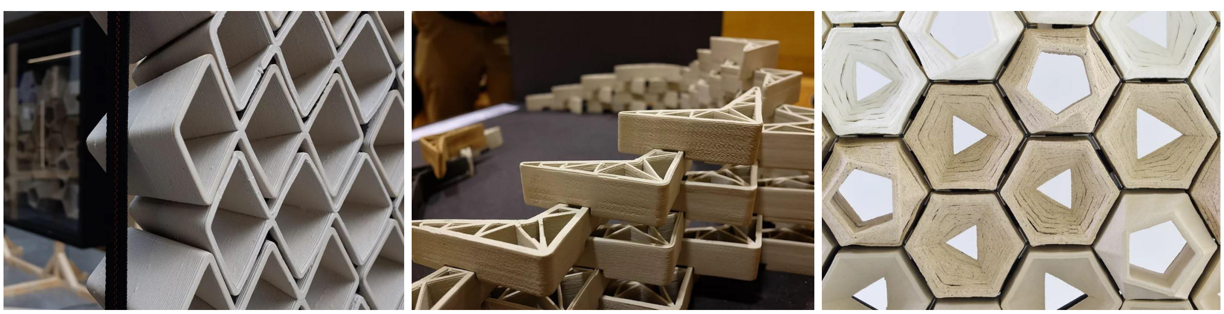

Figure 22 - Prototypes of the KERAMOS project (source: ACL, 2022)

ACL is one of the few initiatives in Portugal to explore the potential of combining advanced digital manufacturing technologies with natural clay-based materials. This way they are taking an important step in the direction of finding sustainable, contemporary alternatives for current construction methods and materials.

Looking at the current state of academic education and research in Portugal, it is possible to see some intention to recover and even to take to another level the knowledge connected to raw earth and natural stone and the related techniques. However, the initiatives are quite isolated and a general strategy and networking for their implementation is missing. As remarked by some of the interviewed architects and university professors, architecture education in Portugal needs to be changed structurally (Domingos). Architecture and engineering knowledge should be more integrated and the theoretical and practical components more balanced. The range of architectural tools as well as the themes taught at university need to be widened in order to offer more alternatives and choices for students.

Examples could be taken from past initiatives where training and workshops in natural materials (raw earth) and techniques were organized to employ young people in the restoration of heritage buildings and the construction of new ones – this is how the new market of São Luís was realized (Beirão, 2005). Events of this kind, if organized within the framework of university courses, could provide a good opportunity to gain valuable skills and establish networks between students and professionals in the field, assuming, at the same time, the active engagement of local authorities as well.

4.3.2. Practice

The present chapter aims to outline examples of the contemporary use of raw earth and natural stone in Portuguese architecture. The selected projects, constructed over the course of the past decade, represent a versatility of application of the two materials in different contexts and programmes. They reveal individual approaches and visions for adapting them to the architectural needs of today.

"I think there is a tradition and history of Portuguese architecture that created a kind of matrix for what is done today", as explained by architect Pedro Domingos (YouTube, 2017). The legacy of being a country with limited economic means has defined certain conditions and principles for the utilization of resources and the territory and, inherently, a specific "way of working". Trying to understand the complexity and add to the context in which the architect is working has been the basis to do architecture. Working with few means and readily available resources, unimposing to the landscape, are characteristics inseparable from this working method. Growing from an economic necessity, the cultural aspects of this heritage are still present in today's architecture, reflected in the simplicity and purity of spaces and aesthetics. This continuum is being reinforced on an educational level as well. Students are encouraged to work according to these methods and principles, finding their own expression within the context of such legacy.

Today, economic considerations in architecture are still of primary importance in Portugal. From one side, the ecological aspects of construction are related to the lifetime of a building and the usability of space. "Timelessness is the greatest sustainability", as designer Michael Anastassiades advocates (Primeira

Pedra Conference, 2022). To create resistant, atemporal spaces that are able to adapt to different requirements and serve changing needs over time support this idea in the practice of many Portuguese architects. As opposed to this stands the notion of circularity. As architect Anna Heringer puts it, "the importance of durability is overestimated. We don't build to last forever. Nobody builds for eternity." (Heringer, 2022) It suggests an organic approach closer to the character of natural cycles where adaptation happens through constant change. In construction, when buildings are erected using chemically unprocessed organic materials such as raw earth and natural stone, they can be returned to the environment at the end of their useful life, without posing significant negative impact on it. Later, when necessary, the same material can be recovered and used again in new construction. A valuable potential of natural materials is the possibility of their use in a circular economy. Some of the projects presented in this chapter illustrate the different ways of utilizing this possibility.

4.3.2.1. Contemporary examples of earth constructions

As referred before, demand for natural construction in Portugal has been growing considerably in recent years. The number of clients, both Portuguese and foreigners, requesting earth to be used in the construction of their projects has been rising significantly (Mendes, Schreck). Agreement between architect and client and a good congruence of intention and commitment is essential when building with this material, given the underlying difficulties to such construction. As architect Cristina de Mendonça from EMBAIXADA arquitectura suggests, both "architect and client have to have a will to do it [earth construction]" in order to effectively overcome the related constraints. The motivation behind the use of natural materials, outside the self-build context, is diverse. Often it is derived from the desire to recover and rehabilitate old buildings in order to preserve their original character. Besides, many decide to move from cities in quest of a closer connection to nature – this attitude being also reflected in the materials they choose to construct with. It is an example of a specific way of thinking that reveals an ecological attitude and sensitivity to local cultures and to the different dimensions of sustainability.

Despite the trend mentioned previously, earth constructions in Portugal still suffer from a lot of negative connotations. Regardless of its numerous advantages, the image associated with the material is, more often than not, unfavorable. It is therefore important to have good quality contemporary projects that are able to convince with their aesthetics. "Architecture should be beautiful, functional, responsible and emotional", architect Miguel Mendes reflects. Beauty and the emotional effect of building are the two most powerful factors to affect people in a positive way and overcome cultural resistance and negative perception.

In Portugal, there seems to be two distinctive approaches to building with earth, each constituting one end of a gradient where the next set of projects can be positioned. One advocates a traditionally conceived earth construction based on traditional methods and vernacular principles where the result is perceived as the continuation of an old legacy reinterpreted to fit the requirements of each context. This approach supports the minimization of the use of industrial materials in the construction process, replacing, whenever possible, concrete and steel with natural elements such as stone or wood. It builds strongly on vernacular architectural traditions as the best reference for bioclimatic design principles. Parallely, there exists another approach to earth construction, one of a modern and experimental character. It is based on the will to take advantage of the valuable assets of raw earth in ecologizing construction, achieving better indoor comfort and reviving traditional know-how. However, it promotes contemporary aesthetics and principles and it does not reject the use of industrial materials for complementary structures. The next projects aim to describe the characteristics of both perspectives. The examples are taken from similar climatic contexts – coastal and inner Alentejo, according to material availability – which implies similar comfort requirements imposed on all of them.

Housing, Odemira

One of the pioneers to reintroduce earth construction in Portugal during the turn of the century is architect Henrique Schreck. Having learnt from his master, architect Bartolomeu Costa Cabral, he has been realizing architectural projects from the end of the 80’s up until the present day. He has been working both independently and in collaboration with Visionarte atelier de arquitectura almost exclusively with raw earth. The guiding principles of the architect are very strong and give consistency to his work. "The understanding of the natural cycle leads me to prefer simplicity to the self-centered attitude of personal affirmation", he states in an interview (Jornal sudoeste, 2020). Working for others, constructing with the least impact possible, taking into account the context, the landscape and the resources are essential characteristics of his philosophy of architecture. His buildings are rooted very deeply in the traditional vernacular architecture of Alentejo, the features of which he is employing to improve the living conditions of the future inhabitants of the buildings he constructs.

A representative example of his works is his own house that he designed and constructed himself in 1998. It is located in São Teotónio, Odemira in the south of Portugal. The single-storey house consists of three rectangular volumes enclosing a patio. The public functions of the house (kitchen and living room) are separated from the private ones (bedrooms and bathrooms). There is also an office area situated in the loft of the house.

The architect seeked a fullest possible integration of the construction to the terrain and surrounding landscape. The interior spaces of the building follow the inclination of the natural terrain. The use of natural materials is favored in all parts of the building (Figure 23). The walls of the house are made of locally available earth using the rammed earth technique. The roof consists of a timber structure insulated with a 2cm cork layer. The openings of the building are kept relatively small to control heat gains, which, together with the thermal inertia of the thick walls, result in a good indoor climate during summertime. In the thermal comfort assessment of the house, the occupant reported a ‘fresh’ indoor climate on a 7-step scale from ‘very fresh’ to ‘very warm’. The enclosed northwest-oriented patio provides an outdoor extension of living spaces while ensuring proper sun exposure both in winter and summer seasons.

Figure 23 - Exterior and interior views of the house in Odemira (source: Correia Macedo, 2009)

Besides the good physical properties of earth concerning hygrothermics and inertia, intangible material assets were also taken into consideration. "Monotonous and absolutely functional spaces do not lead to happiness no matter how safe and comfortable they are", architect Schreck reflects. Earth is capable of conveying an emotional expression that goes beyond functionality, providing an additional rich layer to the conceived spaces.

By examining the architect's works, a very organic, intuitive approach emerges. "I’m not ecological, ecology is within me", he expresses almost as his ars poetica. Articulating his own language built closely on traditional knowledge, the architect is continuing the old legacy related to earth construction in Portugal thus contributing to its preservation and further development.

Turismo Rural, Aljezur

The following project is the development of a rural tourism facility completed by Colectivo Aljezur Arquitectos, an architecture and design studio based in the south of Portugal. The guesthouse is located in Carvalhal, Aljezur near the Atlantic coastline, inserted in a rural landscape surrounded by vineyards (Figure 24). The building is composed of several interconnected rammed earth volumes, each featuring a living room, kitchen and bedrooms with private bathrooms.

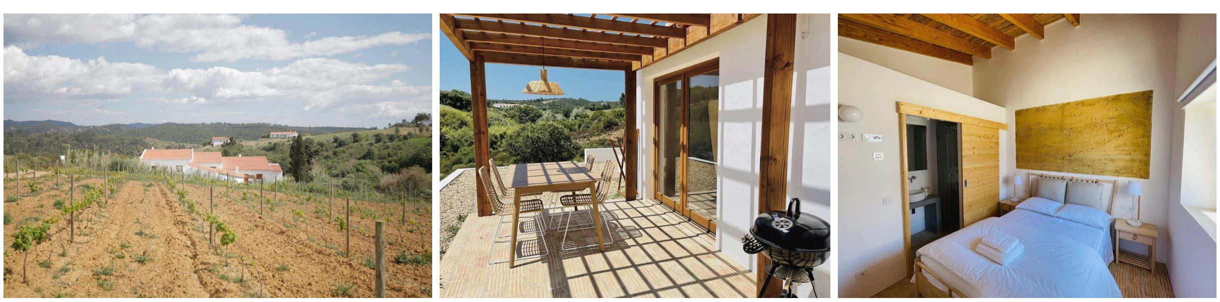

Figure 24 - Exterior and interior views of the guesthouse in Aljezur (source: Instagram, 2022)

Colectivo Aljezur has a strong preference for natural materials such as earth, stone and wood which is reflected in this project. Whenever possible, the studio opts for the use of locally available resources which have diverse advantages according to architect Raquel Melo Morais. The use of the existing raw material reduces transportation needs and the carbon footprint of construction. Raw earth and stone can easily be recycled and used in new construction over time. Earth provides good thermal comfort, a balanced indoor humidity and excellent aesthetic qualities. When well designed and protected from the top and bottom against direct humidity, earth walls require hardly any maintenance.

The guesthouse has a simple volumetry reflecting the vernacular architectural language of the area. The load-bearing external walls of the building are made of rammed earth plastered with lime on both the interior and exterior sides to protect the walls. The pitched roof is made of timber with an interior layer of cane. Most of the windows of the building are relatively small to avoid excess solar gains during summer. Bigger openings are applied by the accesses to the terraces which are protected by wooden pergolas.

Based on the experience of the studio, the biggest obstacle to natural construction is the lack of skilled labor. This could be overcome by the promotion of related courses and training among construction companies, the architect suggests. Another constraint to building with earth is its sensitivity to climatic conditions. Construction time can be prolonged considerably if weather is unfavorable – which is true for current construction materials as well – and the drying of the material takes significant time. Earth is also vulnerable to some atmospheric agents such as salination near the ocean but proper protection can ensure its durability. Although there are some limitations and difficulties to earth construction, the associated "obstacles can be overcome as long as there is a willingness from the side of the designer and the client to use this material and techniques".

The example of the guesthouse shows the approach of Colectivo Aljezur to create buildings of contemporary aesthetics while drawing on local vernacular traditions and bioclimatic principles. The works of the studio represent a conscious use of material, a knowledge that was gained and developed over time based on the experience of architects and master builders in the field. It allows for taking advantage of the valuable material assets to the fullest while showing its potential of creating spaces of modern standards for present-day use.

Herdade da Cardeira, Borba

The next project presents the extension of the winery of Herdade da Cardeira through new rammed earth volumes (Figure 25). The winery, located in Borba, in the Alto Alentejo region, was completed in 2020 by EMBAIXADA arquitectura. The new complex features a housing volume, bedrooms, a reception and a tasting room with kitchen for guests, according to the needs of the Swiss clients, Erika and Thomas Meier. The volumes are organized on and around a natural hill in a way to separate the private and public areas.

The reception and the tasting room is located closer to the existing cellar, while the living area is on the top of the hill, separated by a pool from the bedrooms that can be accessed from a lower level.

Figure 25 - Exterior and interior views of the winery of Herdade da Cardeira in Borba (photos of the author)

The guiding design principle was to integrate the new construction with the surrounding agricultural landscape and vineyards and with the preexistences (EMBAIXADA, 2022). To address the rural context, the local climate and out of environmental concerns, the volumes were chosen to be constructed in unstabilized rammed earth which was made possible due to the availability of good quality soil on site. The 50cm thick walls provide good thermal inertia, the advantage of which is most noticeable during summertime – there is no need for a mechanical cooling system. Instead, the passive measure of natural ventilation is used with the help of skylights. Still, the indoor thermal comfort in summer is described by the owner as ‘warm’ on a 7-step scale from ‘very fresh’ to ‘very warm’. During winter, an additional floor heating is necessary to provide sufficient thermal comfort. Specific data with regard to indoor temperature and humidity values are provided in the next chapter where the hygrothermal behavior of the building during summertime is analyzed in more detail and compared to the behavior of a traditionally conceived rammed earth house discussed earlier in this chapter.

Construction with earth in the case of Herdade da Cardeira was made relatively easy thanks to a good network of professionals involved in the project. The contractor of earth construction had ample experience in the field and provided a skilled team and all the necessary equipment for the execution of the walls. Architect Henrique Schreck was consulted for the analysis of soil and for the rammed earth design. The composition of the volumes is based on contemporary principles quite contrary to traditional earth construction which is justified by the programme of the building. According to the owner, the most important asset of the place is the landscape itself – dissolving the distinction between exterior and interior by letting the surrounding landscape into the building through big sliding windows gives a feeling of spaciousness to visitors. The openings and terraces are protected against excess solar gain by pergolas intended to be overgrown by greenery. The geometry of the volumes is relatively complex and their organization scattered when compared to the compact rectangular volumes of traditional vernacular buildings of the region. It is explained by the mixed use function of the place and the intention to simultaneously separate and integrate the different programmes. The materiality and constructive systems used in the project are diverse. The foundation walls and the ring beam over the load bearing earth walls are made of reinforced concrete which provide protection against seismic loads. The responsibility for the construction was assumed by the structural engineers. The roof, to keep it as light as possible, is constructed in steel with a timber layer on the interior side. The non-load bearing walls are made of bricks. The interior of the walls are covered with natural lime plaster while on the exterior the rammed earth was intended to be left exposed. The intense weathering and erosion of the corners, however, required the addition of a protective layer of lime plaster as well, one year after completing the project. According to the client, there was no need for any further maintenance since then. The only disadvantage highlighted by the owner is the longer duration of construction due to the use of earth and the traditional, manual construction techniques. In the context of lacking technology to standardize and control the process further in Portugal (e.g. prefabrication), it is a factor that both the architect and the client need to accept. As Erika puts it, longer construction time "is the very nature" of building with earth. This aspect also had an impact on the overall construction cost. As the architect explains, the costs at the time were the same compared to a similar project built fully in industrial materials. While the main construction material was readily available for free, the long building process raised the cost of labor significantly. Additionally, the scarcity of companies that specialize in the execution of earth structures increased prices even further.

The project proved to be an outstanding example in the area showing the potential of earth as a building material. According to the owner, the project raised a lot of curiosity and attracted many people from the region where this technique has otherwise been quite forgotten in the building practice.

Casa da Vinha, Montijo

The following project is a residential building located in Montijo, in the Lisbon region in central Portugal (Figure 26). The Casa da Vinha was completed in 2015 by blaanc arquitectura. The single storey house is situated on agricultural land surrounded by vineyards. It consists of three interconnected rectangular volumes with different functional zones, also distinguished by their materiality (blaanc, 2022). A rammed earth volume houses the common areas, kitchen, dining and living room, while the private functions, bedrooms, office and bathrooms, are placed in the remaining two concrete blocks.

Figure 26 - Exterior and interior views of the Casa da Vinha in Montijo (source: blaanc, 2022)

Demand for a sustainable solution that enables a strong fusion with the surrounding landscape was the main motivation behind the introduction of a rammed earth volume. The architects, Ana Morgado and Maria do Carmo were confident in the added environmental and aesthetic value that the technique represents. The qualities of earth to create good thermal and acoustic comfort inside the house and to regulate indoor humidity were taken into consideration. Besides that, the project has a sociocultural importance in reviving the traditional know-how and forgotten historical value connected to this technique that has a strong local legacy. The architects believe that creating a hybrid building by combining tradition and modernity allows them to take advantage of the best of each (archdaily, 2015a).

The design of the building is based on modern principles. The compact volumes are covered by a flat roof and feature generous openings with large spans. According to the architects, the biggest constraints derive from achieving the contemporary aesthetics suggested by these options in a rammed earth structure. To overcome these constraints, special solutions were required. The door frames, made of laminated wood, were used as bracing elements and as remaining formwork for the rammed earth at the same time. Two buttresses were introduced on the longer walls in order to improve structural stability and resistance against tensile forces. The rammed earth was reinforced with fiberglass mesh in between the layers and on the corners of the volume which allowed the construction of continuous earth layers without vertical joints. The exterior walls are left exposed but are protected by an external layer of water glass and casein. The flat roof consists of laminated wooden beams that are attached to the upper lintel and covered with sandwich panels. The big openings of the western façade are protected from solar gains by an attached terrace on the entire length of the wall and a pergola. The remaining two volumes are constructed in concrete and brick masonry with external insulation.

The earth construction was executed by the company JP Bernardino Lda - Ecological Constructions, a knowledgeable team with a lot of experience in this technique. The material was taken directly from the site and also from 50km away to complement the high sand content of the locally available resource. The walls were made using mechanical compression. Due to good design and execution, there has been no need for any maintenance so far. Regarding the cost of construction, there was no significant difference between the rammed earth and the concrete volumes, according to the studio.

The Casa da Vinha is a good example of adapting earth construction to modern functional and aesthetic needs. Through implementing projects of this kind, the studio intends to promote the material and related techniques, especially in the context of developing countries.

The previous examples show a diversity of attitudes to building with earth. It ranges from a traditional to a contemporary approach. The works of architect Henrique Schreck constitute a representative example of the former. This approach can be characterized by the adoption of a traditional expression drawing on vernacular principles. The buildings are composed of simple, rectangular volumes with pitched roofs, unimposing to the landscape, they adopt small openings to minimize solar gains and a conscious orientation. They usually feature pergolas or other shading elements on the most exposed façades. Their material palette is rich, though they are trying to focus on the use of natural materials.

The contemporary approach reflected in the works of Herdade da Cardeira or Casa da Vinha accepts that "ecological discourse is not a negation of an industrial cultural and economic context" therefore, "there is a need to search for an architectonic language that does not deny this contemporary condition which is simultaneously critical of and in debt to industrialisation" (Carvalho et al., 2005). This approach welcomes the complementary use of industrial materials and modern techniques (mechanical compression) in an experiment to find a contemporary expression for earth construction – the projects present complex, irregular volumes with flat roofs; generous openings are applied in order to achieve spacious, bright spaces. Such novel options require alternative solutions which make them feasible, that can be a strong impetus to bring Portuguese earth architecture forward.

The previous examples indicate that it is possible to achieve a wide range of different architectural expressions and fulfill the need of diverse programmes in earth construction. They also show that, with a knowledgeable team of craftsmen and builders, earth construction can be a relatively easy process with high quality results. However, it is also apparent that a good choice of material alone is not enough to create an environmentally conscious building with low energy consumption and good indoor comfort. Solar gains, orientation and other passive strategies need to be taken into account to make the most out of good material properties as the thermal measurement results in Chapter 5 justify. There is always a relation between contemporary needs (such as spaciousness and abundance of light) and their ecological implications (more solar gains and energy consumption to adjust indoor comfort). It is therefore important to synchronize the needs of inhabitants and the consequent impact of the construction on its environment.

4.3.2.2. Contemporary examples of stone constructions

With regard to the use of natural stone in contemporary Portuguese architecture, the viability of newly quarried material proves to be questionable due to economic and environmental reasons. Stone quarries such as the Arrábida lime quarry or the Estremoz marble quarry generate a lot of waste and pollution and modify the surrounding natural landscape. According to a resident of Borba, the activity of the Estremoz quarry has a significant impact on the everyday lives of people inhabiting the area. Apart from the pollution and the visually imposing presence of the huge piles of marble waste, the disused pits of extraction are left exposed without surveillance which poses a danger in itself and which has already caused accidents.

The inherent logistics to stone such as its extraction, transportation and execution make it a rather expensive and energy intensive solution. Consequently, and as underlined by architects with related experience, the present-day potential of stone is primarily in the use of already existing material such as the reuse of existing buildings or resources from ruined ones but also in the reutilization of quarry waste mentioned in the previous chapter. The next set of projects present sustainable examples for a diversity of different applications of the material in new construction, in line with the above-outlined potentials. They reveal different contexts and approaches to utilizing this abundant resource. The examples are taken from central and northern Portugal where stone constructions are more common due to material availability.

Casa dos Feitais, Mangualde

The following project is a rehabilitation and extension of an agricultural complex into a guest house in the rural center of the village of Contenças de Baixo in the north of Portugal (Figure 27). The project was completed in 2015 by Atelier José Lobo Almeida.

Figure 27 - Exterior and interior views of the Casa dos Feitais (source: archdaily, 2015b)

The complex consists of a two-storey stone house, dating back to 1870, and other annex buildings. The latter, being in bad condition and not fitting the new programme, were demolished. The main building was kept due to the fine quality of its construction and was complemented by a new volume to house the accommodation units. The programme of the tourism development is distributed in a way that the common areas are located on the ground floor of the existing house, while part of the accommodation units are on the upper level and part of them are in a new two-storey building (Espaço de Arquitetura, 2017).

The outer walls of the new volume were constructed using the stone masonry resulting from the demolished buildings on the land. It was a rational, sustainable choice to reuse the already existing material in the project and, given the availability of a skilled stone mason in the village, the process was relatively easy. In the absence of specific legislation for stone constructions, the general rules for thermal and structural performance of buildings were used in the project. The new volume has a simple rectangular layout with a double layer of external walls. They are made of stone masonry on the exterior and of bricks on the interior, with a core insulation in between. This way, the building does not require any mechanical heating or cooling system. It was necessary to complement the stone structure with additional insulation because of the example of the original house. It has single layer stone masonry walls with an insulated timber roof. The thermal comfort of the building is described by the architect as slightly cold in the winter, therefore requiring heating. During summer, however, there is no need for a complementary cooling system to adjust indoor temperature. Stone is only used as an exterior load-bearing structure – both buildings have concrete floor slabs for acoustic reasons and brick partition walls.

The biggest constraint described by the architect is the size of achievable spans when working with stone. The living rooms, situated on the upper floor of the new building, are oriented towards the surrounding mountainous landscape. They thus required big openings to take advantage of the view and natural light. While it was possible to create smaller windows that serve the bathrooms and bedrooms with stone lintels, the big openings of the living rooms were bridged by a timber ring beam. The house offers two different images defined by this constraint – a traditional look towards the garden and the interior of the plot and a modern façade overlooking the landscape.

The durability represented by the preexistences and the quality of stone to age nicely are highlighted by the architect as some of the advantages of working with this material. No maintenance of the stone walls have so far been necessary. Financially speaking, at the time of building, the project proved to be cheaper compared to concrete construction. It was because both a skilled workforce and a big part of the necessary construction material was readily available. Today, though, with rising labor prices and the cost of newly quarried stone it would probably be a cheaper option to build fully in current construction materials, as the architect argues.

Casa de Walter e Christiane Grünecker, Pedrógão

The next project presents the reconstruction of a residential building located in Figueiró dos Vinhos in central Portugal completed in 2018 by ateliermob (Figure 28).

Figure 28 - Exterior and interior views of Walter and Christiane's house in Pedrógão (source: ateliermob, 2022)

The reconstruction took place after a large fire in Pedrógão Grande spread and destroyed many buildings in the surrounding area in 2017. The rebuilding was part of a large-scale project of rehabilitation funded by the Calouste Gulbenkian Foundation to indemnify residents who suffered losses. The main objective of ateliermob was not simply to replace the lost houses but to "improve the living conditions of local communities" (ateliermob, 2022). In the case of Walter and Christiane's house, it was only the stone walls that resisted the fire. A complete structural and functional reorganization, built within the original volume of the house, was necessary to answer the demands of the German couple. The programme is distributed in the two-storey building according to their level of privacy. The common areas, kitchen and living room, are located on the ground level and the private spaces, bedroom and office, are on the upper floor.

The remaining stone after the fire was recovered for the new construction as a remembrance of the original building. Using the readily available material was a sustainable choice while it also guaranteed better quality than most current construction materials. Besides that, it already proved its resistance to fire, a major concern of villagers after the incident. Building in stone reinforces local vernacular traditions and contributes to maintaining a coherent image of the area, as architect Paula Miranda highlights. Skilled local craftsmen were available and employed in the reconstruction projects. It guaranteed good quality results while it also allowed for the preservation of the disappearing know-how related to stonemasonry.

The clients, Walter and Christiane, were much concerned with the sustainability of construction and opted for the use of natural materials whenever it was possible. As opposed to the owners of other reconstructed buildings realized within the same context, the German couple was more open to different solutions than the Portuguese owners, as explained by the architect. While most villagers wanted to avoid the use of wood in the new houses in fear of fire, the house of Walter and Christiane is made of timber roof and floor beams instead of concrete. In order to comply with general structural regulations however, a reinforcing concrete layer was projected on the interior of the stone walls. It was done even despite the calculations of the structural engineer which verified the stability of the walls without such support. It conveys a feeling of mistrust still prevailing about this material, originating in the lack of specialized regulations. Besides that, the original stone blocks were kept visible wherever it was possible – there is no additional external insulation except for a cork insulation layer in the roof. The thermal performance was guaranteed following general regulations. According to the clients, there is a need for additional heating during winter, though.

Regarding the cost of construction, there is no significant difference when compared to building with 'conventional' materials. When contrasting two scenarios, the costs balance themselves – gaining on one factor while losing on another. In this case, the main construction material was readily available and there was no need for insulation nor additional coating. The stone walls do not require maintenance, only the timber elements. At the same time, stone construction usually takes longer and requires specialized workers which increases the price of labor considerably. In the case of current constructions, the pattern is quite the opposite – less is spent on labor and more on the material. As the architect reflects, using newly quarried stone would have increased the price of the project significantly.

ARH House, Alcanede

The ARH House was completed by phyd arquitectura in 2021 (Figure 29). It is located in Alcanede in central Portugal (PHYD Arquitectura, 2022). The two-storey building houses common spaces and bedrooms on the ground level and two other suites in the upper volumes.

Figure 29 - Exterior and interior views of the ARH House in Alcanede (source: phyd arquitectura, 2022*)*

The main concern of the studio is to use local materials in their projects whenever possible – "to think global and use local", as architect Paulo Henrique Durão explains. The elongated ground level volume of the house is made of waste material from a nearby stone quarry. The reuse of stone blocks from industrial extraction represents a sustainable approach and verifies the potential of quarry waste in the construction industry. The blocks had to be cut to size which constituted the only cost associated with the material in the project. The floor slabs and the structure of the upper volumes are made of reinforced concrete. The building has a simple rectangular layout with a flat roof. On the southern façade, recessed glass walls lay behind a loggia formed by stone columns and walls. The loggia provides shading during summer while it allows for solar gains during winter. The northern side is composed of a perforated stone wall. Due to the good thermal inertia of the thick stone walls, there is no additional external insulation applied.

One of the biggest challenges to stone construction, as highlighted by the architect, is legislational. Stone, not being a certified building material, is not considered in regulations, therefore it requires special measures to overcome this obstacle. Another challenge is to incorporate contemporary technical infrastructure in stone construction. It needs both the architect and the engineer to think “outside the box”. At the same time, stone offers a good quality final result with low maintenance needs. The cost of construction shows a similar pattern as was mentioned earlier. The material comes free and only needs to be standardized to be used while the cost of labor is relatively high. Construction costs strongly depend on the current market conditions as well.

The ARH House shows an example of achieving a new, contemporary expression in stone construction using local resources – it presents a different, progressive way of working with this material compared to the previous projects.

JA House, Guarda

The next project presents the conversion of a stone ruin into a residential building (Figure 30). The JA House is located in Guarda in the north-center of Portugal and was completed in 2014 by Filipe Pina and Maria Inês Costa. The house features two volumes connected in the middle by a patio and a staircase. The ground level houses the public areas such as the living room and the kitchen, and the second floor accommodates the private functions such as the bedrooms and a library (archdaily, 2014).

Figure 30 - Exterior and interior views of the JA House in Guarda (source: archdaily, 2014)

The main principle of the architects was to "separate the new and the old construction" (archdaily, 2014) – the stone building represents the preexistences and is complemented by a new concrete volume. "The house was meant to combine the rural and the urban lifestyle." (archdaily, 2014)

The materiality reflects a contrast between the harsh granitic and concrete exterior and the warm timber and white plastering of the interior. The two masses "were sculpted in the same way". The front facade conveys a feeling of integrity – the volumes are of similar dimensions and the distribution and the size of the openings are closely related. Both the new concrete volume and the existing stone walls were complemented by insulation and a hollow brick layer on the interior to provide good thermal comfort. The durability of stone makes maintenance unnecessary and due to its persistence it is able to age nicely. The main constraints related to stone construction are identified by the architects as the disappearing skilled labor, the lengthy duration of construction and the limited size of spans and openings. The latter can be overcome by the introduction of other materials that are able to withstand tensile forces.

Creating a hybrid building by complementing traditional preexistent constructions offers another way to make use of the otherwise decaying stone heritage of the region. By the necessary measures (insulation, extended material palette) they can be adapted to the contemporary requirements of living.

The projects selected in this chapter, though diverse in terms of location, programme and approach, reveal general patterns characterizing some of the aspects of building with the two materials in focus. The similar nature of the related benefits and difficulties allows for drawing a general conclusion about future perspectives of earth and stone architecture in Portugal.

Regarding the future of the use of natural stone, most of the interviewed architects agree that it probably won't grow as a structural material but remain the resource for smaller scale, exceptional projects. The logistic and economic constraints related to stone construction are posing difficulties to its widespread use while the limitations of (human and material) resource availability and the sustainability of newly quarried material remains questions to consider. In rural areas, with a more established specialized network of professionals and available resources, the use of stone seems to be a more viable solution.
With regard to earth construction, there is one distinctive factor that sets the material apart from current industrial materials. The use of raw earth requires a different way of thinking and the constant invention of new solutions that respond to the given context (Mendes, Schreck). The material varies from place to place and has certain limitations. It means that there is always a need for the evaluation of possibilities and for adjustments contrary to the mechanical application of rules related to current construction materials (Mendes). The effort and learning required to use raw earth seems to be an unappealing aspect to most practitioners.

One of the main factors that is currently preventing both earth and stone from becoming a widely used material is the strong presence of lobbies of current construction materials. "The construction paradigm has to change" (Morais) in order to successfully integrate them into the market without losing their fundamental values. Many architects believe that raw earth could become a widely used conventional material in some parts of the country again due to the availability of good quality material, suitable climate and a long tradition of related constructive culture (Schreck, Rocha, Morais, blaanc). From the conversations, alternative ways emerge to make earth construction more competitive. Cristina de Mendonça argues that a more widespread earth architecture should start on an academic level by promoting the associated knowledge through courses and research studies. Parallely, there is a need for a system of validation of skills to prevent mistakes in construction and a consequent bad publicity of the material and its techniques (Mendes). Reducing the labor intensity of earth construction would be another step forward in regaining its popularity that could be achieved by the help of technology. In Portugal, building with earth is still a very traditional process characterized by a learning-by-doing approach with all its advantages and drawbacks. There has not been much room for technological development that could make it a more controlled and thus more trusted process. Introducing different, semi-automated construction technologies such as the CEB could change the current situation due to its easy, standardized production, according to Rocha. He also highlights the importance of the education of the public through example projects such as social housing or public buildings made of earth – "the first step toward change is awareness" (Branden) and in this sense, the promotion of raw earth on a municipality level could showcase alternative architectural solutions to a wide audience contributing to a potential change in their perception.

5. HYGROTHERMAL PERFORMANCE OF EARTH AND STONE BUILDINGS

The aim of the following chapter is to present in more detail the hygrothermal performance of three buildings made in rammed earth and natural stone. One of the case studies is a residential building designed and constructed in rammed earth by architect Henrique Schreck, located in São Teotónio, Odemira. The second one is the rammed earth housing volume of the winery of Herdade da Cardeira, located in Borba, Central Alentejo. The third one is a recently renovated stone holiday house located in Granja do Tedo, in the district of Viseu, Northern Portugal. From the comparative analysis of thermal and hygrothermal measurements, it is possible to draw an image of the performance of two contemporary earth buildings, one of a traditional and one of a modern architectural language, and a refurbished traditional stone construction, during summer season.

It is important to note a deviation of the final result from the original intention. The dissertation initially set the goal to perform a comparative analysis of buildings made of raw earth and stone. However, due to the limited time available for the measurements, the difficulty of establishing contact with and the reluctant attitude of some of the residents of the originally chosen buildings, it was not possible to perform an analysis on a stone construction. Instead, the chapter relies partially on external data – the initially chosen example of the winery complex is compared to another contemporary rammed earth building conceived on traditional principles and to a refurbished traditional stone building. Data on their hygrothermal performance was already available based on two previous studies (Correia Macedo, 2009; Fernandes et al., 2020).

5.1. Methodology

The case studies were selected based on the following criteria:

- Time of construction – the focus is put on contemporary earth buildings of contrasting characters to examine the different approaches of material use. Also, a recently refurbished traditional stone building is included in the analysis to compare the performance of the two materials.
- Geographical location and climatic conditions – rural regions in diverse climatic conditions are selected. The examples are taken from the south of the country, representative of hot summers and mild winters, and from the north of the country with harsh winters and warm summers.
- Typology of the building – the chosen case studies are single family houses.
- Constructive system and materials – two of the buildings are constructed using the rammed earth technique and the third one is made of natural stone.
- Availability of the building for measurements – the most defining aspect for performing the measurements was the availability of the house and the consent of the owner to its use for the purpose of this study as well as the availability of previous studies as complementary elements for the comparative analysis.

The analysis of the case studies followed the guidelines below:

- Climatic conditions – the external temperatures including summer and winter average mean temperatures of the given locations were collected based on data from the Portuguese Meteorological Institute and the Iberian Climate Atlas.
- Site visit – a contact was established with the owner of the place and the chief architect of the project in the case of Herdade da Cardeira and the rammed earth residential building.
- Materials – to specify the main materials and constructive systems of the projects, an interview is scheduled with the architect of Herdade da Cardeira and the rammed earth residential building.
- Indoor thermal comfort – to assess the owner's perception of the indoor environment, an informal discussion took place that targeted the owner's overall satisfaction and the existence of heating or cooling systems in the case of Herdade da Cardeira and the rammed earth residential building.
- Interior and exterior temperature and humidity – two data loggers were installed in the housing volume of Herdade da Cardeira: Onset HOBO U12-012 relative humidity and temperature recorders that were documenting values at regular intervals for a one-month period between August and September to understand the building's hygrothermal performance.

The collected data was analyzed and the newly obtained results from the winery were compared to the existing data from the previous studies that were based on a similar methodology as the one outlined above.

5.2. The studied buildings

To understand the climatic conditions and the related comfort requirements of the studied buildings, Figure 31 below shows the Köppen Climate Classification and climatic conditions of the case study locations.

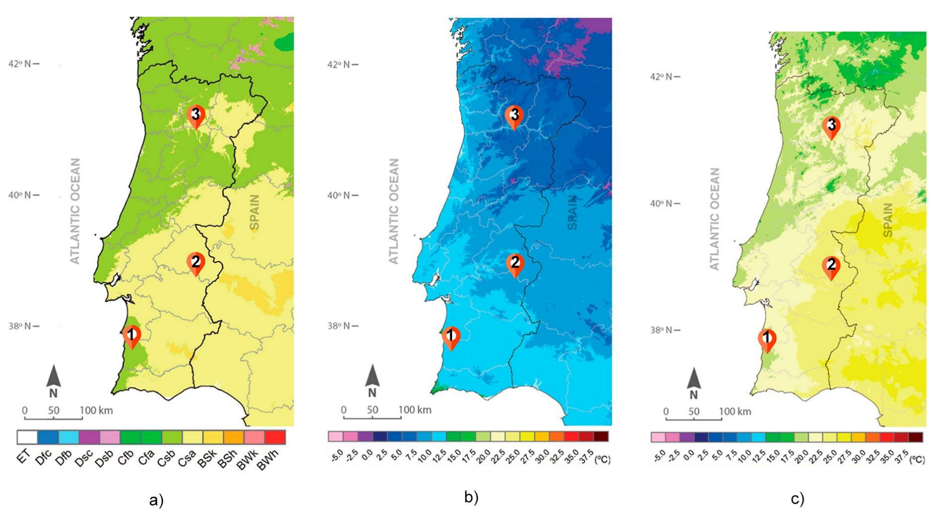

Figure 31 - a) Köppen Climate Classification of Portugal; b)-c) Average mean temperature in winter and summer (ºC) (adapted from: Fernandes et al., 2020)

Case study 1 – Private residential building

Table 3 - Case study 1 – Private residential building

(source: Correia Macedo, 2009)

Year	1998
Author	Arq. Henrique Schreck
Typology	single-family house, new construction
Location	São Teotónio, district of Odemira, Coastal Alentejo
Climate	Köppen Climate Classification - Csa region, characterized by a Hot-summer Mediterranean climate Climatic Zoning - V3 summer region, external mean temperature, T_{ext}= 22,2ºC - I1 winter region, heating degree days equal 1089 Temperature averages - annual average mean temperature is 16,5ºC - average mean temperature in winter is 10,8ºC - highest average temperature is 27,8ºC in August (Weather Atlas, 2022a) - lowest average temperature is 9.2ºC in February In the coastal regions, the cooling effects of the ocean during summer and its heating effects during winter are perceptible which results in a more temperate climate. Still, summer is the most critical season in achieving good indoor thermal comfort in buildings.
Constructive system and materials	Walls - external: 50cm rammed earth without insulation - internal: rammed earth Finish - exterior and interior lime plaster in some areas, otherwise earth exposed

	Roof - timber structure, 2cm cork insulation + ceramic tiles roof cladding Foundation - cyclopic concrete Floor finish - concrete and ceramic tiles Windows - wooden frame, single glazed
Source of material	raw earth from site
Passive design strategies	thermal inertia, solar exposure/orientation, controlled glazing ratio
Renewable energy sources	–
Heating/Cooling	Heating - fireplace, heaters Cooling - no mechanical cooling, natural ventilation
Occupancy profile	occupied permanently 3 occupants, spend 10-12 hours inside on a typical day (Correia Macedo, 2019)

Case study 2 – Herdade da Cardeira

Table 4 - Case study 2 – Herdade da Cardeira



(source: photos of the author)

Year	2020
Author	EMBAIXADA Arquitectura
Typology	mixed-use winery, new construction
Location	Borba, district of Évora, Central Alentejo
Climate	Köppen Climate Classification - Csa region, characterized by a Hot-summer Mediterranean climate

	Climatic Zoning - V3 summer region, external mean temperature, T_{ext}= 24,7ºC - I1 winter region, heating degree days equal 1150 Temperature averages - annual average mean temperature is 17,4ºC - average mean temperature in winter is 10,0ºC - highest average temperature is 33,7ºC in August (Weather Atlas, 2022b) - lowest average temperature is 5.2ºC in February This region has the highest average mean temperature of all the locations of the case studies. There is a big deviation between summer and winter temperatures and also in diurnal temperatures. Winter is cold, while summer is particularly harsh and thus is a demanding season in terms of providing satisfactory indoor thermal comfort in buildings.
Constructive system and materials	Walls - external: 50cm rammed earth without insulation - internal: fired bricks Finish - exterior and interior lime plaster Roof - steel structure with an interior timber layer + natural zinc roof cladding Foundation - reinforced concrete Floor finish - concrete and ceramic tiles Windows - aluminum, double glazed sliding doors
Source of material	raw earth from site
Passive design strategies	thermal inertia, natural ventilation
Renewable energy sources	solar panels
Heating/Cooling	Heating - floor heating during winter, wood-burning fireplace Cooling - no mechanical cooling, natural ventilation
Occupancy profile	occupied periodically – few weeks each month occupied during measurements

Case study 3 – Holiday house

Table 5 - Case study 3 – Holiday house

 (source: Fernandes et al., 2020)	
Year	18th century, refurbished in 2005
Author	no information
Typology	semi-detached single-family house, refurbishment
Location	Granja do Tedo, district of Viseu, Northern Portugal
Climate	Köppen Climate Classification - transition between the Csa region, characterized by a Hot-summer Mediterranean climate and the Csb region, characterized by a Warm-summer Mediterranean climate Climatic Zoning - V3 summer region, external mean temperature, T_{ext}= 22,7ºC - I2 winter region, heating degree days equal 1764 Temperature averages - annual average mean temperature is 16,4ºC - average mean temperature in winter is 10,0ºC - highest average temperature is 28,8ºC in July (Weather Atlas, 2022c) - lowest average temperature is 2,3ºC in February This area has the lowest average mean temperature of the locations of the case studies. Winter is the harshest season which means that minimizing heat losses and increasing solar gains during the cold months is essential while keeping the interior fresh during summer is equally important.
Constructive system and materials	Walls - external: 50-55cm granite walls without insulation - internal: plasterboard walls Finish - interior plaster, exterior stone facade exposed Roof

	- timber structure, 4 cm extruded polystyrene + ceramic tiles roof cladding Foundation - stone Intermediate floor - timber beams Floor finish - ceramic tiles, timber floor Windows - wooden frame, single glazed
Source of material	locally available granite stone
Passive design strategies	natural ventilation, solar exposure/orientation, glazed wooden balcony to increase solar gains, thermal inertia, controlled glazing ratio, compact volume to reduce heat losses
Renewable energy sources	–
Heating/Cooling	Heating - closed wood-burning fireplace Cooling - no mechanical cooling, natural ventilation
Occupancy profile	occupied periodically – weekends, holidays occupied during half of the measurement duration
Other	the case study is situated in a small village in a rural area in northern Portugal where the primary building material is granite the composition of the building follows that of traditional vernacular constructions in the area: - 2 storey: traditionally storage/livestock on ground level, human occupancy on upper level - few, small openings and compact layout to avoid heat losses during winter - use of glazed wooden balcony during renovation, some changes were introduced in the layout: - upper floor is reorganized to accommodate two bedrooms and a bathroom - additional insulation in the roof - new partition walls (changing original tabique to plasterboard) - partition wall between balcony and upper-floor room removed today the building is used for a holiday house mainly occupied during holidays and weekend, occupied during most of the summer season (Fernandes et al., 2020)

5.3. Measurement results

Case study 1 – Private residential building

A total of four recorders were placed in different rooms of the rammed earth residential building – in a bedroom, in the living room, in the kitchen and in the loft. Figure 32 shows the final position of the loggers.

Figure 32 - Location of measuring instruments (source: Correia Macedo, 2009)

The monitoring was performed in the period of the 17th to the 31st of July, 2009. Figure 33 below shows the reading of air temperature and relative humidity values (Correia Macedo, 2009).

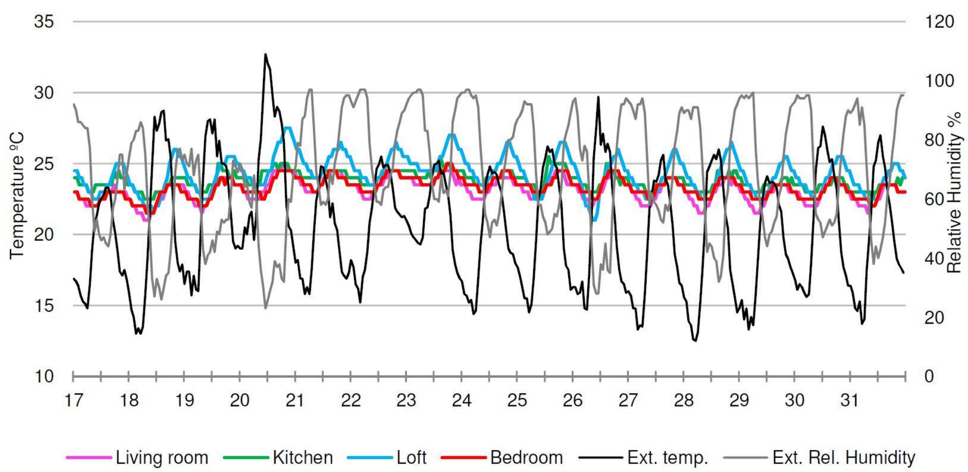

Figure 33 - Temperature and relative humidity values of Case study 1 (ºC, %) (source: Correia Macedo, 2009)

The chart shows regular indoor temperature values throughout the monitored period, regardless of outside conditions. The values remain between 22-28ºC which corresponds to the human thermal comfort range. The design of the building relies strongly on vernacular principles and passive strategies which is directly reflected in the measurement results. The controlled size of glazed openings limits solar gains which otherwise are responsible for the overheating of the interiors during summer. At the same time, it allows for taking full advantage of the thermal mass of the thick earth walls – the effect of thermal delay is observable in the graph. There is a considerable interval between the time in which outdoor temperatures reach their maximum and the time in which indoor temperatures do so. The occupants of the house report a retained ‘fresh’ indoor climate for which the effects of night cooling ventilation are essential to achieve. The weakest point of the house according to the chart is the loft. The poor insulation of the roof allows for higher heat gains there than in the rest of the rooms (Correia Macedo, 2009).

Case study 2 – Herdade da Cardeira

Two temperature recorders were placed in the kitchen and in the living room of the housing volume of the winery, also measuring the outside temperature on the northern porch. Figure 34 illustrates the final position of the loggers (placed 1 meter above ground level) and Figure 35 shows the natural ventilation scheme.

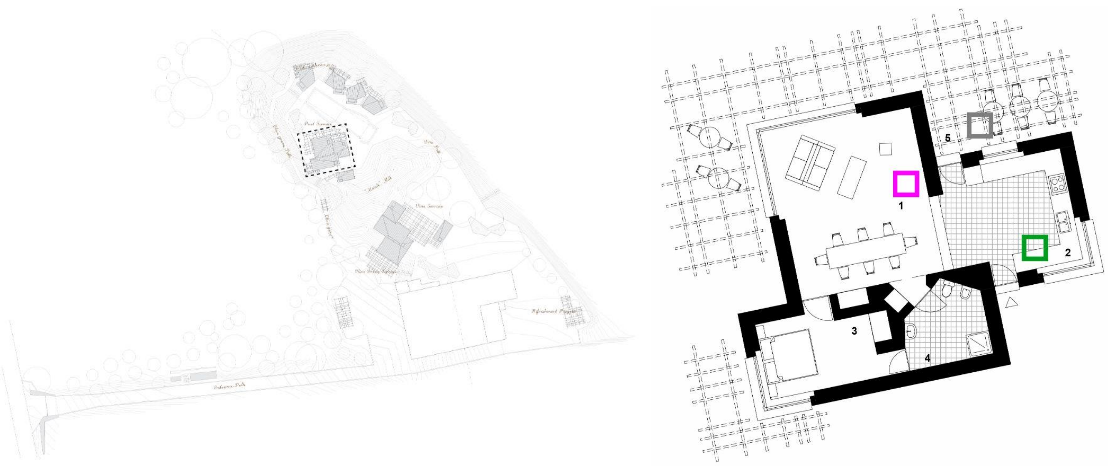

Figure 34 - Site plan and layout with location of measuring instruments (1–living room; 2–kitchen; 3–bedroom; 4–bathroom; 5–outdoor porch (source of site plan: EMBAIXADA, 2022)

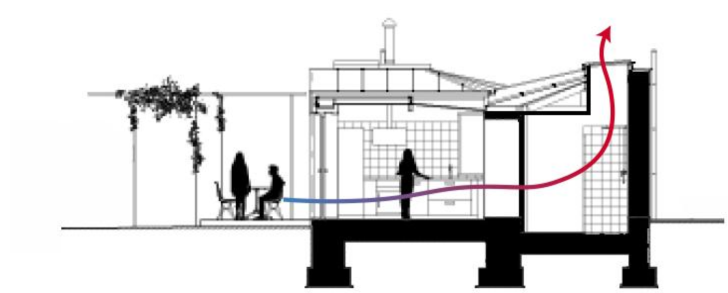

Figure 35 - Natural ventilation scheme of the housing volume (adapted from: EMBAIXADA, 2022)

A reading in each 15 minutes was performed in the period of the 24th of August to the 27th of September, 2022. Figure 36 below shows the reading of air temperature and relative humidity values.

The mean outdoor temperature around the building in the monitoring period was 21,4ºC. There was a high daily thermal amplitude, between 10ºC on more temperate days to 17ºC on warmer days.

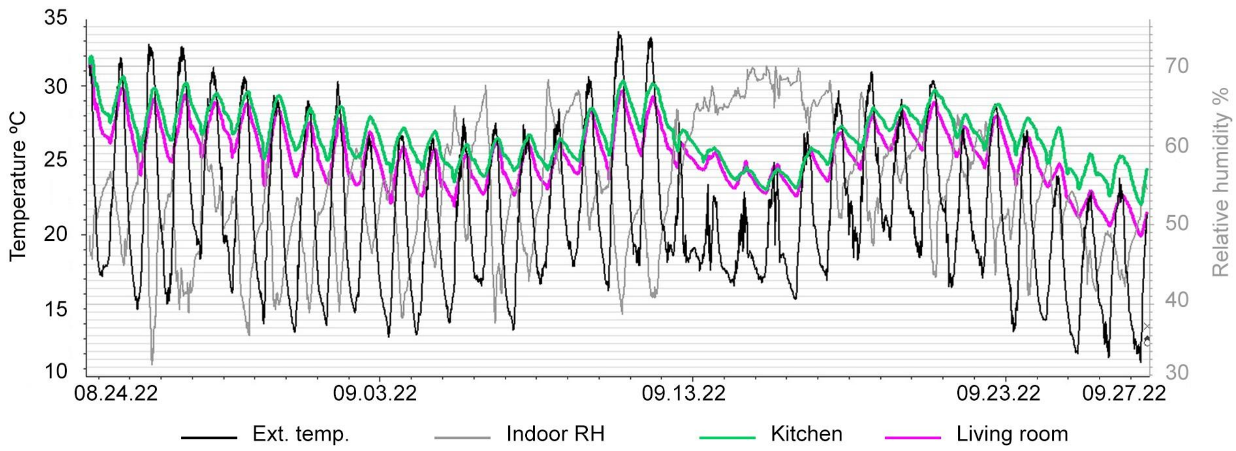

Figure 36 - Temperature and relative humidity measurement values of Case study 2 (ºC, %)

The housing volume of the winery reveals a different thermal behavior compared to the previous example. The chart shows fluctuating indoor temperatures which are quite close to exterior conditions. It varies between 19 and 31ºC while the relative humidity is between 35 and 70%. The thermal instability can be the result of different factors, the most noticeable of which is the building's glazing ratio and the orientation of openings. The design of the building reflects a modern architectural language characterized by generous glazed openings. The floor-to-ceiling sliding doors are placed on the corners of both the living room, the kitchen and the bedroom, the latter two facing south-east and south-west, respectively. There are pergolas around the bigger openings intended to be overgrown by vegetation which has not happened yet. Potentially, shading provided by the greenery could improve indoor comfort conditions. Still, without that, the size and exposure of the openings account for excess solar gains that cause the overheating of the interior and makes the effect of thermal delay of the earth walls impossible. The occupant of the house reports a 'warm' indoor climate for which the inadequate use of night ventilation can also be responsible.

Case study 3 – Holiday house

A total of four temperature recorders were placed in the stone holiday house to monitor the indoor temperature and humidity changes. One was placed in the kitchen and living room on the first floor of the building and the rest was distributed upstairs in the bedroom, bathroom and another bedroom with a glazed balcony. The position of the recorders is shown on Figure 37. Figure 38 shows the natural ventilation scheme of the building and the operation of the glazed balcony during summer.

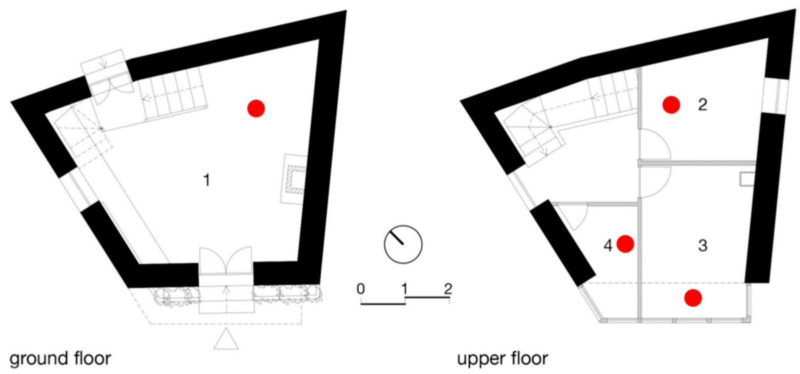

Figure 37 - Location of measuring instruments (1—living room/kitchen; 2—bedroom; 3—bedroom with balcony; 4—bathroom) (source: Fernandes et al., 2020)

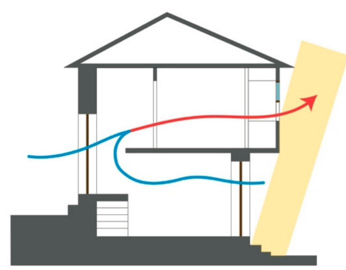

Figure 38 - Schematic section of the glazed balcony operation – summer solstice (source: Fernandes et al., 2020)

"The monitoring was carried out from 18 July to 18 August, 2015. In this period, the mean outdoor temperature was 24ºC, there was a high daily thermal amplitude, with several days reaching most of the time maximum values around 35.0ºC (and a peak of 39.1 C), and minimum values around 15.0ºC" (Fernandes et al., 2020). Figure 39 below shows the reading of air temperature values.

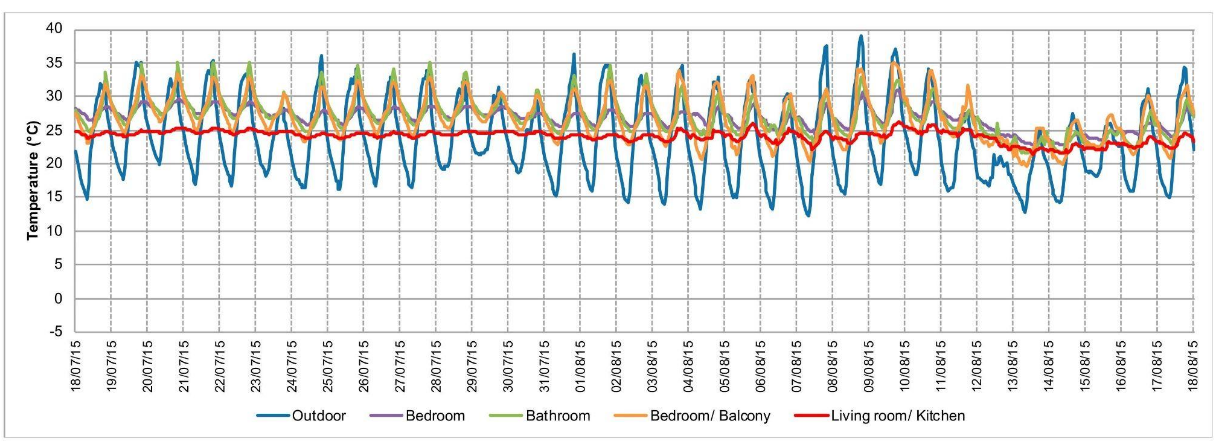

Figure 39 - Temperature measurement values of Case study 3 (ºC)(source: Fernandes et al., 2020)

Figure 40 below shows the reading of relative humidity values.

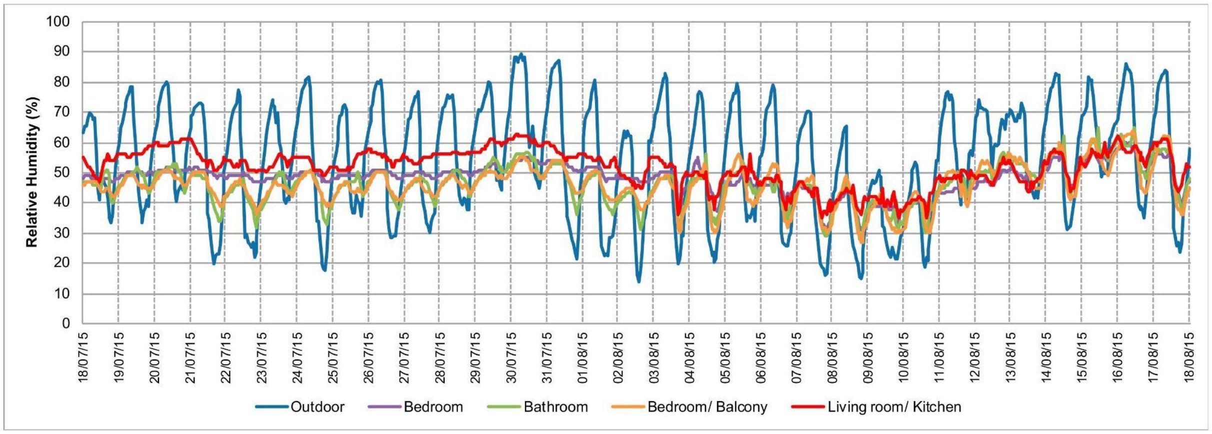

Figure 40 - Relative humidity measurement values of Case study 3 (%) (source: Fernandes et al., 2020)

The graphs show a diverse thermal behavior of the different rooms of the house. The most stable indoor temperature is maintained in the kitchen and living room on the ground floor of the house, "with a mean temperature of 24.1ºC" (Fernandes et al., 2020). Having traditionally been a storage facility, the ground floor features few openings and thus limited direct solar gains that explains its regulated thermal conditions. The thick stone walls of the ground floor provide good thermal inertia. The biggest fluctuations of indoor temperature can be observed in the upper floor rooms connected directly to the glazed balcony. Here, indoor temperatures follow quite closely the outdoor conditions. The reason for this is the large glazed area of the balcony, facing southwest, that accounts for excess solar gains. Since the building began to be occupied (4th of August), the effects of night ventilation became noticeable with the minimum air temperature at night getting slightly lower. It can be concluded that, while the solution of the glazed balcony can be favorable during winter to increase solar gains, without an external shading device it is difficult to control the indoor climate during summer. (It is important to note that in the original configuration of the building, the balcony acted as a buffer space separated by a wall from the rest of the rooms which controlled their summer heat gains considerably (Fernandes et al., 2020).) In line with this, the other second-floor bedroom, being separated from the balcony, shows more stable temperature values although it performs worse than the ground floor spaces due to its position in the attic. The indoor humidity level in the rooms is relatively stable, ranging between a minimum of 30% and a maximum of 60%. In the thermal comfort assessment and the occupant satisfaction monitoring, two rooms were examined – the kitchen and living room and the bedroom with balcony. Both were found to be within the human comfort range. Two of the occupants reported being 'neutral' in the ground level, while one of them answered being 'slightly warm' and the other 'neutral' in the upper-level bedroom with balcony. "The difference between the answers is mainly related to different clothing insulation levels" (Fernandes et al., 2020).

5.4. Interpretation of the results

The chapter outlined the analysis of the hygrothermal behavior of three case studies. For reasons previously outlined, it presents only one example of a traditionally conceived contemporary rammed earth building, a modern rammed earth building and the contemporary refurbishment of a traditional stone construction. Case study 1 and 3 are representative examples of the specific constructive solutions and design principles in their given climates. Consequently, some general conclusions can be drawn from the outcomes of the analysis regarding the relationship between design principles and building performance.

As the analysis revealed, the traditionally conceived rammed earth building is able to provide good indoor thermal conditions during warm summer months. The heat-storing capacity of the material through its thermal mass is significant when diurnal temperature differences are greater. The most obvious difference resulting in such a contrasting thermal performance of the private house and the winery (although built with the same material) is the conscious use of passive strategies incorporated to the design of the former. It clearly reveals that the material alone cannot guarantee good indoor comfort – all building elements have an influence on the overall performance of the house (Correia Macedo, 2009). The amount of glazed openings and their orientation define solar gains which need to be controlled to provide a comfortable indoor climate. In Southern Europe, the recommended glazing ratio for southern façades is 30% if they are not properly shaded in summer and a maximum of 20% for south-western to north-eastern faces (Correia Guedes, 2019). In case of the winery, however, the northern and south-western façades have a glazing ratio of roughly 39% and 53%, respectively, which are much higher than the recommended 20%. The glazing ratio of the north-eastern and southern faces are 19% and 30%, respectively, which are within the recommended value of 30%. Today the modern architectural language of buildings that most architects seek is directly associated with large glazed façade areas. This approach renders the use of earth and stone inadequate and makes it difficult to utilize their real potentials apart from that of aesthetics.

Regarding the use of stone, similar principles apply. As Case study 3 reveals, the spaces with the best thermal performance in summer are those on the ground floor with few openings where the thermal inertia of the stone walls can effectively provide a delay of heat exchange between exterior and interior. On the upper floor with the glazed balcony, "the results show that the thermal comfort conditions are within the comfort limits but with some risk of overheating" (Fernandes et al., 2020). The excess solar gains counteract the heat storing capacity of the thick stone walls, similarly to Case study 2. This way, the advantages of this type of stone building with the large glazed balcony are more perceptible during cold winter times which is justified by related measurement results (Fernandes et al., 2020).

In all cases, the actions of the occupants are also decisive to improve indoor environmental quality as was reflected in the cooling effects of night ventilation or the use of shading during direct sun exposure (Fernandes et al., 2020). The presented case studies indicate the importance of harmonizing functional needs and passive strategies to achieve buildings of a good indoor climate with low energy consumption.

6. CONCLUSIONS

"For me, sustainability is a synonym for beauty [...]. Something has to be in harmony not only with its urban setting but with much more than that, with the different layers of society and the environment." (Heringer, 2022)

The main objective of this dissertation was to investigate the current context of the use of raw earth and natural stone in contemporary Portuguese architecture and examine their suitability regarding climate and geography, performance and comfort, functional requirements, economy, social perception and architectural language. To contextualize the research, the European tendencies regarding earth and stone architecture were also outlined. The subject was addressed from a sustainability perspective and thus the materials were also examined regarding their life cycle, environmental impact and physical characteristics.

A global understanding of the consequences related to the unlimited resource exploitation and pollution of the planet has been amplified in the recent decade and solutions have been long sought to tackle the problem. The construction industry, being largely dependent on fossil fuels and a major contributor to resource consumption and CO_2 emissions worldwide, needs to have "a rapid and comprehensive realignment" (Angelika Fitz in (Heringer, 2022)) in order to address the effects of climate change. A change in the construction paradigm assumes a shift in the role and attitude of the architect as well – becoming "less that of the author of a work [...] than that of a “continuator” or an “interpolator” within a serial work started before them and open to changes in the future" (Architecture Triennale 2022, exhibition board). It requires a comprehensive way of thinking embracing circular growth models rather than linear systems. Today, sensitivity toward the problem mentioned above is emerging and its importance is reflected in a broader scale as it was mentioned in Chapter 4 and 5.

As the consequences of climate change are becoming ever more tangible, the environmental impact of construction materials – their life cycle and the energy needed for their manufacture and transportation – has become essential to consider. In this sense, natural building materials such as raw earth and stone offer several advantages over industrially and chemically processed resources. Their low embodied energy, local availability and minimum transportation requirements make up some of their valuable assets. The potential of their use in a circular economy is considerable given the life cycle of the materials – they are recyclable and can be used multiple times over time without losing quality or returned to nature without significant harmful impact at the end of their useful life. Having been widely used in vernacular architecture, earth and stone have proved their suitability to local climatic and socioeconomic contexts. Additionally, the good material properties they possess can contribute to creating healthy indoor environments. As it was outlined in Chapter 1, though, there are several difficulties that still prevent their widespread use in contemporary architecture worldwide. The main reasons are of economic, legislational and social nature – the strong presence of lobbies in the construction industry which raw earth and natural stone are not part of, the lack of standardization and regulatory framework for their adequate use, the labor intensity of construction, their often unfavorable social perception and the lack of educational offer about them.

When comparing the broader European tendencies characterizing the use of raw earth and natural stone in contemporary architecture with the current situation of Portugal, there are some similarities and differences worth highlighting regarding the approach formulated on the level of academic education, research and practice. As far as academic education is concerned, there are some well-established as well as emerging institutions and courses both in Portugal and in other European countries that focus on the contemporary potential of natural materials and the different aspects of sustainable architecture. Still, these are few and quite isolated cases without a comprehensive strategic network. A broader educational reform would be necessary to achieve changes in the current architectural paradigm and move from a profit-driven attitude to a planet-driven one.

Examining the field of research and practice reveals a progressive approach characterizing many European countries which are experimenting with integrating technological and scientific advancement – such as prefabrication, robotic fabrication and nanosciences – with natural materials. They do so to tackle the problem of labor intensity related to natural materials but also to find a contemporary language for earth and stone constructions. In this sense, Portugal is somewhat different – constructing with raw earth and stone is still very traditional. In most of the cases, it is a learning- by-doing process where a handful of skilled professionals pass their knowledge on to the ones interested. Not much progress has been made in the past decades to develop the related construction techniques and processes further.

Another interesting aspect the research revealed is the different evolution of earth and stone as building materials in contemporary research and practice. In Europe, although both materials are investigated, there is much more research and development about raw earth. In Portugal, stone is almost non-existent in research and can mostly be found in very specific, rehabilitation projects in practice while there is an abundance of research and several newly built examples in raw earth. Besides the recognized material properties and life cycle of earth, it is probably due to its wide availability, ease of extraction, versatility of use as well as its aesthetic qualities that it is on the rise again. Whereas in the case of stone, its extraction and transformation into building material is a more energy and time intensive process that requires specific infrastructure and logistics. Besides that, construction companies and lobbies are primarily promoting its use as a cladding material and all the industry around stone is targeting the manufacture of finishing products. This way, it is not easy to establish new uses for the material especially as most practitioners are not considering such a possibility.

In Portugal, through the insight of professionals involved in natural building practices it was possible to target the main obstacles to construction with earth and stone as well as to formulate future perspectives for their development.

One of the biggest challenges is to overcome the lack of information present about natural materials on different levels. Often, both professionals and non-professionals are unaware of the alternative solutions earth and stone offer in contemporary architecture. The absence of the related topics in academic education results in a scarcity of skilled architects and builders capable of carrying out such projects. On a professional level, lack of information about the use of these materials can generate further problems regarding building performance. As the hygrothermal measurement results and comparative analysis showed, the inadequate use of the materials can undermine their valuable properties in creating comfortable indoor environments. The use of passive strategies, the conscious control of solar gains and orientation of glazed areas is of primary importance in making the effects of the thermal delay of earth or stone walls perceptible. To design a well-functioning building requires the thorough study of the material. It is important that practitioners accept the limitations of the materials together with specific design requirements that allow for taking full advantage of them. There is still a need to develop an architectural language adequate to the use of earth and stone in Portugal which allows for utilizing their valuable assets while providing contemporary aesthetic qualities appealing to a wider public. Changing the generally unfavorable social perception of these materials could be achieved by the promotion of newly constructed buildings using earth or stone as their primary building material as well as exhibitions or other awareness-raising actions. The future of a more widespread earth and stone architecture depends largely on how effectively knowledge can be disseminated on an academic, professional and public level that breaks the ‘myths’ about natural constructions.

A standardization of the materials and related construction processes could contribute significantly to raising the competitiveness of earth and stone on the market. Along with that should come the introduction of norms specialized to each material which could facilitate their use and regain public trust. For that, more research would be necessary that targets the vulnerabilities of the materials such as strength or seismic resistance and provides satisfactory solutions for a widespread applicability. The labor-intensity associated with earth and stone building techniques constitute another disadvantage especially when the steady rise of current labor prices is considered. It could be reduced either through the use of construction techniques which apply standardized elements (such as CEB in the case of earth) or through the integration of advanced technology to the construction process in order to make it more controlled. The latter could be supported by specific applied research projects on an academic level.

Finally, given the limited time available for the completion of the dissertation, there are some topics that could not be elaborated to a desired detail which leaves room for further investigation. It would be interesting to explore the potential ways of a technological advancement of the construction techniques related to earth and stone in Portugal. Besides that, a deeper comparative study of the thermal performance of earth and stone buildings would be useful to conduct which could allow for more comprehensive conclusions to be drawn considering wintertime performance as well.

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APPENDIX

Appendix A – Questionnaires of the interviews

Questionnaire for architects

Questionnaire for the Master Thesis 'Raw earth and natural stone in contemporary Portuguese architecture' at Instituto Superior Técnico by Réka Szilvási

General questions

- How did you gain interest / start practice in architecture with natural building materials?
- Did you learn about natural building materials and techniques in 'conventional' education (courses at university)? If not, how did you acquire knowledge about natural building materials and techniques?
- Is there any supporting framework for the implementation of projects using natural materials in Portugal? (building codes, available know-how from craftsmen…etc.)

Questions about the characterization of building with earth/stone

- What are the advantages of building with earth/stone?
- What are the obstacles of building with earth/stone? (material characteristics, climate/geography, legislation, social, construction process/skilled labor…etc.)
- Are there any constraints in building with earth/stone that could affect the overall duration of the construction?
- Are there any structural constraints in building with earth/stone? (achievable heights, spans, openings, seismic loads) In a specific project, were there any features that could not be realized because of material constraints?
- What are the most widely used construction techniques when building with earth/stone today in Portugal? (foundation, load-bearing and non-load-bearing walls, floors, roof)
- Can earth/stone be combined with other materials in the construction process? How?
- What are the costs in comparison to a project built with industrialized materials? (transportation, labor, material, operational costs…etc.)
- What are the maintenance needs of a house made of earth/stone? How durable are earth/stone constructions?
- In the context of missing building codes, who is taking the responsibility for the construction?
- Usually, what is the profile of the client commissioning a project/reconstruction with natural building materials? What is their main motivation?

Questions about the present/future applicability of earth/stone

- According to your experience, what is the perception of earth/stone as a building material in Portugal? Why?
- Do you think earth/stone could be conventional/widely used in Portugal? Why?/Why not?
- In your opinion, can earth/stone construction be applied in the urban context? Why?/Why not?
- Can you imagine combining the use of earth/stone with state-of-the-art technology in the Portuguese context? (prefabrication, 3D printing, CNC, robotics…etc.)

Thank you very much for completing the questions. Please let me know if you agree on being contacted again in case of any further inquiry about the subject.

Questionnaire for university professors

Questionnaire for the Master Thesis 'Raw earth and natural stone in contemporary Portuguese architecture' at Instituto Superior Técnico by Réka Szilvási

General questions

- Do you have any interest in architecture with natural building materials?
- Did you learn about natural building materials and techniques in 'conventional' education (courses at university) / How did you acquire knowledge about natural building materials and techniques?

Questions about present education

- Today, are there any university courses addressing natural building materials in Portugal? / Has the situation changed since the past? How?
- If so, what is the main content/focus of these courses?
- What opportunities do students have to fulfill their interest in architecture with natural building materials in Portugal today?

Questions about research

- Is there any ongoing research about earth/stone at the university you are teaching at? If so, what is their main focus?
- Are there any research lines at the university you are teaching at, focusing on combining the use of earth/stone with state-of-the-art technology already available in other parts of Europe? (prefabrication, 3D printing, CNC, robotics…) Why?/ Why not?

Questions about contemporary Portuguese architecture

- How would you characterize contemporary Portuguese architecture?
- What is the role of materiality in contemporary Portuguese architecture? / What connection do you see between the material used and the architectural language achieved?
- What connection do you see between educational methodologies and the architectural language of contemporary projects in Portugal?

Questions about the present/future applicability of earth/stone

- Do you think earth/stone could be conventional/widely used in Portugal?
- In your opinion, can earth/stone construction be applied in the urban context? Why?/Why not?
- According to your experience, what is the perception of earth/stone as a building material in Portugal? Why?
- What do you think is the potential of earth/stone construction in Portugal for the present and future? Could natural materials be an alternative on an industrial scale for the economy? Why?

Thank you very much for completing the questions. Please let me know if you agree on being contacted again in case of any further inquiry about the subject.

Questionnaire for occupants

Questionnaire for the Master Thesis 'Raw earth and natural stone in contemporary Portuguese architecture' at Instituto Superior Técnico by Réka Szilvási

General questions

- What was your motivation to commission a project in earth/stone / live in a house made of natural materials?
- How long are you living in an earth/stone house?

Questions about the general operation of the house

- In comparison to a 'conventional' house, how would you describe living in an earth/stone building? (general comfort (temperature, light, spaciousness…etc.), aesthetic satisfaction, cost of operation (heating/cooling needs, maintenance…etc.)

Thermal comfort in winter

very cold	cold	slightly cold	neutral	slightly warm	warm	very warm

Is there any heating system used?

Thermal comfort in summer

very cold	cold	cool	neutral	slightly warm	warm	very warm

Is there any cooling system used?

- Are there any maintenance needs of the house? If so, do you do it yourself or do you hire skilled labor?

Questions about potential constraints resulting from the chosen material

- Did you have to compromise any of your requirements because of the chosen material/technique? (function, comfort/light, equipment…) Were there any features that could not be realized because of material constraints?
- Were there any disadvantages for you as a client during the construction process from the material point of view (duration, unexpected cost, shortage of skilled workers…etc.)?
- How long did the construction take?
- Who was taking the responsibility for the construction? / Did you consider taking a risk by commissioning a building made of earth/stone?

Questions about present/future applicability of earth/stone

- According to your experience, what is the perception of earth/stone as a building material in Portugal? Why?
- Can you imagine earth/stone materials becoming conventional/widely used? How?/Why not?

Thank you very much for completing the questions. Please let me know if you agree on being contacted again in case of any further inquiry about the subject.

Appendix B – Case study 2 hygrothermal measurement results

To be able to consult the results of the measurements performed by the author in more detail, the temperature and relative humidity values of the winery of Herdade da Cardeira are presented below.

Measurement period: 24 August, 2022 - 27 September, 2022

Measurement device: Onset HOBO U12-012 relative humidity and temperature recorders