UNIVERSITÀ degli STUDI di CATANIA

Ph.D. in Evaluation and Mitigation of Urban and Land risks XXXIII Cycle

Ph.D. Thesis

Sustainable engineering of rammed earth construction

Material, design, and performances optimization

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Climate chaos, brutal inequality and social disintegration are pushing human communities towards the abyss. We can allow the process of destruction, disintegration, and extermination to continue undisturbed or we can awaken our creative energies and reclaim our future as a species and as part of the Earth family. We can continue to sleepwalk towards extinction, or we can become aware of our own potential and that of the planet.

Vandana Shiva, climate and politic activist

To remain indifferent to the challenges we face is indefensible. If the goal is noble, whether or not it is realized within our lifetimes is largely irrelevant. What we must do, therefore, is to strive and persevere and never give up."

XIV Dalai Lama

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1. Introduction

This section introduces the topic of the thesis. First, it is explained the context within the research moves, which concerns the issue of bringing sustainability values into construction sector, using natural based materials whose carbon emissions are low both in production, use and end of life phases.
Then, it is introduced the motivation for the study of an innovative rammed earth constructive technology, which has to deal with high performances requirements thus maintaining low environmental impacts.
From this issue, it is defined the main aim of the thesis, which is the definition of a holistic design approach for an innovative rammed earth construction technology; to fulfil this aim, it is investigated by its division into three objectives which are: base material optimization, improvement of rammed earth constructive system and process, validation of hygrothermal and energy performance of the system.
The methodology used in this thesis is the research by design, which is characterized by the use of different research methods in order to seek the answer to the main research question. More in detail, experimental methods have been used to address the question about the rammed earth material; prototyping, in its various phases, has been used for the improvement of the design of rammed earth constructive system and process. Finally, a simulation study has been used concerning the hygrothermal and energy validation of the system.
The significance of this research is found in the strong ecological connotation, in the seismic resistant design applied to the constructive system, in the low energy consumption resulting from the characteristics of the designed rammed earth envelope and in the reduced construction times and costs due to the optimization of the construction process.
Finally, in this section is presented a map of the thesis.

It is nowadays well known the enormous impact of some anthropogenic activities on the planet. These activities include the permanent effects of production and disposal of some materials at the basis of today's technologies, the footprint determined on natural ecosystems by mining, deforestation and urbanization. These effects have led several authors to advance the hypothesis that a new era had begun: the Anthropocene, an era of human dominance over the environment, whose effects are under everyone's eyes [1 – 3].
Even ordinary processes, such as technological innovations, demographic changes, social transformations, or simple economic activities, often cause significant consequences on the surrounding environment and on some hydrometeorological or geophysical phenomena, at least in the long period. It should be noted that there is almost always an anthropogenic responsibility on the vulnerability of populations and resources to a certain danger, as the effect or omissions of human activities, affecting both post-disaster behaviors (rescue, aid, etc.), as well as pre-existing ones, referring to incorrect and not sustainable behavior and growth patterns, prevention, and preparation to the emergency.
Within this framework, we will now clarify the responsibilities that the construction sector has in defining environmental risks or in failing their mitigation at an urban level.
As it is well known, contemporary society has a strong dependence on the use of fossil fuels such as coal and oil, the so-called non-renewable energy sources which, according to some projections using the energy consumption scenarios of the last thirty years, could be exhausted by 2050 [4]. This scenario is exacerbated by the general concern about the health of our planet, which is increasingly affected by climate change that has been shown to be also linked to the emission of greenhouse gases into the atmosphere. European directives today, following the international guidelines defined at the Environment and Climate Summits of the last

thirty years (including the Rio's 1992 Conference, the Johannesburg Summit in 2002, the Rio Conference in 2012 and the last summit held in New York in 2019), aim to reduce greenhouse gas emissions into the atmosphere by at least 40% (compared to 1990 levels), to achieve the development of renewable energy sources by up to 32% and to increase energy efficiency by 32.5% by 2030 [5].
In the last 17 years, United Nations set a series of Sustainable Development Goals [6], to achieve a better and more sustainable future for all world populations. These goals address the global challenges that we must face; they are interconnected, and they are supposed to be achieved by 2030:

- Goal 1: No poverty;
- Goal 2: Zero hunger;
- Goal 3: Good health and well-being;
- Goal 4: Quality education;
- Goal 5: Gender Equality;
- Goal 6: Clean water and sanitation;
- Goal 7: Affordable and clean energy;
- Goal 8: Decent work and economic growth;
- Goal 9: Industry, innovation and infrastructure;
- Goal 10: Reduced Inequalities;
- Goal 11: Sustainable Cities and Communities;
- Goal 12: Responsible production and Consumption;
- Goal 13: Climate action;
- Goal 14: Life below water;
- Goal 15: Life on Land;
- Goal 16: Peace, Justice and Strong Institutions;
- Goal 17: Partnerships for the goals.

These objectives are transversal and involve social, economic, and productive issues. It is worth nothing that several goals directly refer to the environmental issues, as Goal 6, Goal 7, Goal 13, Goal 14 and Goal 15. At the same time, Goals 9, 11 and 12 address to the change of our development, production, and consumption models inside complex systems as contemporary cities.
In this context, the responsibility of the construction sector, both for residential and non-residential buildings, in terms of energy consumption and emissions of pollutants into the atmosphere, is quite high: the International Energy Agency indicates that it accounts for 36% of global energy demand and 39% of carbon dioxide emissions, while the annual production of solid waste, in 2016, amounts to 2.01 billion tonnes, of which at least 40% consists of construction material [7]. The 193 million EU-27 buildings cause, globally, about 50% of SO_2 emissions, 22% NO_x, about 10% of particulate emissions, and, more generally, a third of emissions total greenhouse gases [8]. Of these, two thirds are caused by residential buildings, while the remaining are caused by commercial buildings [9]. These emissions are mainly linked to the use phase of buildings, while emissions related to the production phases of construction materials are attributed to the industrial sector and i.e., in Western Europe, are equal to 8-12%, plus the contributions related to transport and other activities [10, 11].

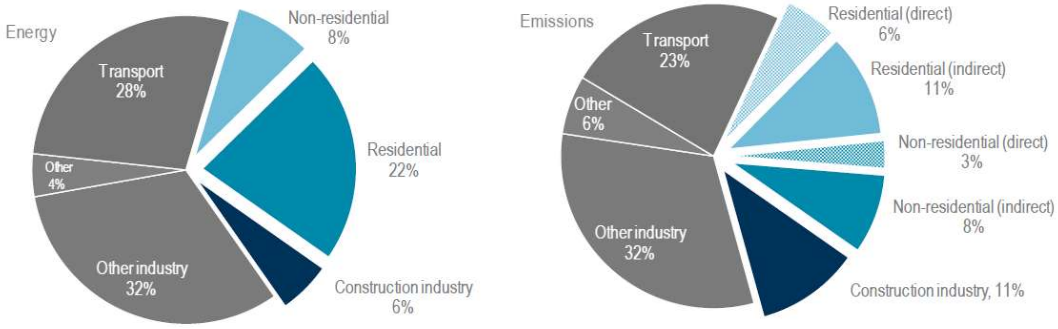

Figure 1 - Energy demand and emission of global carbon dioxide of the constructions sector [12].

From this brief overview on the responsibility of building sector on environmental pollution and production of waste, we can assume that the memory of what is happened in the past can guide us to a more sustainable future [13]. The growth models promoted until few decades ago are no longer sustainable for our planet. We need to rethink the paradigms of development and our way of imagining the contemporary and resilient cities. Referring to the construction sector, we need to reduce energy consumption in the production, construction, use and maintenance phases, according to the concept given by the life cycle perspective. Based on the analysis of factors harmful to the environment, it appears that most of them (greenhouse effect, acidification, toxicity, etc.) derive from the combustion of fossil fuels. The greenhouse effect prevails during the use phase of the building, while the others (i.e., the toxicity) during the production phase [14].

In accordance with the UE directives provided by the Energy and Climate Package 2030, the mitigation of these effects in our cities, environments and the territories and the implementation of techniques which promote the use of renewable and energy-efficient sources, must be the main objective of the design in all areas of human activity and in this case, of construction activities.

It is therefore understandable how improving the performance of buildings is fundamental to achieve the Sustainable Development Scenario: research and technological innovation aim to reduce the energy consumption of buildings, making their envelopes more efficient and reducing the environmental impact and the amount of construction waste. As is well known, in Central Europe, the need to ensure effective airtightness to reduce energy demand for winter heating has often led to the definition of technological solutions capable of reducing heat loss through the envelope using hyper-thermal insulated buildings. In hot climates, on the other hand, the control of air flows and ventilation, together with a bioclimatic design of the buildings, can make it possible to maintain temperatures close to comfort without resorting to HVAC systems, at least during the summer season [5]; in the same countries, the maximization of free energy supplies (solar radiation) through technological solutions of massive storage, possibly combined with the use of glazing, can significantly reduce heating costs during the winter period.

After the 70's oil crisis and the rising of energy costs, it was observed a change in the design goals for constructions, denying the experience of the International Style. This movement had tried to conceive a building type which could be valid for the whole world, forgetting the importance of the adaptation of constructions to the various climates and geographies [15- 17]. From then, researchers, building practitioners and professionals from all the world had learnt the lesson about the need to adapt buildings to the places where they are meant to be set. This adaptation is nowadays more and more pursued by using resources available on site, with lower construction and management costs, and with design strategies which help to maintain low energy consumptions during the use phase and therefore nearly zero impact on the environment.

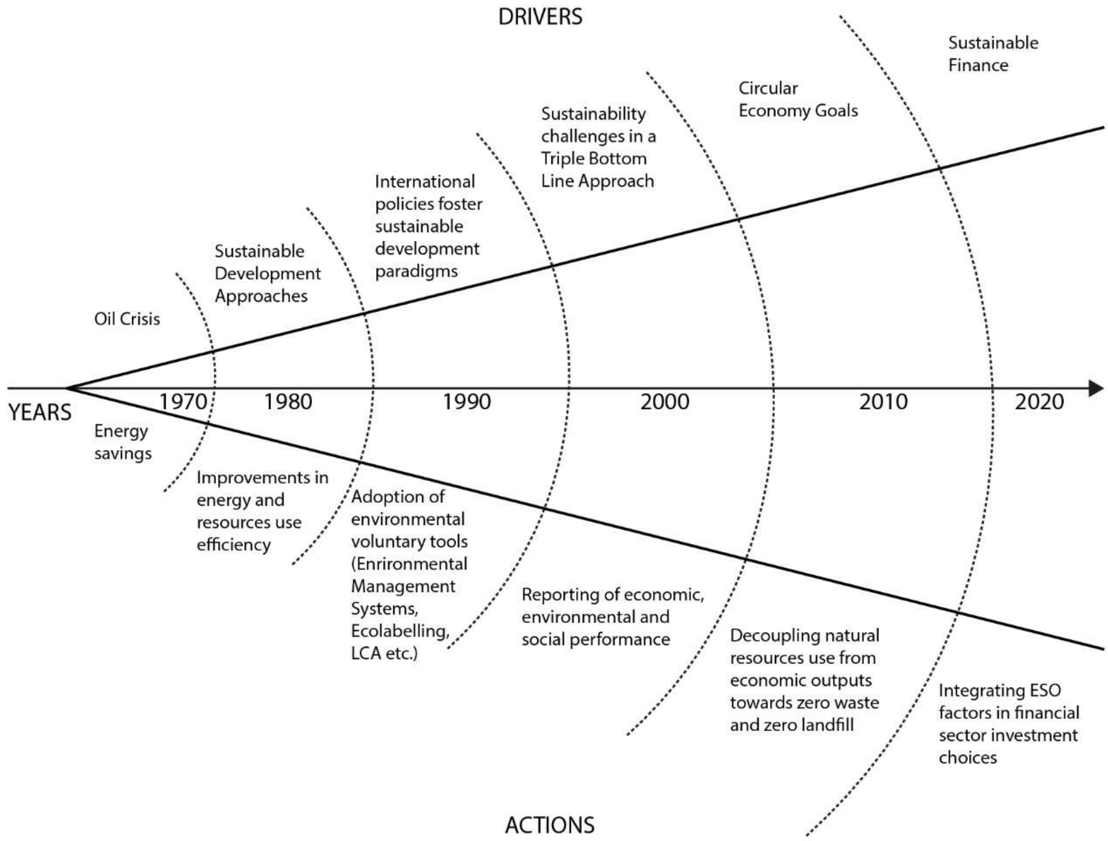

Figure 2 - Evolution of human actions in building sector as answer to modified environmental conditions.

Contemporary architecture is strongly concerned with sustainable building technologies and design. Practitioners are nowadays called to design buildings which are environmentally sustainable both for the use they make of natural resources, for how they process them and for the use of energy during the life of the buildings.

The key to this change in green architecture was found by many architects and engineers in the rediscovery of building traditions (as in Hassan Fathy's experience in hot arid climate) and in their use of local building materials, which most of the time are also natural-based materials, to create energy efficiency and comfortable spaces, at a low environmental cost. Traditional constructive techniques are based on local materials and know-how to adapt to the characteristics of the climate and building site and minimize the issue of resources supply and energy consumptions. Vernacular architectures use natural-based and local building materials to ensure the healthiness and non-toxicity of living environments, the good thermo-hygrometric performances, the cost-effectiveness of construction and the management processes. Moreover, the use of local resources for constructions has positive influences on local economies communities [18]. Design approaches such as the ones proposed by bio-based construction are trying to follow this line of research, choosing a valid alternative to contemporary high embodied energy technologies consuming synthetic and chemical materials for insulations, reinforced concrete and steel in buildings.

Natural – based technologies and materials such as raw earth, straw, wood, bamboo and natural fibers in general, offer a valid alternative to contemporary buildings with a more conscious use of environmental resources.

As [19] point out *"…What is needed at the beginning of the new millennium is an architectural perspective in which valuable vernacular knowledge is integrated with equally valuable modern knowledge…"*. For the authors, the huge amount of vernacular architecture in the world could work as an infinite database of technological and sustainable building solutions. Aspects and details of vernacular architecture are being rediscovered through limited performance-based examples. They also assume that this happens because there is still a strong opposition between the conventional notions of "traditional" and "modern" in the architectural research.

Conversely, the ingenuity of technological solutions in vernacular building technique is something that does not need to be proved. The resilience and the durability of these constructive systems is clear and witnessed by the fact they resisted for millennia.

Vernacular Earthen building technologies, in their multiple facets, have been used worldwide since the beginning of human settlement history, around 10000 years ago. Earth construction techniques as rammed earth, block masonry, adobe, cob, wattle and daub are spread from the Mesopotamia area to the Huang Valley, from Australia to Latin and North America, from Africa to Northern Europe [20]. Such big use of this material can be understood in respect of the availability of earth material, the simplicity of the construction procedure, the historic knowledges, and the progressive adaptation of the techniques to renewed uses.

After Industrial revolution, this material has been progressively forgotten and relegated to more rural context, emergency uses or self-constructing experiences, replaced by more controlled and high-performing material as concrete and steel.

However, in the last few years, earth material has acquired new resonance in building material production, because of its sustainable advantages, recycling properties, low-embodied energy aspects, low CO_2 emission, good thermal inertia and architectural plasticity (which greatest features in this case is certainly given by rammed earth masonries). Therefore, the research on earthen materials is receiving day by day more attention.

Research and studies on earthen constructions are moving on different ways in the meanwhile: more common topics are suitability of soils for constructions, mechanical characterization, durability, thermal performance, seismic behavior of earth buildings (both on historic heritage and new constructions). The strong focus on the physical properties of soils is the first step to build a solid scientific basis for earth material science, and it is fundamental because its characteristics change continuously. This lack is reflected in most of the corresponding Standards, hence earth material is not seen yet as confident as other construction materials.

So, even if the research is moving on, lacks in standards produce less experimentation in production, with the result that earth products are not highly industrially manufactured and unknown to many professionals and builders in more industrialized Nations. The lack of several practical experiences generates lack of progresses in the development of new and performant constructions techniques, and the topic of integration of reliable earth products in safe and earthquake-resistant constructions is not even treated.

Raw earth buildings have historically suffered the lack of standardized performances and seismic hazard as witnessed by many vernacular earthen architectures [20]. So, when attempting at defining an innovative raw earth constructive technology, attention must be given to these aspects. Indeed, new contemporary technologies, based on raw earth materials (which are sustainable because of their low embodied energy and high recyclability) can be optimized and implemented inside seismic-resistant constructive technology, thus ensuring also good hygrothermal conditions. This optimization can be pursued by the control of materials' production chain. This perspective is confirmed by the birth of similar research aiming at innovating the use of raw earth in construction, like the COBbauge project [21] leaded by the University of Plymouth.

It is obvious that technological solutions that provide massive masonry, such as raw earth masonry, are preferable in contexts characterized by mild climates, precisely because their high thermal mass moderately balances the temperatures and humidity inside buildings, maintaining comfort conditions in buildings, as reported by several authors [22 - 24].

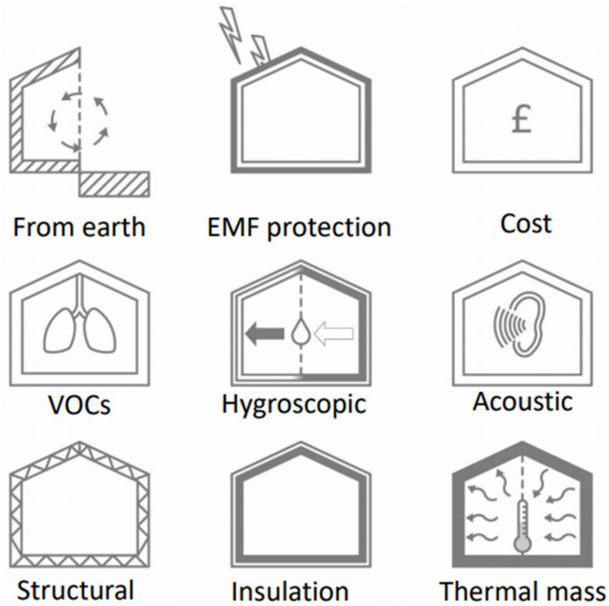

Figure 3 – Advantages of raw earth constructions explained in the COBbauge project [20].

Raw earth construction also boasts the possibility of being adopted practically everywhere and has a low environmental impact in terms of manufacturing and processing. Finally, when not mixed with chemicals that lead to material changes, the raw earth composites can be reused and therefore have a practically infinite life cycle. It is therefore understandable how the study of a new raw earth constructive technology (combined with other natural and/or recycled materials such as fibers or framing in reeds, wood, etc. to improve its structural behavior), is driven by the context within which we are moving to achieve a high thermophysical performance to meet the high energy standards required by current regulations.

National Italian production strategies point out the importance of innovative and environmentally friendly materials as possible development trajectories in the field of Smart and Sustainable cities. The choice of rethinking raw earth production in a 21st century point of view seems to be promising, but it is hindered by the backward Italian building code. Indeed, Italian technical standard for constructions [9] does not address indications for new earth-based buildings, and poor attention is given to historical raw earth heritage. Earthen architecture heritage is rich in variety and spread all over the Peninsula [25], and some regions as Piedmont and Sardinia are endowed with some guidelines for the rehabilitation of rammed earth and adobe vernacular buildings respectively [25 -27]. Even so, a national debate on new constructions based on the use of raw earth material is still missing. The lack in standards produces reluctance in the construction and production sector, with the result that Italian earth-based production is mainly working on raw earth coatings and plasters. In the NTC 2018 [28] there are not guidelines for the structural design of load-bearing raw earth walls, fact that usually discourage designers; a solution for this issue could be found using mixed constructive systems, where raw earth walls are combined with standardized load bearing structures (concrete, steel or wood) which can enhance the brittle seismic behavior of raw earth walls, improving their structural performance, without increasing their environmental impact.

In the last years, we observe a progressive adaptation of earthen techniques (above all rammed earth) to existing concrete and steel technologies, which means combining rammed earth walls with high embodied energy materials, more expensive and less sustainable ones. The lack of data about the compatibility between these materials which have different hygroscopic and seismic behaviors, and which have not been used together historically, raises strong doubts about the durability of these hybrid technologies.

The idea behind the research is that it is possible to identify a rammed earth-based contemporary technology that combines the advantages of working with natural, healthy, poorly processed and reduced environmental impact material, with the need to ensure certainty in the mechanical and thermophysical performance of the system.
This can be done by partially industrializing the production process of earthen masonry, without altering the beneficial properties of the earthen material and avoiding the use of highly polluting materials such as concrete, steel and thermal insulations from chemical synthesis, as done by most of the earthen-based construction systems currently in use in Western Countries.
The motivations which move this study are in this way related to the needing of finding new sustainable constructive technologies for rammed earth construction, which can be nevertheless highly performative in terms of structural and energy performances, characterized by simple and economic constructive processes.
Therefore, the main aim of the research is to design a type of engineered rammed-earth construction capable of high performance without losing its environmental sustainability characteristics. This technology aims to be reliable, recyclable and competitive in the current construction sector by the adoption of semi-industrialized production processes.
The importance of performance oriented-design for rammed earth construction can be understood regarding the high qualitative standards required by construction sector, which is, as we said, traditionally diffident towards natural material-based products.
Construction sector needs to look to brand new rammed earth products as confident building materials to be implemented inside constructive systems which can conjugate efficient structural performances (even against seismic events) with high thermal and energy performances, cost-effectiveness, and environmental sustainability. To pursue this programmatic aim, we needed to separate it in several practical objectives, which are:

1) the design of a premix material for rammed earth masonries, with superior physical, mechanical and thermal performances;
2) the adoption of seismic-resistant design principles for rammed earth buildings; this involves finding correct design principles for the reinforcements of the constructive system and to adapt the constructive process for their integration;
3) the validation of the correctness of vertical envelope's stratigraphy design by the control of the building system's hygrothermal and energetic performances.

The adoption of earthen construction in general, and rammed earth construction, can contribute to the reduction of environmental risks related to the construction sector, in line with current trajectories of energy containment and reduction of environmental impacts related to the production, construction, use and end-of-life of buildings.
Therefore, the present thesis will focus on the feasibility of designing an innovative rammed earth construction whose performances (on the material, on the building and energy system scales) are defined by a careful design of the production and construction process, by maintaining the sustainability of raw earth construction. Answers to this design issue have been investigated in the rammed earth-base material composition, in the constructive system design and process and in the validation of the hygrothermal and energy performances trough different research methods (respectively experimental research, prototyping and simulation), following the methodological approach of the research by design. These aspects have been investigated from a production point of view, seeking to standardize the performances of the material used in the designed constructive system.

In the guidelines provided by the Italian SNSI document – National Strategy of Smart Specialization [29], there is a great focus on how the tendency to innovation in less developed regions or countries is often realized by informal activities, without structuring framework provided by National guidelines. The Italian Innovation system, which represents the universe of actors and relationships which co-create the knowledge and its transformation in new processes and products, is nowadays pointing out at bio-economies as one of the main trajectories of development. As [29] points out, there is a delay in the connection between productive sector and Research, with the big penalization of preventing the integration of scientific research results inside new products and services. This attention must be incorporated within the Research Activity to reflect on the real world, in the so called third-mission activities (development of patents, spin off companies).

The basic idea of the SNSI is to identify, strengthen and valorize some productive sectors which have paramount importance for Italian Peninsula, and to encourage the constitution of nets and national research and innovation supply chains, so to cause a transformation in the Italian Production System and, finally, to enhance the welfare of the citizens. In this sense, the collaboration of Universities, Research Centers and local Actors from the Productive sector is firmly encouraged. The SNSI found some National Thematic Areas of intervention, through an entrepreneurial discovery campaign. These thematic areas therefore provide for the integration into a "single sustainable economic cycle" of the demand and supply of innovative products and services and the simultaneous development of the enabling technologies necessary for the creation of subsequent generations of products.

Based on the evidence that emerged from the analysis of the economic and technical-scientific context and the regional Intelligent Specialization Strategy Papers, combined with the strategic needs of the territory dictated by a harmony between top-down and bottom-up processes, 12 areas of specialization have been identified:

1. Aerospace;
2. Agrofood;
3. Blue Growth;
4. Green Chemistry;
5. Design, creativity and made in Italy;
6. Energy;
7. Intelligent Factory;
8. Sustainable Mobility;
9. Health;
10. Smart, Secure and Inclusive Communities;
11. Technologies for Living Environments;
12. Technologies for Cultural Heritage.

The following research works mainly in the field of intelligent factory, having contacts with agrofood, energy and technologies for living environments thematic areas. Moreover, it fits in the context of integration of Research Activity and Production Sector, through the collaboration with a local company called Guglielmino Società Cooperativa [30], based in Misterbianco (Catania, Italy). This company, originally manufacturing bricks, is nowadays focusing on the re-discovery of traditional mortars based on lime technology, natural premixes, and green building products. This company has provided the soil used in the first part of the investigation, an educational activity on natural materials-based technologies and know-how transfer. Also, it has participated in the patent application on the constructive technology herein presented and facilitated the construction of the prototype of the wall for the technology validation.

1.2 Thesis roadmap

In order to help the reader, in figure 4 it is shown a map of the thesis.

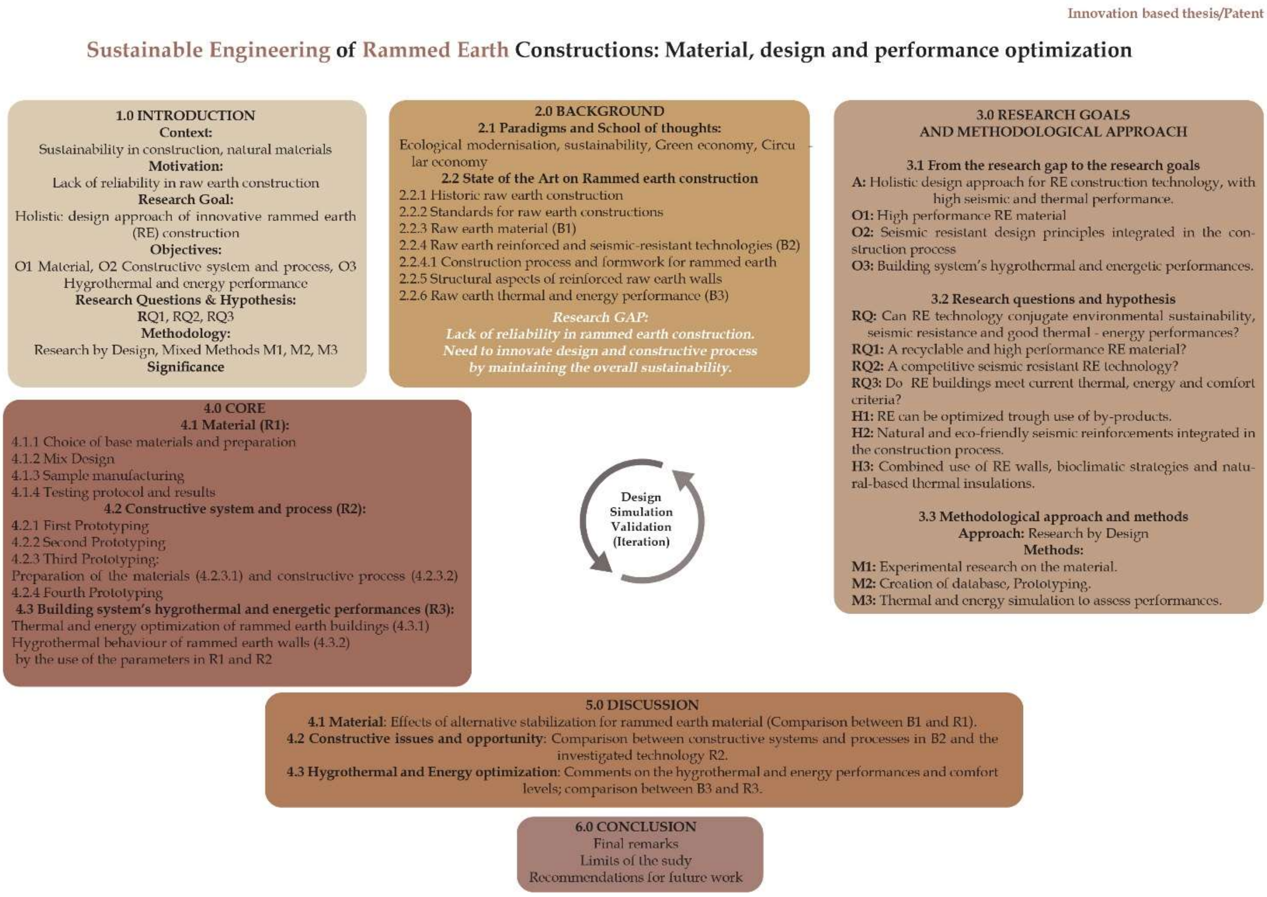

Figure 4 – Map of the thesis.

The following Ph.D. Thesis has been developed within the Ph.D. Course of Evaluation and Mitigation of Urban and Land Risks of the University of Catania. More in detail, it inherits the research curriculum of "Planning and project for the territory and the environment" of the abovementioned Ph.D. Course, as the Thesis moves in the context of increasing the sustainability in construction sector and performance optimization of bio-based materials for future building stock. The thesis belongs to the Area 08 - Civil engineering and architecture, and in particular to the scientific sector ICAR 11 – Building Production of the academic discipline list for Italian university research and teaching. This research has been funded with a PON Research and Innovation 2014-2020 for Innovative Ph.D. at Industrial characterization.

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2. Background

In this section we will focus on the background of the conducted research. In the first paragraph, we deal with the paradigms and school of thoughts the research belongs to.

In the second paragraph, a wide state of art on contemporary raw earth construction is presented, where information is organized in several sub-paragraphs including:

- *an overview on historic raw earth construction (2.2.1) ;*
- *a summary of the most important standards for raw earth construction with focus on the seismic-resistant standards (2.2.2);*
- *a literature review concerning the cutting-edge research on raw earth material optimization (2.2.3);*
- *a state of the art on raw earth reinforced and seismic resistant construction systems and processes (2.2.4);*
- *a focus on the structural behavior of reinforced raw earth construction (2.2.5);*
- *a literature review on raw earth thermal and energy building performance (2.2.6).*

As we will see in the section, the analysis of the background has highlighted the need to increase reliability on raw earth and rammed earth construction through the material's performances optimization and the improvement of the design and constructive processes of raw earth buildings. Finally, the analysis shows also the need to assess the real thermal and energetic performances of rammed earth building on the base of experimental results on materials.

2.1 Paradigms and School of Thoughts

As it is one of the most energy-intensive and polluting sectors, the construction sector has long been subject to strong pressure (regulatory and productive) to reinvent itself in order to reduce its environmental impact, [1, 2]. The current European development guidelines outline a clear plan of action for the existing and emerging building stock, in which the requirements for energy saving, resource management at the basis of the production, construction and use phases, and the containment of the quantities of waste and pollutant emissions produced, become real design paradigms.

These previous issues represent the background for the research paths exploring new and integrated approaches to the circular economy and the 'three Rs' (reuse, reduce, recycle) approach.

The circular economy approach contests the take-make-waste extractive model adopted by industry nowadays; rather, it aims to redefine the concept of growth, based on the combination "positive society – wide benefits". The basic idea is to dissociate economic activities from the depletion of finite resources and production of wastes. Circular economy builds economic, natural and social wealth being supported by the shift to renewable energy sources, through the minimization of waste and pollution, by keeping the products and materials in use and regenerating natural systems.

In this system, economic activity builds and rebuilds system health, working effectively at all scales: from large and small businesses to organizations and individuals, both globally and locally. Circular economy does not aim to change and reduce the negative impacts of linear economy; it also embodies a systemic change that builds long-term resilience, generating business and economic opportunities, thus providing environmental and societal advantages [3].

The circular economy model differentiates between technical and biological cycles. It is assumed that consumption happens in biological cycles, where food and biologically based materials are designed to feed back into the system through processes (like composting and anaerobic digestion). These cycles regenerate living systems, such as soil, which provide renewable resources for the economy. Indeed, technical cycles recuperate and refurbish products, components and materials through strategies like reuse, reparation, remanufacture or (as last expedient) recycling.

Circular economy has its roots in historic and philosophical ideas of feedback of cycles in real-world systems. This notion lived a revival in industrialized countries after the second World War, when computer-based studies of non-linear systems explicitly revealed the complex, interrelated, and unpredictable nature of our reality, in a world which works more like a metabolism than a mechanism.

Finally, it should be noted that circular economy model synthesizes several major schools of thought, like:

- the functional service economy (or performance economy) of Stahel [4];
- the Cradle-to-Cradle design philosophy of McDonough and Braungart [5];
- the biomimicry as enunciated by Benyus [6];
- the industrial ecology of Lifset and Graedel [7];
- the natural capitalism by Lovins and Hawken [8];
- the blue economy systems approach by Gunter Pauli [9].

Conversely, the 'three Rs' (reuse, reduce, recycle) approach examines the concept of "waste hierarchy". Waste hierarchy is defined as the order of priority of actions to be taken to reduce the amount of waste generated from human activities and to improve overall waste management processes and programs.

The waste hierarchy consists of 3 R's as follows:

(1) reduce
(2) reuse

(3) recycle

Sometimes another 'R' is added making it 4Rs. That fourth 'R' is "recovering". The 4Rs solutions often results from an industry benchmarking or technological innovations in more innovative companies. After applying the 3Rs principles, it may be possible to recover materials or energy (like electricity, heat, fuel and compost through thermal and biological means) out of the waste which cannot be reduced, reused or recycled.

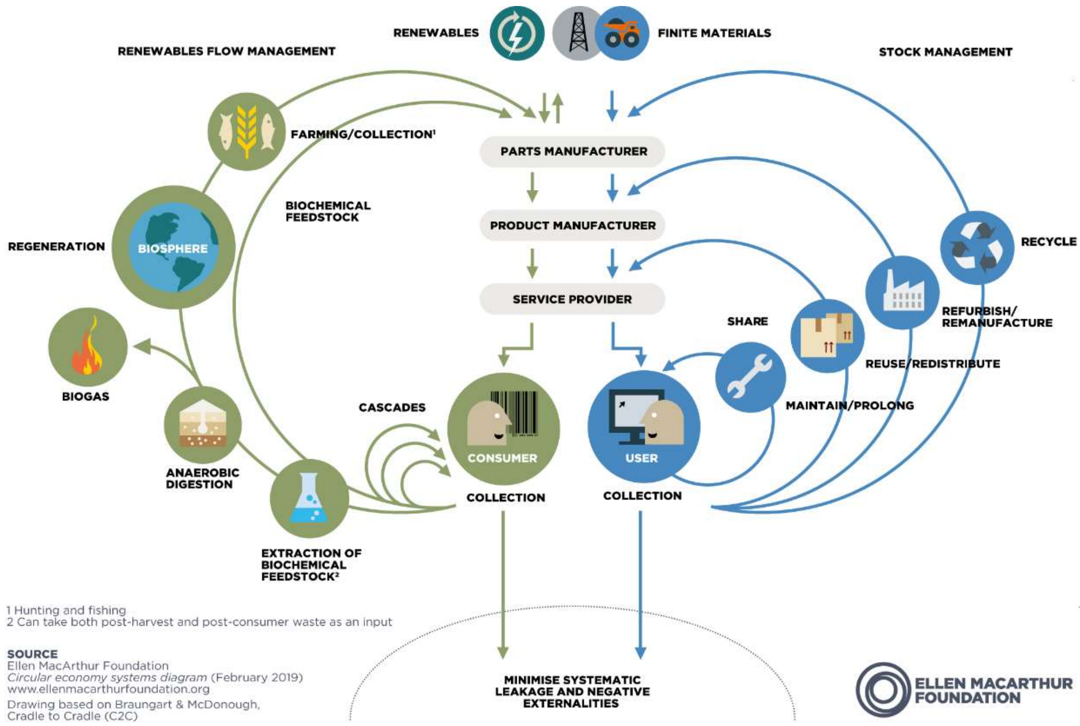


Figure 1 - Circular economy system diagram, Ellen MacArthur Foundation, 2019

The "three R's" of waste management is the guidance suggested for creating a sustainable life: *"The three R's – reduce, reuse and recycle – all help to cut down on the amount of waste we throw away, conserve natural resources, landfill space and energy. Plus, the three R's save land and money that communities must use to dispose of waste in landfills. Siting a new landfill has become difficult and more expensive due to environmental regulations and public opposition"* [10].

We will now briefly explain the three approaches to waste reduction to better understand the importance of the order in waste hierarchy. First of all, the concept of "reducing" what is produced and what is consumed is essential to the waste hierarchy. The logic behind it is simple to understand – if there is less waste, then there is less to recycle or reuse. Secondly, learning to "reuse" items or to repurpose them for uses different from what they were thought for, is essential in the waste hierarchy. Repurposing items saves them from landfills and does not necessitate the additional expenditure of natural resources to create new items to be used in a system. Finally, the last stage of the waste hierarchy is to "recycle". To recycle something means that it will be transformed again into a raw material that can be shaped into a new item. There are very few materials on the earth that cannot be recycled. One of the issues concerning recycling efforts is that while the recycling collection and sorting process may be reasonably implementable, there still has to be a facility (and a convenience) to receive and transform (through the use of energy) the discarded waste into a new raw material.

Embracing the principles of circular economy, the idea is to couple recycling plants with industries that can process the waste material through agreements and incentive credits. This could generate several benefits, as:

- a significant reduction in the amount of waste and toxins dispersed into the environment, with an automatic reduction of the levels of greenhouse gas emissions and pollution;
- the elimination of improper waste disposal practices (burning waste and trash chaotically in an uncontrolled manner) and the encouragement to a more eco-friendly waste management, lessening the risk of damage to the environment;
- the contraction of the use of newer resources and energy, promoting, at the same time, resource efficiency by reprocessing the already available resources;
- the contribution to a more sustainable energy consumption as the resources available on hand are used, and excessive consumption is cut down.
- the development of green technology as ways to create cleaner, safer means of waste disposal while reducing the impact on the environment and all habitats;
- the increased use of renewable energy sources like solar, wind, geothermal, etc. as well;
- the conservation of energy and resources, the generation of jobs in resource management and the boost for local economies.

The combination of these two schools of thoughts has led to the rediscovery of natural and recycled building materials, which are characterized, at least on paper, by low emissions during production and low environmental costs for their disposal and/or reuse [11]. In this sense, the search for a new, more environmentally conscious, and responsible contemporary building embraces broader issues of climate and environmental justice. Therefore, the research goes beyond the traditional disciplinary boundaries in order to frame future construction models that also have positive consequences in the social and economic spheres [12, 13].

In the context of a research which aims at reintroducing materials of natural origin as the basis of tomorrow's construction, the historical memory of traditional building techniques plays a key role in sustainable design [14]. Building techniques based on the use of materials such as raw earth, historically used in a wide variety of geographical and environmental contexts, are now experiencing a strong revival because of their intrinsic sustainability [15-23]. This is due to the high availability of the base materials, the total recyclability of the earth mixtures (when they do not contain additives that alter their chemical composition), the low energy content and therefore the negligible environmental impact in relation to their manufacturing and transformation processes. The greater attention paid to raw earth construction can be further confirmed by the increased diffusion of several dedicated standards [24-33].

Figure 2 – Waste hierarchy scheme

2.2 State of the Art on Rammed Earth construction

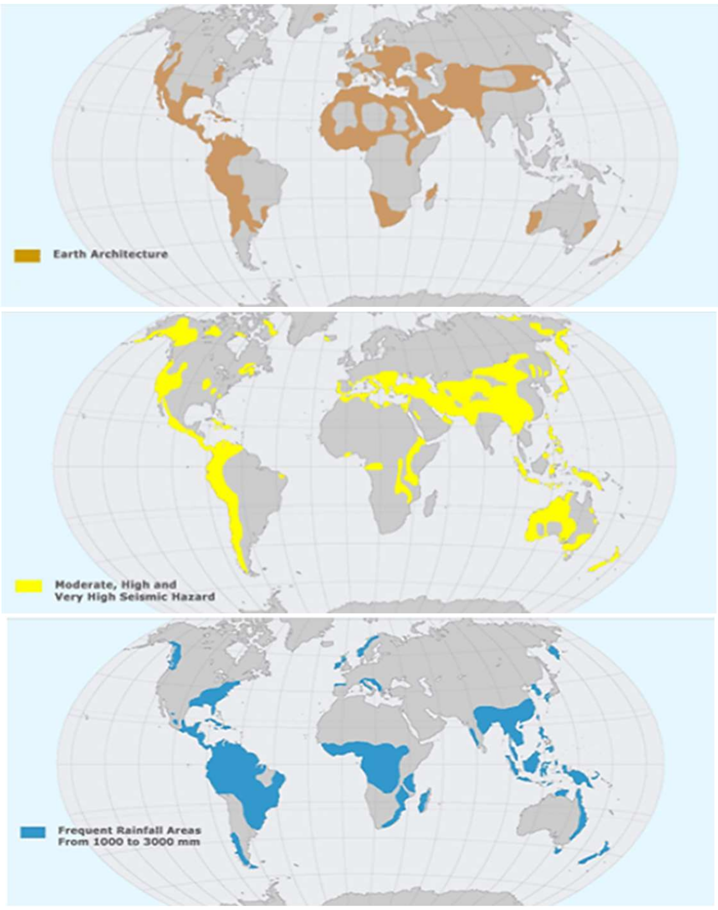
2.2.1 Overview on historic raw earth construction

Vernacular earthen building technologies, in their many facets, have been used throughout the world since the beginning of the history of human settlements some 10000 years ago. Earthen construction techniques such as rammed earth, adobe masonry, cob, lightened earth and wattle and daub are widespread from the Mesopotamian area to the Huang Valley, from Australia to Latin and North America, from Africa to Northern Europe [24], so that nowadays one in three inhabitant lives in earthen dwellings [34].

Such a large use of this material can only be understood if one considers the availability of earthen material, the simplicity of the construction process and the progressive adaptation of techniques to new uses.

The national and international literature on earthen architecture is copious and it is beyond the scope of this thesis to propose a more specific examination of earthen construction techniques. Here we will present a brief summary of the main historical earth building technologies, which will then guide us in understanding the main innovations made in today's earth building sector and the innovations proposed in this thesis.

Earthen architecture has always been considered the expression of a poor and not safe constructive technique, a belief that has been emphasized because of the industrialization process that has affected the building market from XIX century, further aggravated by the spread of false myths about the poor durability of earthen buildings to weather and seismic events. An interesting study carried out by the Houston Museum of Natural Science has highlighted how unfired earthen buildings are often concentrated in areas characterized by heavy rainfall and a discreet seismic risk, witnessing the fact that local populations have managed to refine their building traditions to make them safe against these risks (figure 3).



Figures 3 - Earthen architectures in the world (in brown) compared to high-seismic risk zones (in yellow) and frequent rainfall areas (in blue) [Source: Houston Museum of Natural Science].

As known, the use of earth as a building material is linked to the wide availability of the base material, which is the subsoil. The subsoil is the bottom part of the ground, which lays below the topsoil, an organic-rich layer used for agricultural purposes. Mostly, the earth used for construction is a mix of gravel, sand, silt and clay (the finest fraction of material which gives cohesion and binds together all the other components).
Depending on the composition of the soil, different uses have been adopted: local builders discovered by experience that more clayey soils (with clay percentages superior to 40%) should be mixed with sand or other aggregates (like straw or other natural fibers) to prevent shrinkage and cracking problems and to get more resistance; more sandy ones could increase the strength of the material, but they could lack of cohesion. The diversity of the composition of the base material is the reason why we see such a broad diversity of earth technologies and constructive systems. The synoptic CRATerre wheel [24] on earthen techniques is a good summarizing tool to understand the applicative possibilities of soil in construction (figure 4).

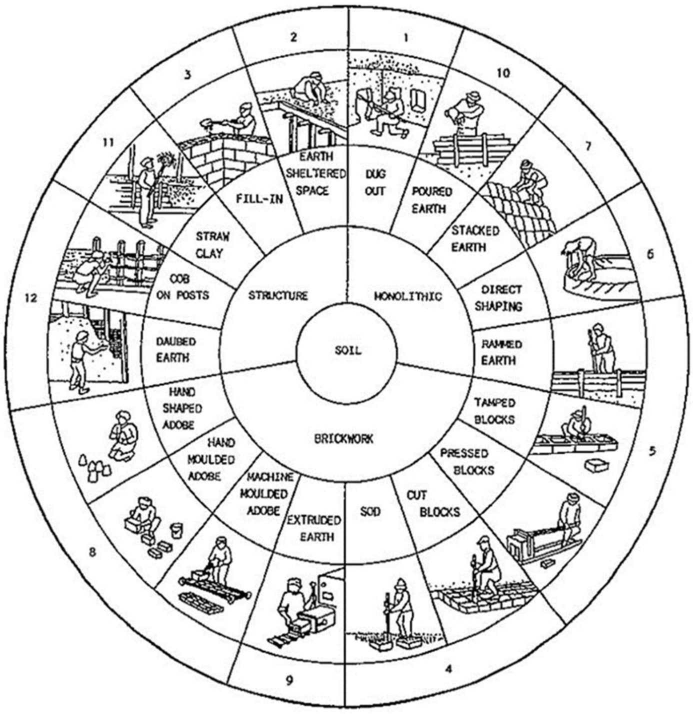


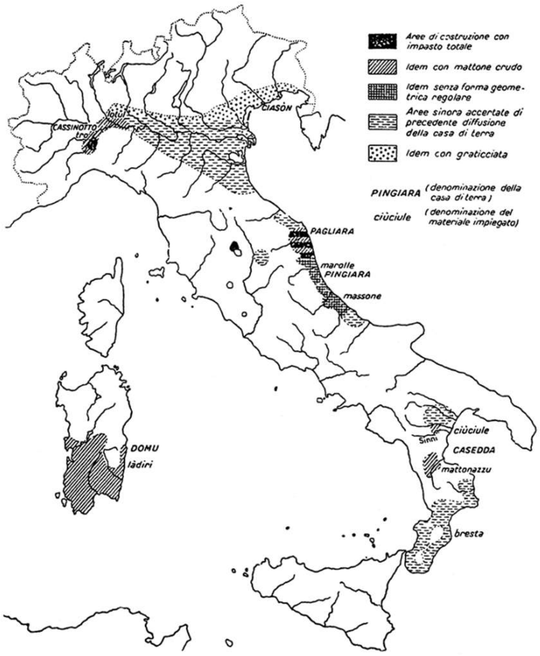
Figure 4 - CRATerre wheel on raw earth applications [24].

The traditional classification of earthen construction proposed by the CRATerre consists in a subdivision of techniques based on the load-bearing system. Three types of earthen construction are identified: monolithic, masonry and infill. To these is added the group of raw earth techniques used for finishing purposes (plasters, floors, etc.). Among the monolithic techniques, the most famous are the rammed earth (or pisé in French), the *bauge* (French term) or cob (corresponding English term) and the innovative earth concrete (*terre coulée* or *béton d'argile* in French).
The masonry techniques include adobe masonry, from which descend contemporary masonry composed by compressed earth blocks and extruded blocks.
Finally, the term “infill techniques” refers to non-load bearing uses of raw earth in constructive techniques. These include all construction techniques in which unfired earth is used in combination with a main load-bearing skeleton, usually wooden, canes or bamboo frames, onto which the unfired earth mixture is then adhered (*inter alia*: wattle and daub, *quincha*, *tabique* etc.).
Unlike other European countries, Italy has not preserved a consistent amount of earthen architecture heritage, except for some areas where they have been maintained and studied. This situation is due to a process of

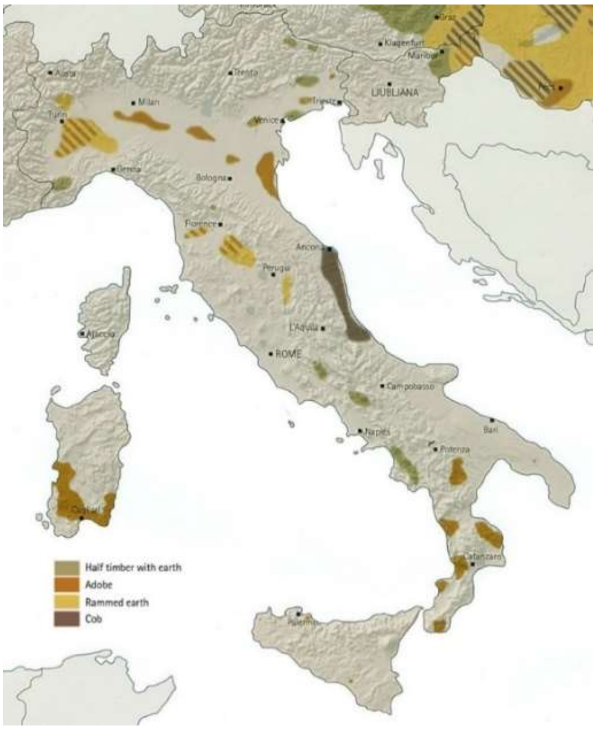
oblivion and removal in the late 19th century, which has affected both the construction technique itself and the existing building stock. Among the causes of this abandonment, the loss of the traditions caused by agricultural production and the increased economic resources due to the advent of industrial production.
The most common construction techniques on the Italian peninsula are adobe, rammed earth and *massone* (similar to cob technology) [35].
In Lombardy, rammed earth constructions are present in Pavia and Mantova areas (the so-called *Oltrepò*). This heritage is increasingly at risk because it is localized in rural farmhouses, considered poor artefacts and therefore unworthy of appropriate monitoring and conservation. In these farmhouses, the degraded rammed earth structures have gradually been replaced by burnt brick walls that have altered the original structure [36].
A similar situation has occurred in Piedmont, in Alessandria area, where the rammed earth farmhouses have been remediated with not compatible interventions which have accelerate the degradation processes. Despite this, it is worth mentioning the case of Piemonte as the only region at national level which is endowed with guidelines [37] for the recovery of rammed earth historic buildings, which have been protected since 1990, to promote conservative restoration interventions.
In Abruzzo and Marche, the presence of a considerable earthen heritage, combined with the creation of the CEDTerra (Centre for Documentation on Earth Houses) has led to greater attention to this heritage, which has been involved in recovery plans such as the Macerata's one, in 1995. In these regions earthen architectures are now subjected to the jurisdiction of the Superintendence and they are interested by several activities of research, dissemination, and documentation [38].
At a national level, the Study Centre on Earth Architecture of the University of Cagliari (LABTerra) stands out for the process of study, survey, cataloguing and recovery it has carried out on many adobe artefacts in the Sardinian territory [39 - 41]. The research activity of the UniCa group has also led to the publication of various scientific contributions and construction/recovery manuals. This commitment has led to the recognition of the title of UNESCO Chair in Earthen Architecture to this research group.
Finally, in Calabria, numerous cases of raw earth buildings have been found; in this specific case, many of these are *case baraccate*, seismic resistant houses built after the 1783 earthquake in Southern Italy: in these buildings, walls are made with half-timbered technology with a raw earth infill at the plastic state. In Sicily, few traces are left: the *Timoleonte* fortifications of Capo Soprano, in Gela, whose top part was built in adobe, and some adobe walls in civil homes in Cefalù (Palermo) [42- 43].
As we will see in the next paragraphs, the recognition of an existent raw earth vernacular heritage is only the first step to raise awareness on this type of construction. It allows for the implementation of processes of:

- valorization of traditional earthen architectures;
- sustainable recovery of the architectural heritage and maintenance of the territory;
- recovery of isolated houses and villages as presidium for the understanding of the rural landscape;
- participation of the community in the conservation of its cultural and economic heritage;
- implementation of recovery practices as premise for the development of a contemporary raw earth-based construction.

Concerning the last point, Italy seems to be quite reluctant to open up to contemporary raw earth construction. This assumption is supported by the delay in the elaboration of a specific standard (see paragraph 2.2.2) by competent authorities, fact which is quite surprising when we consider the amount of conducted research (and consequent results) provided on raw earth materials and constructions in several Italian Universities as, for instance, University of Florence, Polytechnic University of Milan, and University of Cagliari. Nevertheless, this keen academic interest on the rediscovery of this type of building technology is maybe the most interesting signal when we consider that investigations are quite often realized together with national industrial partners. Companies today feel the need to spend in the innovation of the construction sector in a green perspective, not only pursuing economic savings in the long run, but also because it is necessary to create a strong ecological and sustainable corporate image. Following the examples of what happened in France, Austria, Germany, Spain and England (just to cite some European examples), the thriving collaboration between universities, companies, architectural and engineering firms and practices may lead to the need for adoption of a standard for new earthen construction.



Figures 5 - Earthen Architecture mapping in Italy in 1958 [44].



Figures 6 - Earthen Architecture mapping in Italy in 2011 [45].

2.2.2 Standards for raw earth constructions

The international regulatory panorama on raw earth (in general) and rammed earth (in particular) appears to be very fragmented: the analyzed documents are Standards from national Standards Bodies and Regulations, Rules, Guidelines. This means that the nature of these documents is not always prescriptive. However, a good number of Nations have already endowed themselves with regulations covering various aspects of raw earth construction. These aspects generally include the study of the base material and the determination of its performances, especially in relation to the mechanical strength and durability. These indications are useful because they make it possible to control the production process, the design and construction phase.

The most authoritative regulatory examples are the package of standards adopted by New Zealand has adopted and the Peruvian standard, which are also the only two standards related to construction in seismic zones. Another very complete regulation is the German one, issued in 2013, which, together with the above-mentioned ones, deals with subjects as the choice of soils, the structural design phase and aspects related to the durability of buildings. Provisions relating to the construction and execution phases are found in the Peruvian, New Zealand, New Mexico, Zimbabwe and ARSO standards.

Comparing the different standards, it is the performance of the finished product (adobe or CEB masonry, rammed earth wall) that must be verified, through a series of laboratory tests properly explained in the texts. In all the standards examined, the possibility of using the raw earth wall as a load-bearing material is reported. There are often limitations related to height and therefore above-ground floors, use-categories, surfaces and operating loads. In the following table 1 we present a brief overview on contemporary normative documents on raw earth construction.

Table 1 – Adaptation of the table proposed by Achenza et al [46]

Normative Group	Name	Ref	Building Technique	Contents					
				Soil Type	Product Performance	Laboratory Characterization	Manufacturing aspects	Construction	Design
African Regional Organization for Standardization - ARSO	ARS 682/1996	47	CEB	x	x	x	x	x	x
Brasil	ABNT NBR 10836/2013	48	CEB, solid and hollow	x	x	x	x	-	-
Colombia	NTC 5324/2004	49	CEB	x	x	x	-	-	-
France	XP P13-901/2001	50	CEB	x	x	x	-	-	-
Germany	DIN 18945/2013	51	Adobe	x	x	x	x	x	x
India	IS 13827/1993	52	Adobe, CEB, Rammed Earth	x	x	x	-	x	-

Contents

Normative Group	Name	Ref	Building Technique	Soil Type	Product Performance	Laboratory Characterization	Manufacturing aspects	Construction	Design
Kenya	KS 1070:1993	53	Adobe, CEB, Rammed Earth, Poured Earth	x	x	x	-	-	-
New Zealand	NZS 4297:1998 NZS 4298:1998 NZS 4299:1998	29,30, 31	Adobe, CEB, Rammed Earth, Poured Earth	x	x	x	x	x	x
New Mexico	NMAC 14.7.4/2004	54	Adobe, CEB, Rammed Earth	x	x	x	-	x	-
California	Proposal RB299-19	55	Cob	x	x	-	x	x	x
Peru	NTE E 0.80/2017	25	Adobe, Rammed Earth	x	x	x	x	x	x
Spain	UNE 41410/2008	56	CEB	x	x	x	-	-	-
Sri Lanka	SLS 1382/2009	57	CEB	x	x	x	x	x	x
Tunisia	NT 21.33/1996	58	CEB	-	x	x	-	-	-
USA	ASTM E2392 M-10	59	Adobe, Rammed Earth	x	-	x	x	x	-
Zimbabwe	SADC ZW HS 983:2014	60	Rammed Earth	x	x	x	-	x	x

As we reported, in the last thirty years, technical codes and guidelines for earthen construction have emerged in several Countries. These attempts at standardization are important because, in the absence of a fully defined material science of earthen construction, these standards provide guidelines for the design of the basic material, for the evaluation of its characteristics, and for the identification of a series of useful design expedients to avoid errors or risks to the construction (maximum spans and heights, slenderness of the load-bearing elements, arrangement of openings, reinforcements and connections between perpendicular walls, etc.). Among the listed technical standards, the New Zealand and the Peruvian ones are the most complete.
In the New Zealand Standard [29] are provided indications for the structural and durability design of unfired earthen wall. These walls can be made by adobe, pressed brick, poured and rammed earth which should

comply with the standard [30], more related to test methods to assess material properties and define acceptability criteria. The last part [31] concerns earth buildings not requiring specific designs and reports several constructive details to help builders.
The NZS 4298:1998 is particularly interesting because it provides wide indications about material testing procedures, which have been reported in other international standards; however, most of the recommendations are vague about the physical composition of the material (as the maximum particles size and the amount of the different soil fractions) because it depends on the resources available on site and on clays mineralogy (qualitatively detectable from the determination of Atterberg limits). Soil composition has always to be double-checked using mechanical, visual and physical tests.
Some standards, as the [25, 30] give indications about the storage of samples after manufacturing. The specimens should be stored in a dry place. Considering practical indications given by the constructor Martin Rauch (Lehm Ton Erde), seven days drying process is necessary for 10 cm of unstabilized rammed earth. Samples stabilized with cement will be considered ready from 28 days after their production. All regulations agree on this point.
For [30] curing process should be as follows: seven days of wet curing (under plastic sheet) and then 21 days of dry curing, in a cool, dry place protected from direct sunlight, rain and strong winds.
The lime-stabilized samples (hydrated or hydraulic lime) need more time for curing, about three times the one of the cement-stabilized samples. Curing process should be as follows: 3 weeks of wet drying (under plastic sheet) and thereafter a dry curing in a cool, dry place protected from direct sunlight, rain and strong winds.
Days when the temperature is below 5 degrees should not be included in the count.
The most important mechanical test to be ran for structural purposes is the unconfined compressive strength test, where the rammed earth samples (prisms or cylinders, depending on the standard) should exceed basic resistances going from 1.0 MPa [25] to 1.3 MPa [30]. Not all the cited standards agree on the shape and dimension of samples for UCS measurement on rammed earth, cubes are accepted in [25, 34, 35, 47, 48], but for rammed earth is sometimes suggested to use an aspect ratio (ratio between height and width) ranging from 0.4 to 0.5 (i.e. h=10 cm, l=20 cm) and loaded as they would be inside the walls (force is applied perpendicularly to the horizontal layering). The ultimate tension must be multiplied by a correction factor, k_a, which considers the non-confinement of the sample. The test must provide information on the age of the samples, their dimensions, and their mass.
Other important tests for rammed earth, contained in [30], are:

- the wet/dry appraisal test: it aims to assess the effect of stress determined on the earth mixes by wetting and drying procedures;
- the erosion test (with the pressure spray method and the Geelong method): both used to assess if erosion caused by water is too severe on the earthen material;
- the shrinkage test: to check if excessive shrinkage of mixes is registered. Specimens have to be manufactured as the wall material (same compaction energy, same moisture content and texture). The material has to be put in a shrinkage box with dimensions 4 x 4 x 60 cm, which has to be protected by fat or oil. The sample has to cure for 28 days in the case of cement stabilized specimens, at least 3-times more than for lime stabilized specimens. When curing is over, the linear shrinkage of the specimens has to be less than 0.05 % of the initial length;
- the mix moisture content drop test: to check the correct amount of water for the installation of rammed earth in the building site;

An important test is missing in [30], but it is reported in [32]: the absorption test, an easy durability test made on cube-shaped samples. For this test, samples have to be put in a recipient with a 3 cm height of water and allow to soak water in order to understand their behavior towards the phenomena of capillary absorption. Measurements of the height of rising water are made at regular time intervals on the sample's faces and have to be compared to reference ones to consider the samples acceptable.
Most of the standards in table 1 reports a massive use of reinforcing devices inherited by concrete-based technologies. Use of steel rebars in raw earth and rammed earth construction is explicitly recommended to increase their structural performance, especially when used in earthquake prone countries [29 – 31, 36, 37, 41 - 43, 47, 48]. Furthermore, explicit reference to soil stabilization (i.e. optimization) by the use of Portland cement and lime is present in most of these standards [29 – 31, 36, 37, 41 - 44, 47, 48]. The use of these products should be avoided when possible because it reduces the recyclability properties of natural earths.
The Peruvian Standard NTE E.080 [25] follows a different design philosophy about materials and buildings. For its peculiar attention to the use of natural-based and economic reinforcements, easier to be found in the difficult social, economic and geographic conditions lived by most of the country (especially the Andean territories), it stands as a *manifesto* of a sustainable earth building standards to be used also in territories characterized by a high seismic risk. Moreover, it promotes the construction of accessible, low-cost, environmentally sustainable, energy, thermal and acoustic efficient reinforced earth buildings.
All the detailed information from here on reported have been acquired during the visiting at the Centro Tierra – Pontificia Universidad Catolica de Peru, and kindly granted by the local tutors Prof. Arch. Sofia Rodriguez Larraín Degrange and Prof. Eng. Julio Vargas Neumann.
For the past fourty years, earth construction standards have complemented the fundamental function of the E.030 Peruvian Earthquake Resistant Design Standard, which aims to avoid loss of life, ensure continuity of basic services and minimization of property damage.
The main advances of the NTE E.080 [25] with respect to previous standards are:

- the need to find safe location for buildings;
- the identification of minimum requirements to be met by the soil;
- the requirement of mandatory reinforcement for earth walls;
- the requirement of compulsory connection elements between footings, walls and roof structure;
- the inclusion of rammed earth constructive technique.

The design philosophy is to allow slight wall cracks during mild earthquakes; during moderate earthquakes, are allowed larger cracks without causing damage to the occupants, with consequent structures reparation costs to be reasonable. Finally, in severe earthquakes, considerable structural damages are allowed, with permanent deformations. Fragile failures and partial collapses that endanger the lives of the occupants must not occur.
Some basic requirements for this kind of buildings are the choice of building location in areas without danger of flooding, avalanches, alluviums and geological instability. Raw earth building should be realized as single story house, and only where seismic risk is lower, it can reach up to two floors. The structural design of these buildings is based on Resistance, Stability and Seismic-resistant behavior. From a geometric and architectural point of view, wide walls for greater resistance and stability against overturning must be adopted, with cross section thicker than 0.40 m; walls must be provided of horizontal braces (floors and ceilings) as well as vertical braces (buttress or transversal walls). The density of walls in the direction of the main axes have a minimum value according to the use of the construction.
In fig. 7 are reported the main geometrical limits concerning walls and voids.

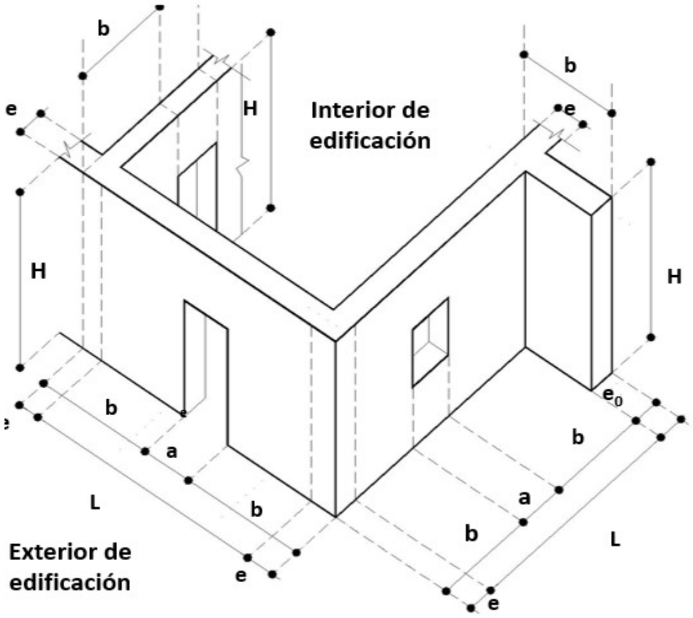


Figure 7 - Geometrical limits for walls and voids for the NTE E.080 [25].

In order to understand these limits, some entity must be defined (see tab. 2).

Table 2 - Geometrical limits for walls and voids for the NTE E.080 [25].

Formula	Description
I) $e_0 \geq e$	Relation between the thickness of the buttress and the wall. Buttress can be rectangular or trapezoidal. Buttresses can be built to the inside or to the outside, depending on the designer.
II) $a \leq L/3$	Opening width must be inferior to the third of the length of the entire wall.
III) $3e \leq b \leq 5e$	The distance between openings and buttress must be comprised between three and five times the thickness of the wall.
IV) $L + 1{,}25H = 17{,}5\ e$	This expression relates the vertical slenderness ($y_v=\lambda_v=H/e$) and the horizontal one ($y_h=\lambda_h=L/e$). In general, walls must respect these values of slenderness: - $\lambda_v \leq 6$ e or any other value respecting the (IV) - $\lambda_h \leq 10$ e
V) $\lambda_h + 1.25\lambda_v \leq 17.5$	Same as (IV)

The Stability criterion defines the limits of thickness, vertical slenderness and horizontal slenderness of the walls. Vertical slenderness is somewhat more critical than horizontal slenderness, due to the lack of upper support. It considers the size and location of the voids, to avoid arrangements that make the walls and masonry dihedrals unstable.

The performance criterion on seismic behavior complements the design criteria based on Strength and Stability (which alone or in combination are not sufficient) and requires the placement of reinforcements to control displacement during earthquakes. It establishes the need of connections between roofs, walls and foundations, upper collar beam, flexible lintels, orthogonal reinforcements (mesh type) on both sides of the walls joined.

The standard encourages the use of natural and vegetal reinforcements as:

- entire canes (hollow or solid), approximately 25 mm in diameter as vertical reinforcement and split ones, as internal horizontal reinforcement;
- Wooden post with diameters greater than 25 mm as vertical reinforcement and natural ropes with a minimum diameter of 6 mm as horizontal reinforcement;

- Woven vegetable fiber branches, in packages with diameters of 25 mm as external vertical reinforcement and loose braided branches or ropes as external horizontal reinforcement, with diameters greater than 6 mm;
- Ropes made of *cabuya*, sisal or natural fibers braided into external orthogonal meshes.

Alternatively, meshes of synthetic material can be used, as polymeric geogrid. These meshes must respect these characteristics:

- Have a rectangular or square grid, with a maximum opening of 50 mm and integrated knots;
- Minimum tensile capacity of 3.5 kN/m, in both directions, for an elongation of 2%;
- All walls, including spans, must be wrapped with geogrids, tensioned manually and uniformly. The geogrids on both sides of the walls should be connected with synthetic ropes, with a maximum separation of 0.30 m;
- The geogrid should be properly anchored to the base of the overlay and to the upper collar beam.

If nylon ropes are to be used:

- Synthetic ropes with a diameter of 5/32" (3.97 mm) or larger must be used, except for ropes that connect the mesh on both sides of the wall, which must be at least 1/8" (3.17 mm) in diameter;
- The reinforcement meshes shall be external and embedded in the plaster, which also serves to consolidate existing constructions;
- The meshes must be formed by vertical and horizontal loops that wrap around the walls. The vertical confinement loops must be suitably anchored to the footing and to the upper collar beam;
- The meshes of each wall face must be joined every 0.40m maximum by cross elements (ropes);
- The separation between the horizontal ropes must be less than 0.4 0m for the lower third of the height of the wall, less than 0.30 m for the central third and less than 0.20 m for the upper third (without coinciding with the horizontal joint). The separation between the vertical ropes must be less than 0.40 m.

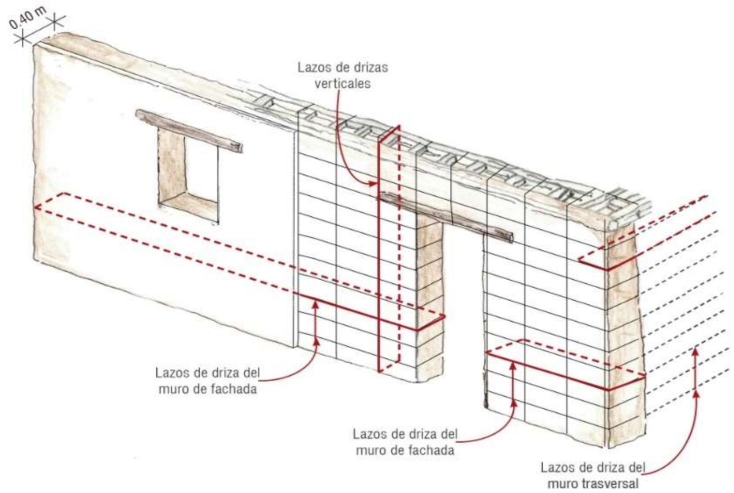


Figure 8 - Vertical and horizontal rope reinforcement (image granted from Centro Tierra PUCP).

In all suggested reinforcement technologies of the NTE E080, big attention is given to the wood ring beam at the top of the wall, because it constitutes a superior support for the walls and a stiffening diaphragm that achieves the joint work of all the walls it connects. It must be rigid, connected to the walls through the vertical reinforcements and made of material compatible with the earth.

Each longitudinal section of the ring beam is a beam itself, that controls the lateral movements of the upper edge of the walls. It is advisable to connect these longitudinal elements between them, by using diagonals instead of cross elements. The ring beam can be complemented with diagonal elements that join the thirds of the span of the four connected walls.

Other indications concerning floors and rooves are:

- Rooves should be lightweight, distribute their load over as many walls as possible and avoid stress concentrations;
- Rooves must be adequately fixed to the walls through the upper collar beam;
- The truss beam should not create horizontal thrusts on the walls;
- If the roof is not a rigid diaphragm, it is not considered as a superior support when designing the walls.

The NTE E.080 also indicates some protection systems against rain and rising damp. These indications are simple and traditional technological suggestions which influence the project enabling a more durable building:

- Foundations and basements prevent the walls from getting wet.
- Coatings or plasters protect the walls from rain, humidity and wind, and should allow the evaporation of humidity from the wall.
- Eaves not less than one meter (1.00 m) of cantilever should be used, adequately anchored and with sufficient weight not to be lifted by the wind.
- Perimeter slopes towards the outside of the building, allow the removal and evaporation of water.

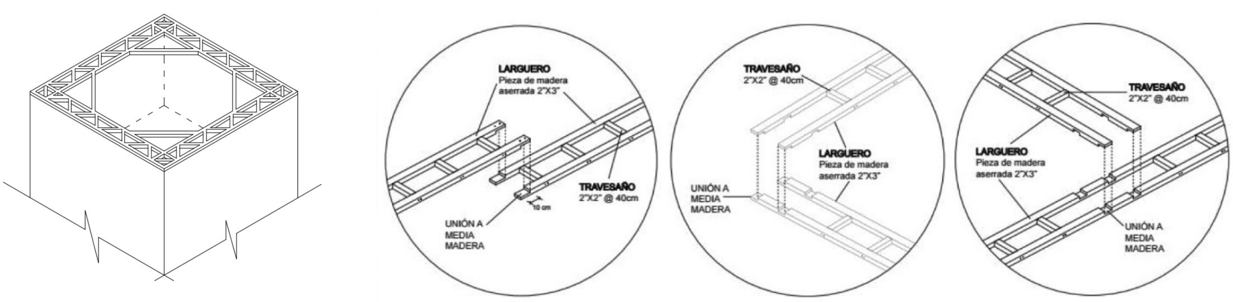


Figure 9 - Examples of wood ring beam (images granted from Centro Tierra PUCP).

2.2.3 Raw earth as construction material

Raw earth as a construction material is basically a mixture of grains of different sizes (gravel, sand, silts) bound together by the clays; the composition of soils varies significantly and for this reason different techniques were developed throughout time. We will now resume some of the traditional compositions and manufacturing techniques for different raw earth materials, depending on the adopted technology.

Contemporary adobe or unfired earth brick are prepared from natural cohesive soil where gravel is usually removed. Mixes are usually done adding materials as a percentage of earth material dry weight, blending the obtained mixes with an amount of water ranging from 15% to 35% and sprayed to avoid the formation of clay lumps. After that, the materials are blended (with mechanical equipment) until the mixture is uniform. Some authors [26] suggest leaving the earth hydrating by the action of water, for period of 12 to 48 h, to enhance the binding forces of clays. After that, bricks can be manufactured and cured in controlled conditions for a period ranging from 28 to 60 days.

More sandy-silty soils were traditionally used at a humid state to build rammed earth walls, where the material's resistance is enhanced by a compaction process implemented using wooden or iron "rammers" which where dynamically dropped on the surface of thin layers of the material, of about 10–15 cm. The amount of earth volume to be compacted is affected by the variability of manual work, building traditions and habits, and by the materials used for the "rammers", usually realized with materials available in the site. Soil grading used for rammed earth walls depends on the traditional mixes adopted by local builders and by the final properties which must be achieved: in no-seismic countries, soil used for rammed earth usually contains a clay percentage from 5 to 35% of the material's dry weight, silts from 10 to 30%, and sand percentages from 45 up to 80% [61], gravels and pebbles are often included in the mix, as they enhance durability of the surfaces [62]. In seismic countries as Peru and Chile, the coarse fraction (gravel and pebbles) is often reduced and natural fibers are added in the mixtures to improve their binding force, with positive effects on the compressive and tensile strength of the final material [25]. These materials are first dry mixed and then an amount of water corresponding to the optimum moisture content [30] as defined by a Proctor Test is added, usually ranging from 5 to 15 % of dry weight (several authors suggest using the Modified Proctor Test [63-64]). Some qualitative tests are available to double-check if the amount of water used is the right one (e.g., the Drop test, as for [65]). After mixed, the material can be poured inside formworks and rammed manually or through pneumatic rams, in layers with heights ranging from 10 to 15 cm.

A third family of earth techniques is the one using an earth slurry or clay slip mixed with big amount of fibers to implement a lightweight material, with high thermal insulating performances: it is usually known as straw–earth, light earth or lightweight straw loam in western countries, while in Latin America it is called *paja-barro* or *tierra alivianada*. Volhard [66] and Minke [67] among the others, explain that contemporary light–earth is usually prepared mixing the natural fibers with the earth slurry (a viscous liquid composed by water and smaller particles of earth, with diameters smaller than 0.5–2 cm), handy or electrically mixed (with agitators or compulsory mixers), and finally left soaking as to activate the bonding properties of the clay particles. Sometimes, liquifying agents (deflocculants) as sodium carbonate, water glass, ulmic acid, or tannic acid are used to reduce the amount of water required, decreasing the shrinkage issue and the drying time [26].

It is interesting to point out that similar techniques have been developed with small but substantial differences depending on the context: for instance, European or North African Rammed Earth building have been historically based on chemical lime stabilization, while Latin American ones have preferred the use of natural local fibers to fight shrinkage. The progress of contemporary technology has made it possible for natural soils to be modified depending on their use through an engineering process of the base material that, properly

stabilized, is able to achieve physical–mechanical characteristics that natural soils alone would not have achieved [50, 55].
The construction industry today demands ever higher quality standards for building materials, which must guarantee good mechanical properties, optimized thermal performance and adequate durability. In the field of raw earth research, there are numerous experiments aiming at identifying new stabilizing materials (natural or not) that improve raw earth composites performance.
Following the definition of Houben & Guillaud [24], the earth can be stabilized through different procedures:

- Mechanical stabilization: the earth is densified through compaction, increasing mechanical strength and reducing the permeability and porosity of the material;
- Physical stabilization: the grain size distribution of the earth is altered and/or fibers are added to the mixture;
- Chemical stabilization: the earth is mixed with chemicals to improve its cohesion and durability.

A comprehensive review of all the stabilization methods used in the last thirty years in raw earth production is almost impossible. In 2020 an interesting contribution has been published about alternative materials used for stabilization of raw earth mixes, with agro and non-agro waste [67, 68], avoiding the use of cement [69]. These reviews, far from being exhaustive, give an idea about the amount of research which has already been done on this topic. For the sake of brevity, we will now report investigations working on conventional stabilization method (using Portland cement and lime), which are now being abandoned because not effective [70], and other stabilization method based on the use of agro and non-agro additives, which are the new stabilization trends. This change in the production of the material is notable because it reflects the idea to couple the improvement of earth contemporary production with the reuse of natural and industrial by-products of other production chains, closing their production circles and marrying the philosophy of the circular economy. In table 3 we report the chosen bibliography, which concerns contemporary investigations developed in the last ten years aiming at assessing various material performances (mechanical, physical and thermal ones). These investigations adopt standardized production processes for an accurate characterization of raw earth materials' properties. Furthermore, each reference is classified distinguishing the area in which the research has been developed, to understand the social, economic and productive context: this allows for a deeper comprehension of the local available aggregates.

Table 3 - Agro and non-agro stabilization method for raw earth materials.

Ref.	Country	Conventional	Agro Waste	Non-agro waste
71	Australia	Lime	-	-
72, 73	UK	Cement	-	-
74	France	Grading correction	-	-
75	China, Norway	Grading correction	-	-
76	Italy	Cement, Lime	-	-
77	Iran	Cement	-	Pozzolan, Microsilica, Guar Gum, Fiberglass, PCM
78	UK, France	Grading correction	Hemp fibers	-
79, 80, 81	Egypt, Austria	Cement, gypsum	Barley and Wheat straw	-
82	Peru	Grading correction	Straw	-
83	France	-	Barley straw, hemp shiv, corn cob	-
84	France	-	Barley and Lavander straw	-
85	Thailand	-	Coconut Coir	-
86	Romania	-	Hemp	-
87	Ghana	-	Coconut husk, bagasse, oil palm fruit fibers	-

Ref.	Country	Conventional	Agro Waste	Non-agro waste
88, 89, 90	India	Cement	Pinus Roxburghii, Grewia Optiva	-
Ref.	Country	Conventional	Agro Waste	Non-agro waste
91	Vietnam, Taiwan	-	Rice Husk Ash	Fly Ash Sodium Hydroxide
92	Zimbabwe	Lime	Wood aggregates	Coal Fly Ash
93	Brazil	Cement	Sugarcane bagasse ash	-
94	Sri Lanka	-	Pines gum, sugarcane bagasse, Dawul Kurudu resin	-
95	Colombia	-	Cassava Peels	Coal ash
96	Nigeria, Brazil	-	Sisal and Eucalyptus fibers	Sodium hydroxide+sodium silicate Polypropylene fibers
97	Egypt	-	Wheat Hay fibers	-
98	Burkina Faso, France	-	Hibiscus cannabinus (Kenaf)	-
99	Benin, France	-	Kenaf	-
100	Algeria	Lime	Date palm fibers	-
101	Morocco	-	Date palm fibers, olive wase, straw	-
102	Indonesia	Lime	Coconut Coir	-
103	Egypt	Cement	Banana fibers	-
104	Morocco	-	Wool, Sodium alginate	-
105	Spain	-	Wool, Sodium alginate	-
106	Brazil, France	-	Sisal fibers	-
107	Kenya	Cement	Sisal fibers	-
108	Italy	Cement	Sisal and hemp fibers	-
109	Spain	Cement, Expanded clay	Cork, Triturated almond shell, olive stone	-
110	Burkina Faso	-	Digitalia exilis straw (fonio)	-
111	Italy	-	Arundo donax leaves	-
112	India	-	-	Bio-brioquette ash
113	Vietnam, Taiwan	Cement	-	Fly ash
114, 115	UK	Cement, Lime	-	Ground Granulated Blastfurnace slag (GGBS)
116	India	Cement	-	GGBS
117	Australia	Cement	-	Crumb rubber
118	Spain, UK	Cement, Lime	-	Alumina filler waste Coal ash
119	UK	Lime	-	Brick Dust waste, GGBS
120	Spain, UK	Lime	-	Magnesium Oxide
121	Portugal	Cement, Lime	-	Recycled aggregates
122	India	Cement, Lime	-	Iron mine spoil waste
123	Brazil	-	-	Glassfiber reinforced polymer waste
124	Turkey	Lime, Gypsum	-	Waste marble dust Polypropylene fibers
125	Italy	-	-	Waste marble dust
126	Egypt	Cement, Lime	-	Marble Cutting waste
127	Brazil	Lime	-	Fly ash
128,129	Italy, France	Cement	-	Recycled concrete aggregates, Fly ash

Then, in table 4, we will show the main results of these investigations about mechanical, thermal and hygric properties of the tested earthen materials. Mechanical properties comprise dry compressive strength, dry flexural and tensile strength and Young Modulus. Thermal properties are dry thermal conductivity, heat capacity or specific heat capacity. Finally, in the last column, water absorption, absorption coefficient, water vapor resistance factor and equilibrium moisture content are reported.

Table 4 - Performances of agro and non-agro stabilized raw earth materials.

Earthen material				Mechanical properties	Thermal properties	Hygric properties
Ref.	**Stabilizer content [w%, vol %] fiber length [mm]**	**Type of earth mix**	**Density [kg/m^3]**	**Compressive (CS) Tensile (TS) and Flexural Strength (FS) Young Modulus (E) [MPa]**	**Thermal Conductivity (λ) [W/mK] Heat Capacity (c) [J/kg K] (C) [MJ/m^{3}K]**	**Water absorption W [w%] absorption coeff a_w [g/m^{2}s$^{1/2}$] Water vapor resistance factor μ [-] EMC [%]**
71	Lime 0 – 6%	kaolin clay powder, silica flour, sand, and gravel	2030 - 2190	CS 0.86 E 227	-	-
72, 73	Cement 6%	Gravel, sand, silty clay	1980 - 2120	-	λ 0.83 C 1750	-
74	-	Gravel, sand, silt, clay		-	λ 0.40 – 0.69 c 900 - 1030	μ 7 – 19 EMC 4 - 6
75	-	Sand, silt, clay	1500 - 2100		λ 0.52 – 0.93	EMC 1.3 – 4.6
76	Cement 5%, Lime 6 %	Gravel, sand, silt, clay	1613 - 1980	CS 0.75 – 3.28	-	W 4 – 12
77	Cement 2.5 – 10 %, Pozzolan 5-10%, Microsilica 0.75 – 1.5 %, Guar Gum 2.5 – 7.5%, Fiberglass 0.75 – 1.5%, PCM 7.5 %	Sand, clay	1314 - 1967	CS 1.15 – 5.2 TS 0.13 – 0.77 E 80 – 740	λ 0.83 – 0.95	-
78	Hemp 1.5%	Gravel, sand, silt, clay	1770 - 2320	-	λ 0.83– 1.33	-
79, 80, 81	Cement, gypsum, 0%,5%, 10% Wheat, Barley, 0%, 1%, 3%	Gravel, sand, silt, clay	1088 - 1576	CS 0.5 – 5.00	λ 0.31 – 0.96	EMC 1.74 – 7.2
82	Straw 1.5%, 1.8%, 2.1%, 2.5% 3.7%	Soil, Sand	1629 - 1766	-	λ 0.28 – 0.33 c 559 - 587	-
83	Barley straw, hemp shiv, corn cob, 0%, 3%, 6%	Quarry fines	1100 - 1891	-	λ 0.14 – 0.57 c 774 - 809	μ 4.8 – 7.0 EMC 0.8 – 3.5
84	Barley, Lavender straw, 0%, 3%, 6%	Quarry fines	1195 - 1988	CS 3.3 – 4.8 E 31 - 502	λ 0.16 – 0.47	-
85	Coconut coir, 10, 15, 20 vol%	Lateritic soil, river sand	1344 - 1755	CS 1.5 – 8.34	λ 0.71– 1.48	-

Ref.	Stabilizer content [w%, vol %] fiber lenght [mm]	Type of earth mix	Density [kg/m³]	Compressive (CS) Tensile (TS) and Flexural Strength (FS) Young Modulus (E) [MPa]	Thermal Conductivity (λ) [W/mK] Heat Capacity (c) [J/kg K] (C) [MJ/m³K]	Water absorption W [w%] absorption coeff a_w [g/m²s^1/2] Water vapor resistance factor μ [-] EMC [%]
86	Hemp 1:1, 2:1, 3:1	Clayey soil	966 - 1000	CS 0.60 – 0.80 FS 0.32 – 0.46	λ 0.09– 0.18	-
87	Coconut husk, bagasse, oil palm fruit fibers	Clayey soils	1808 - 1951	CS 1.2 – 3.0 TS 0.23-0.40	-	W 0.80 – 9.60
88, 89, 90	Cement 2.5%, Pinus Roxburghii, Grewia Optiva 0.5%,1%,1.5%,2%	Sand, Clay	1700 - 1940	CS 0.95 – 2.25	-	W 2.07 – 52.29
91	Sodium Hydroxide, Fly Ash Rice Husk Ash, 10%,20%,30%,40%	Sand	1930 - 2075	CS 3.5 - 20 FS	λ 0.65– 1.70	W 7.5 – 10.5
92	Lime 4%, 8%, 10% Coal Ash 10%,12%,16% Wood aggregates 1.5% 3%	Clayey soil	1600	CS 2.00 – 8.30	-	W 11-16
93	Cement 6%, 12% Sugarcane bagasse ash 2%,4%,8%	Sandy earth	1930 - 2040	CS 0.7 – 3.77 TS 0.28 – 0.39	-	E 11.57 – 12.61
94	Pines gum, sugarcane bagasse, Dawul Kurudu, resin 5%,10%,15%,20%	Pozdolic soil	1800-2050	CS 0.54 – 1.7 TS 0.25 – 2.5	-	W 9.5 – 15
95	Coal ash Cassava Peels 2.5%, 5%	Clayey soil	-	CS 1.02 – 3.37 FS 0.36 – 1.09	-	W 26.38 – 32.14
96	Sodium hydroxide+sodium silicate, Sisal 10 mm Eucaliptus pulp 0.7 mm, Polypropylene 10 mm 0.5%,1%,2%	Ceramic company soil	1700-1740	FS 3.25 – 5.6	-	W 19 – 21
97	Hay fibers 0.5%,1%,1.5%	Swelling clay	1660 - 1760	CS 0.52 TS 0.06 – 0.08	-	-
98	Hibiscus cannabinus 0%,0.2%,0.4%,0.8% 3-6 cm	Lateritic soil	-	CS 2.45 – 2.85	λ 1.325– 1.655	-
99	Kenaf 1.2%, 10-20-30 mm	Sand, silt, clay	-	CS 4.2 - 6.40 FS 1.5 - 2.75 E 100 - 600	λ 0.9 – 2.1	-
100	Lime 8%,10%,12% Date palm fibers 0.05%, 0.1%,0.15%,0.2%	Soil, crushed sand	1890 - 1936	CS 6.5 – 7.8 TS 0.87 – 1.25	λ 0.76 – 0.85	W 4.5 – 6.6

Ref.	Stabilizer content [w%, vol %] fiber lenght [mm]	Type of earth mix	Density [kg/m³]	Compressive (CS) Tensile (TS) and Flexural Strength (FS) Young Modulus (E) [MPa]	Thermal Conductivity (λ) [W/mK] Heat Capacity (c) [J/kg K] (C) [MJ/m³K]	Water absorption W [w%] absorption coeff a_w [g/m²s^1/2] Water vapor resistance factor μ [-] EMC [%]
101	Date palm fibers, olive waste, straw 10, 20, 30 vol%	-	1219 - 1779	-	λ 0.26 – 0.65 c 800 - 1143	-
102	Lime 1:5.7:1 Coconut coir 4%	Sand, Clay	-	CS 0.80 - 3.50 FS 0.10 – 0.6 E 90 - 200	-	W 30 – 50
103	Cement 7 % Banana fibers 0%, 5%	Gravel, Sand, Clay	1947 - 1968	CS 3.84 – 6.58 FS 0.56 – 1.02 E 73 - 175	-	-
104	Wool 30 – 50 mm 0.25%,0.5%,1% Sodium alginate 1:2	Red clay illite	-	CS 1.23 – 3.04 FS 0.29 – 1.75	λ 0.19	-
105	Wool 0.25% Sodium alginate 3%	Clayey soil	1390 - 1510	CS 1.70 – 3.85 FS 0.39 – 0.91	λ 0.53 – 0.68 C 16.64 – 100.20	-
106	Sisal 20 – 50 mm 0.5%	Gravel, sand, silt, clay	2260	TS 0.11 – 0.215	-	-
107	Cement 5%,9,%,12% Sisal 3 – 10 mm 0.25%, 0.5%, 0.75%, 1.0%,1.25%	Bautzen soil	1790 - 1890	CS 2.3 – 9.1 FS 0.8 – 1.8	-	-
108	Cement 3 - 7% Sisal 3 cm 0.75%, Hemp 3.5 cm 0.75%	Sand, Clayey soil	1900	CS 0.75 – 4.06	-	-
109	Cement 5 – 8% Expanded Clay, Cork, Triturated almond shell, olive stone 20 – 30 vol%	Arkosic sandstone	1490 - 2080	CS 1.47– 5.40	λ 0.19 – 1.35	-
110	Digitalia exilis straw 1 cm,0.2%,0.4%, 0.6%,0.8%,1%	Clayey soil	-	CS 2.3 – 3.00 FS 0.7 – 1.3	λ 0.36 – 1.00	a_w 0.14 – 0.19
111	Arundo donax leaves	Clayey soil	-	CS 2.76 – 2.90	-	-
112	Cement 10% Bio-briquette ash 5%, 15%,25%,35%,45%,55%	Sand	1170-1470	CS 3.20 – 4.19	λ 0.35 – 0.92	W 13 - 25
113	Cement Fly ash 10, 15, 20%	River sand	1900-2090	CS 7.27 – 8.21	λ 0.78 – 1.25 c 920 - 1000	W 0.79 – 8.50
114, 115	Cement, Quicklime and Hydraulic Lime, Ground Granulated Blastfurnace slag 5, 12%	Lower Oxford Clay	1790-1800	CS 1.5 – 7.4	λ 0.37 – 0.51 c 1000	μ 0.5
116	Cement, Ground Granulated Blastfurnace slag 5%,10%,15%,20%, 25%,30%35%,45%	Lithomargic, laterite	-	CS 1.05 – 5.55	-	W 10.9 – 13.9

Ref.	Stabilizer content [w%, vol %] fiber lenght [mm]	Type of earth mix	Density [kg/m^3]	Compressive (CS) Tensile (TS) and Flexural Strength (FS) Young Modulus (E) [MPa]	Thermal Conductivity (λ) [W/mK] Heat Capacity (c) [J/kg K] (C) [MJ/m^{3}K]	Water absorption W [w%] absorption coeff a_w [g/m^{2}s$^{1/2}$] Water vapor resistance factor μ [-] EMC [%]
117	Cement 0 – 6%, Crumb Rubber 0.15-1.18 mm, 5%,10%,20% MICP	Gravel, Sand, Clay	-	CS 0.45 – 15 E 30-490	c 1321 - 1832	W 5.2 – 8.8
118	Cement 0-3% Lime0-3% Alumina filler waste 16%,32%,47% Coal ash 7%	Marl Clay soil	1540-1840	CS 4.5 - 26	-	W 8 – 24
119	Quicklime 3% Brick Dust waste 5%,10%,15% Ground Granulated Blastfurnace slag 11%	Mercia Mudstone Clay	1670-1800	CS 0.3 – 2.1	-	W 2.6 – 8.3
120	Lime 3-6-9-12-15-18%, Magnesium oxide 3-6-9-12-15-18%,	Local soil	1740 - 2000	CS 9.9	-	W 4.5 - 14
121	Cement 8%, Cement 4% + Lime 4%, Recycled aggregates 15%	Soil	1739 - 2002	CS 1.1 – 5.4 TS 0.1 – 1.2	λ 0.58– 1.47	W 7.4 – 29.8
122	Cement+Lime 6+2%, 8+2%, Iron mine spoil waste 30%,40%,50%	Quarry dust	2050	CS 1.5 – 6 FS 0.74 – 1.12	-	W 12 - 19
123	Glassfiber reinforced polymer waste 2.5%,5%,7.5%,10%	Clayey Red Latosol, Sand	1524-1619	CS 1.32 – 2.05	λ 0.68– 0.86	W 9.62 – 15.76
124	Lime 2%,Gypsum 10%, Polypropylene fibers 0.5%,1.0%,1.5%,2.0%, Waste marble dust 10%,20%	Haspolat, Taskent soils	-	CS 1.00-3.60 FS 0.80 – 1.30	-	-
125	Waste marble dust 3%,5%,7%10%	Black Ussana Clay, Yellow Monastir Clay	-	-	-	W 13
126	Cement 5%, Lime 5%,10%,20%, Marble Cutting waste 5%,10%,20%,	Kafr Homied Clay	2310-2730	CS 4.8 - 16	-	W 10 – 13.5
127, 128	Cement 5%,10%, Cement + fly ash 5%+5%, Calcium Carbide 6%	Recycled concrete aggregates, Engineered soil, Crushed limestone	1930-2210	CS 4.2-15	-	-

The wide literature review on material properties showed interesting results on the new stabilization methods adopted to enhance the earthen material properties.
All by-products generated by agricultural or farming activities are known as agro wastes, which may come from plants or animals. Most of the papers reviewed on the use of agro waste included wastes from plants while only two publications [94, 95] included work on animal origin wastes (sheep wool). The plant aggregates/fibers are made of cellulose, lignocellulose and wood fiber, seed fiber, bast fiber, leaf fiber or grass fiber. Their use as reinforcement is encouraged by their lower density compared to other inorganic fiber. On the other hand, the hydrophilic nature of these wastes is sometimes detrimental to their performance, especially when it comes to the water absorption properties [88-90, 95, 96, 102].
In general, a slight improvement of mechanical properties is visible when materials are stabilized with filamentous fibers like sisal, kenaf, coconut and date palm fibers, which bind together the soil compounds creating a diffused reinforcement. This reinforcement enhances compressive and tensile strength of materials, thus improving their ductility [85, 87, 96, 98 – 102, 106 – 108]. As we will see, this is of paramount importance when applied to brittle material as raw earth, when used in seismic countries. Moreover, they lower the thermal conductivity with respect to not fiber-reinforced samples. Other natural fibers as straw, wool, hemp give interesting improvement of hygrothermal performances [79, 81 – 84, 86, 101, 104, 105, 109, 110]. Similar performances are not possible for conventionally stabilized materials using binders as lime and cement [65, 70, 71, 76].
Industrial wastes include by-products generated by other production activities, such as materials generated in mills, factories and mines. Some industrial wastes are fly ash, bottom ash, metals, glass, slag, sludge, plastic fibers, which have been widely used. Fly ash and bottom ash are the residues from various combustion processes of solid materials or power plants. Slag is the residue from the metal industry and sludge is produced by the wastewater treatment plant or by the cutting of stones (marble, in particular). Construction wastes often come from new buildings, refurbishment, or demolition, constituting the recycled concrete aggregates. Wastes from the transport industry are created from vehicle repair such as used tyres, for example. Various types of fiber wastes such as glass, polypropylene, polyester, textiles, etc. are also available from different industries. In general, in these studies, it is common to find the combined use of conventional stabilizers as lime and cement, which are used as alkali-activators of hydraulic aggregates [112 – 116, 118 – 119, 122]; these studies are also characterized by slightly higher thermal conductivities, but some stabilization methods inhibit water absorption [117, 119, 120, 124 – 126].
Few studies [72 - 75, 77, 78, 92, 96, 100, 102] report a moisture-dependent characterization of mechanical and thermal properties, assessing a worsening of performances (reduction of mechanical strength, increase of thermal conductivity) in presence of pathologic moisture, or in general, of moisture values superior to the equilibrium ones. Only few studies report values of the dynamic thermal properties as thermal effusivity and diffusivity [74, 82, 83, 101, 113].
From a mechanical point of view, raw earth materials are brittle materials with poor strength. The addition of stabilizers can help to enhance their final performances; actually, the use of conventional binders like Portland cement and lime help to increase the compressive strength of the material, but not changing is brittle behavior [65, 70, 71]. This aspect is of minor importance when the material is intended to be used in compression only but is of fundamental importance when bending/tensile stresses in the wall continuum have to be taken into account (as in seismic areas). In this sense, the use of fibers to reinforce the material can help to increase the ductility of the material, that is its ability to be deformed plastically under load before breaking, i.e., the ability

to withstand plastic deformation. The greater the deformation achieved before fracture, the more ductile a material is.
We can understand the differences between the mechanical behavior of an unstabilized, a fiber reinforced, and a cement stabilized raw earth material by watching the following diagrams in fig. 10. Diagrams were taken from [80] and reveal a strong difference between the samples a, b and c in both terms of final compressive strength and followed force-displacement path. The sample b, which is a fiber-reinforced one, present a plateau which shows the ductile properties of the material; the other two samples do not present this property.

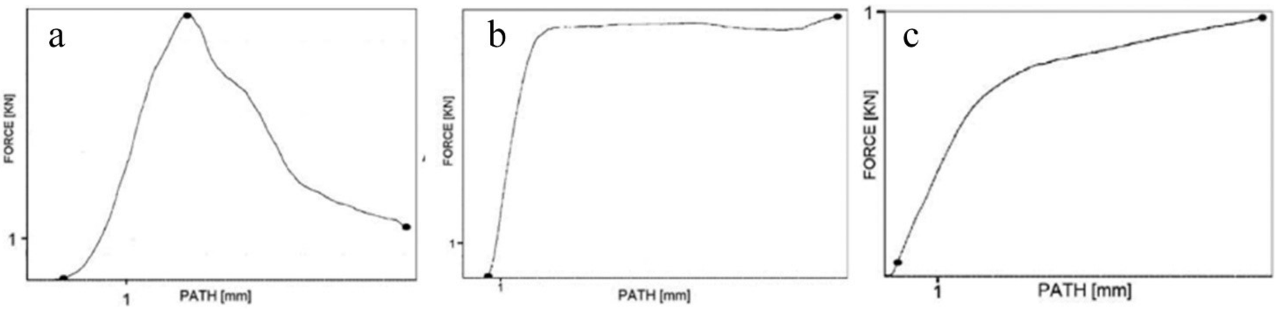


Figure 10 - Different mechanical behaviors of unstabilized (a), fiber-reinforced (b) and cement stabilized (c) raw earth samples [80]

Focusing on the hygrothermal point of view, raw earth behaves as a thermal and hygrometric regulator that slows and attenuates heat waves and stabilizes indoor relative humidity faster than other building materials [26], creating comfortable interiors historically described as "cool in summer and warm in winter" [38]. This description tends to simplify the physical and technical behavior of a massive porous material in which coupled hygrothermal mechanisms coexist at a microstructural scale and depending by the pore network geometry, as fully explained by [129]:

- a heat transmission mechanism for materials with a high thermal mass, which means high thermal inertia and heat storage;
- a phenomenon of evaporation and condensation inside the pores of the material as a result of temperature changes caused by the passage of the thermal wave: raw earth behaves as a low-tech phase change material where evaporation (which is an endothermic process) takes latent heat from the atmosphere during hot times and condensation (exothermic process) releases latent heat during cool times;
- a transfer of water vapor through the thickness of the wall due to the gradient of humidity between the inside and outside: the open network nanopores in earth materials facilitates absorption/release of moisture depending on the current ambient humidity;
- cooling of the wall caused by rising damp;
- surface overheating caused by solar radiation.

It is important to remark that the description of thermal performance of raw earth materials (i.e. thermal conductivity, specific heat capacity) depends on the moisture content and that calculations and simulations for earth constructions must allow for variations due to this hygrothermal behavior. As [130] point out, the determination of moisture content in earth based materials is of paramount importance, as it affects their mechanical and thermal properties, to the point that many researches pointed out the importance of determining the equilibrium moisture content at ambient humidity and to compare it to relative humidity, environmental temperature, effects of soil grading, surface permeability and activity of the clay (which is the affinity of clay to water, higher for swelling clays as montmorillonite).

A constant absorption and desorption of water molecules occurs when a hygroscopic material is placed in the air, depending on the environmental relative humidity and temperature. As in [130], in standard environmental conditions of temperature, pressure and relative humidity (not exceeding the 70%) the Equilibrium moisture content (EMC), which is the condition when an equal amount of absorbed and desorbed water molecules is exchanged by the material, in earth envelopes varies between the 0.5% and 7%. These values changes when earth is stabilized with natural fibers (EMC increases) or chemical binders (EMC decreases). High water retention capacity of earthen materials depends on the porous and microporous structure of the soils and on the physical and chemical affinity between clays and water. Moisture contents above 18% can increase the growth of fungus in earthen materials, especially when stabilized with natural fibers [84]. A complete explanation of hygric behavior of raw earth materials in its three saturation domains (hygroscopic, capillary and gravity ones) can be found in [129] and [72, 73].
Equilibrium moisture content can be assessed by the construction of sorption-desorption curves, by a static method or a dynamic gravimetric technique. Static method consists in the moistening of air using salts solutions, while the dynamic technique is the dynamic vapor sorption, where conditioning units maintain temperature constant, while moving and moistening air in successive stages from 0 to 95%, in steps of 10%. The DIN EN ISO 12271 regulates the first procedure. Samples are placed in boxes containing different saturated salt solutions, put in a climate chamber at various temperatures and humidity levels; then, after 3 to 4 weeks, samples are deemed to have reach the equilibrium moisture content and this is obtained as a percentage of moist sample weight on the dry one, using the well-known Eq. 1:

$$\mathrm{EMC} = \frac{(\mathrm{W_m} - \mathrm{W_d}) * 100}{\mathrm{W_d}}$$

Where W_m and W_d are the moist and dry weight of the sample, respectively.
Vapor diffusion or Water vapor permeability is the capacity of exchanging moisture through the external and internal envelope of the buildings. It is usually interpreted through the evaluation of the resistance factor to water vapor, μ, defined as the ratio between the water vapor permeability of air and that of the earth material: literature shows that the resistance factor to water vapor μ decreases as the relative humidity increase, and usually ranges between 5 and 13 [130, 131]. Water vapor permeability measurement, according to EN ISO 1015-19, can be realized using the dry or wet cup method. Specimens are sealed at the top of a glass container filled with water and 1 cm air layer. If the measure is to be done at different relative humidity values, saturated salt solutions can be used, or the sample can be conditioned inside a climate chamber. The containers are put in a controlled room at 20+/- 2 °C and 50% RH. Due to the difference in partial vapor pressure inside the cup and in the moisten environment, the mass of the cup varies because of the flow of water vapor. Finally, containers are weighted at regular time steps and mass values are plotted depending on time: equilibrium is deemed to be achieved when three values are on the same line, so the amount of water vapor passing through the sample in the unit of time is constant. Materials with higher water vapor permeability have poor vapor resistance coefficient and vice versa, materials characterized by a high μ-value are impervious for water vapor passage.
Liquid water permeability is defined as the product between the intrinsic permeability and the relative permeability coefficient [132]. This can be measured with an oedometer using the variable hydraulic load method, as described by the French Standard NF X 30-442. Alternatively, absorption experiments can be used, like the Initial Rate of Suction (IRS), ruled by the British Standard BS 3921, where sample is immerged in a 3mm batten of water for 1 min, or by the determination of the A-value (as for the EN 1015-18), which expresses the amount of water absorbed depending on the surface of contact and the immersion time.

Finally, hygroscopic buffering potential of earth materials can be assessed through the determination of maximal absorption value and moisture buffering value (MBV). The maximal adsorption value is defined in the German standards, and it is a measurement of earth sample mass, initially stabilized at 50% RH, after 12h at a relative humidity of 80%. The MBV method consists in measures of mass variation caused by moistening cycles, per unit of surface.
Massive materials as earth-based ones show high thermal inertia, which enable walls in attenuating and shifting heat passing through the envelope. It is mainly described by the evaluation of earth's volumetric heat capacity C (J m^{-3} K^{-1}), defined as the product of specific heat capacity c (J K^{-1} kg^{-1}) and ρ (kg m^{-3}), mass density of earth.

$$C = c\,\rho$$

Another useful parameter is the thermal diffusivity a (m^2 s^{-1}) which is a material-specific property which characterizes the speed at which a thermal excitation moves through a material in case of unsteady heat conduction. A high thermal diffusivity corresponds to a fast propagation of the temperature excitation. The thermal diffusivity is related to the thermal conductivity λ (W $m^{-1}K^{-1}$), specific heat capacity and density and defined as:

$$a = \lambda / c\,\rho$$

The thermal diffusivity of a material can be either calculated from known technical properties, or directly measured, e.g., by using the non-destructive flash method on a small specimen. Specific heat capacity can be found using an adiabatic calorimeter: the samples are cured at a high temperature and low RH%. Then, the specimens are put into colder water and a couple of thermocouples placed inside the calorimeter measure the evolution of the temperature of the water, until the system reaches the equilibrium. As the calorimeter is adiabatic, a specific formula is implemented in order to find the specific heat of the material, deduced from temperature, mass and specific heat capacities of water, mass and specific heat capacity of the calorimeter, temperature of the sample and equilibrium temperature:

$$c_{p,mat} = \frac{\left(m_{calo} * c_{p,calo} + m_w * c_{p,w}\right) * (T_{eq} - T_1)}{m_{mat} * (T_2 - T_{eq})}$$

Where m_{calo}, m_w and m_{mat} are the masses of the calorimeter, the water and the material respectively, T_2 and T_1 are the sample temperature and water temperature, and T_{eq} is the temperature of the system once the equilibrium is reached; finally $c_{p,calo}$ and $c_{p,w}$ are the specific heat capacity of the calorimeter and water.
Specific heat capacity and thermal diffusivity can also be measured using a Desprotherm device, an asymmetric hot plate equipment where two plates of a known insulating material are placed on the sides of the specimens. In this case the specimens must have the same dimensions of the heating resistor. Finally, heat capacity can be also determined with an indirect method, using a guarded hot plate apparatus, imposing different thermal stresses, enabling the sample to store an amount of internal energy Q, and calculating the integral of the difference of flows from the initial temperature state, to the final one. For effusivity assessment, samples must be thick enough because heat flow does not have to pass through it, as the measure is done in front of the sample under the hypothesis of semi-infiniteness of the material. For heat capacity assessment, the measurement is done on the opposite side of the heated one, so the sample must be thin enough for heat to cross it. The two methods have proved to be quite uniform in the results.
Moreover, thermal diffusivity is useful to calculate the thermal phase lag φ (s) which determines how long it takes for heat to go through a given thickness of a material d (m). For a sinusoidal wave it is equal to the thickness squared divided by the thermal diffusivity.

$$\phi = {}^{d^2}/_{a}$$

In addition, it is worth to mention the thermal effusivity b or e (J m^{-2} K^{-1} s$^{-1/2}$) which is a measure for the ability of an object to exchange thermal energy with its surroundings.

$$e = \sqrt{\lambda\, c\, \rho}$$

A high value for the thermal effusivity corresponds to a material that can easily absorb and release heat at the surface. Therefore, materials with high thermal effusivity cannot hold heat long enough because heats will quickly dissipate from its surface as soon as surrounding temperature drops. On the other hand, materials with low thermal effusivity will hold heat much longer.

Another fundamental thermal characteristic which is quite difficult to assess in earth-based materials is thermal conductivity, k or λ (W m-1 K-1): it describes the transport of energy (in the form of heat) through a body of mass as the result of a temperature gradient. As it is well known, the lower is λ, the more the material is insulating. The fact that earth is a porous and unsaturated material, reveals that heat transfer is connected to conduction in solid, liquid and gas phases (air), convection, radiation and evaporation/condensation [129]. So, the ordinary assessment made on other materials, for earth materials only assess the apparent conductivity: some authors like Hall and Allinson [72, 73] have developed new procedure to assess moisture-dependent thermal conductivity varying the Saturation Ratio of rammed earth samples.

Usually, thermal conductivity is measured trough the hot wire apparatus, heat flow meter or guarded hot plate. The first one uses a transient method, where a wire is heated and ideally extended through the center of a homogeneous cylindrical and endless sample, and allow to heat up under constant power, so the temperature of the wire rise at exponential rate during time. The hot and cold plates, necessary to cause the heat flow, are the boundary conditions which maintain constant the temperature, so that, if thermal contact between the wire and the sample is maintained, a one-dimensional heat flow can pass through the sample. The meter registers the rate at which the wire warms up, and so thermal conductivity can be derived directly, using a Fourier equation, from the resulting change in temperature detected by a sensor in contact with the test material. The hot wire must be totally embedded in the sample so that no edge effect can affect the measure.

The heat flow meter or guarded hot plate equipment work in a similar way and in steady-state conditions, but slab sample of maximum size of 300 x 300 mm (the thickness depends on the expected conductivity of the sample: more insulating material can be thicker than conductive ones because heat flow is easier) have to be prepared, with a thin capping layer which regularize the surface, realizing the hypothesis of perfect thermal contact. In this case, a downward vertical heat flow takes place between the temperature-controlled hot and cold plates. Different thermal steps can be set, changing the temperature variation and the average temperature. As Hall and Allinson [72, 73] a steady state measurement of thermal conductivity for rammed earth slabs is usually reached in 7 h for 3% stability, and 10 h for 1% stability (acceptable percentage variations). This measure can be done both for oven-dried sample (in this case measuring the dry conductivity of the material) and for moist sample, but in this case, it will explain the variation of λ value varying the saturation rate. This procedure is rarer to be found in the literature: the authors sprayed the slabs with distilled water, and then closed them in a membrane, allowing the distribution of moisture inside the sample for 48 h. In this case, the unsaturated slabs inside the heat flow meter are crossed by moisture transfer, which evaporated at the hot plate and condensate at the cold plate. The same measurement is repeated at different saturation ratio, *Sr*, until the slab is totally saturated, and different λ are assessed.

A brief overview of earthen materials properties, compared to other conventional building materials can be seen in fig. 11, taken from [60]. This figure compares bulk densities, compressive strength, thermal conductivity and capacity and relative water vapor diffusivity in several material as rammed earth (RE), cob (C), mud brick or adobe (MC), compressed earth block (CEB), terracotta (TC), plain concrete (PC), cellular concrete (CC) and plasterboard (PB).

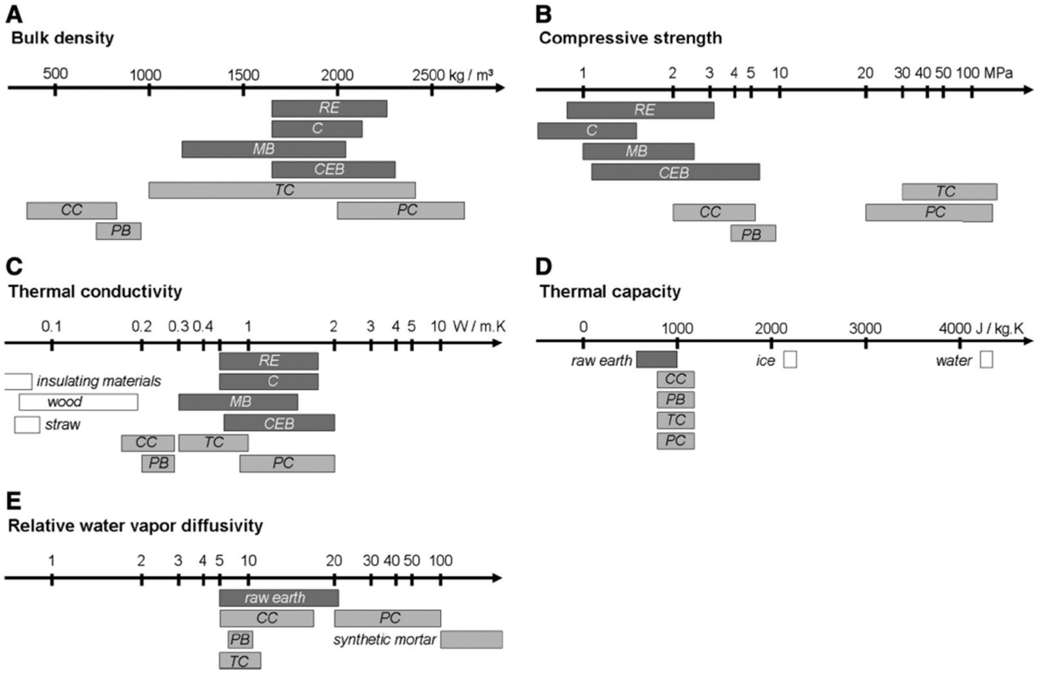


Figure 11 - Physical, mechanical, and thermal properties of raw earth and other reference building materials [70].

In this paragraph, we selected some studies focusing on both mechanical, physical and thermal improvement of raw earth materials, revealing how difficult is the simultaneous optimization for loadbearing, durability and hygrothermal purposes. We have seen that in general lighter materials have better hygrothermal performances despite a worsening in mechanical ones. We also saw the importance of adding fillers or waterproofing agents to earth mixtures, to reduce water absorption and porosity of material and consequently increasing their durability.

Moreover, we saw the difference in stabilization methods used in different areas of the world, seeing that in countries characterized by industrial waste issues, raw earth materials are pushed to stabilization methods using fly ash, bottom ash, metals, glass, slag, sludge, plastic fibers, while in less industrialized countries raw earth is being stabilized by the use of natural fibers and natural polymers. This difference is further highlighted from the comparison of the stabilization methods used in seismic prone and not seismic Countries. Traditional and current raw earth stabilization methods in seismic prone Countries adopt fibers to reinforce diffusively the material and enhance its flexural performance and ductility, excluding gravels from the mixtures. Not seismic countries instead, seems to be more concerned about the durability of material (above all for fair-faced rammed earth wall) and tent to stabilize it by changing the particle size distribution of the soils, according to an ideal earth Fuller distribution [24], and by the addition of additives which could increase overall compressive strength.

From the literature review we understood that to define a suitable base material for an earthquake resistant rammed earth technology, we needed to characterize a new construction material from a mechanical, thermal and physical point of view. In this research, we decided to use sustainable and natural materials and/or waste material deriving from other supply chain, to reuse local resources in a circular economy point of view. In section 4 we will introduce the main results on the research of this innovative and sustainable raw earth building material.

2.2.4 Raw earth reinforced and seismic-resistant technologies

The first step to the identification of a new construction systems for massive earthen masonry to be proposed in Italian seismic zone was a careful analysis of the state of the art. A market benchmarking of raw earth construction products reported in [133] and bibliographic research on historical and contemporary construction techniques in raw earth have allowed us to understand which technologies are currently in use and which quality standards we must reach for 21st century raw earth construction. The analysis conducted has taken into consideration different types of sources: scientific publications and studies, traditional construction manuals, commercial technologies, standardized and patented construction systems.
The objective of this part of the research was to identify the best performing reinforcement systems for raw earth walls. Raw earth walls are usually combined with high-tensile strength functional elements that improve their anti-seismic behavior (wooden frames, reeds, natural and non-natural fibers nets and ropes, etc.).
Results of this wide review is reported in the abacus of reinforced raw earth constructive systems in table 5, which is organized as follows.
In the first column, the constructive system is presented by its name, geographic location, an indication of when it was adopted and the documents we consulted for reference.
The second column gives information about the constructive process used to build the system. The study highlights if the system can be built in situ, can be prefabricated or partially prefabricated (for instance, raw earth infills like adobe or lightweight earth panels can be prefabricated and then assembled in situ inside the framing system).
The third column present a representative scheme of the constructive system, taken from the referenced documents.
Finally, the last four columns present details about the constructive system features, focusing on:

- composition of the loadbearing structure: on site or prefabricated construction; type, number (localized or diffused inside the raw earth walls), and position (internal/external/mixed position with reference to the cross section of the wall) of the reinforcing elements; materials used for the reinforcements (concrete, steel, reeds, bamboo, wood, artificial and natural meshes);
- composition of the floors;
- adopted anti-seismic devices;
- adopted thermal improvements in the constructive systems, if any;
- connection details, if known.

Gaete Cruz [134] composes a matrix of several reinforcement systems adopted in raw earth walls; in the matrix, column A represents internal reinforcements, column B external reinforcements and column C mixed ones (fig. 12).

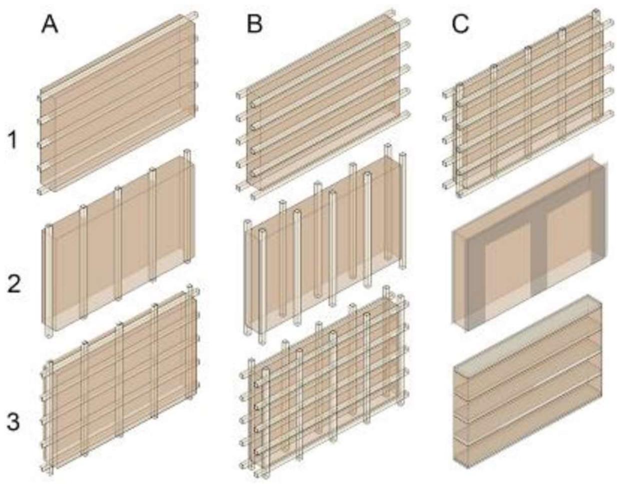
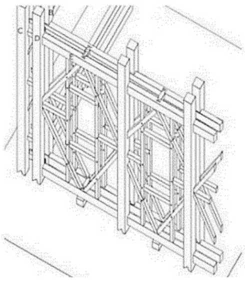
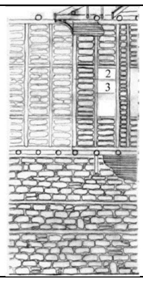
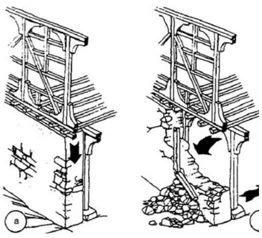
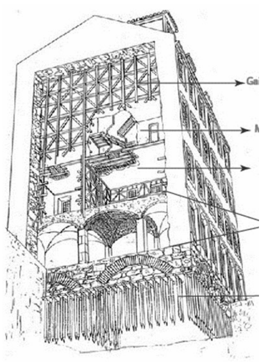
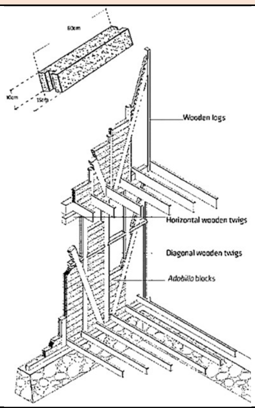
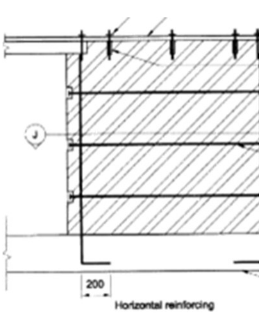
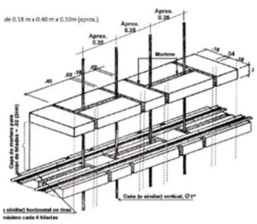
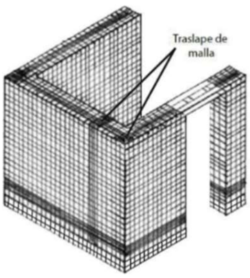
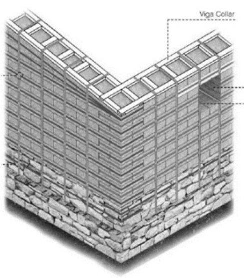
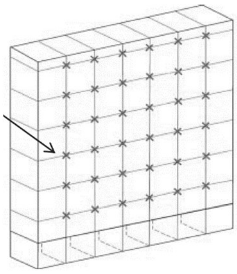
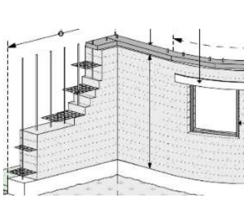
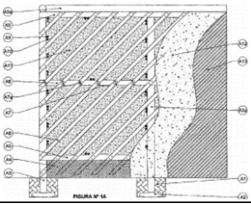
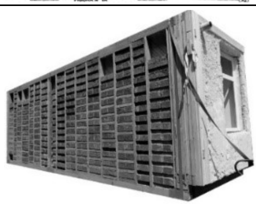
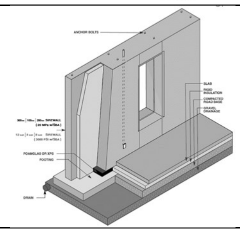
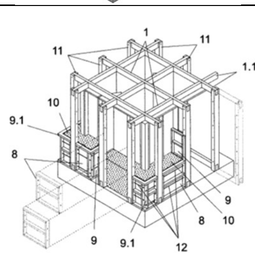
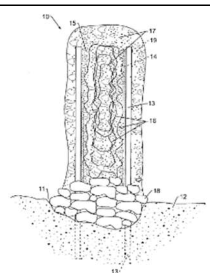


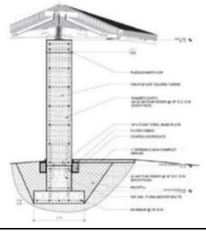
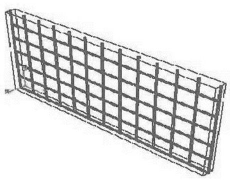
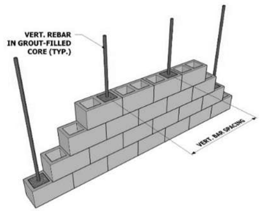
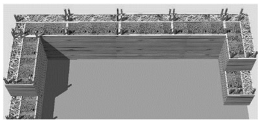
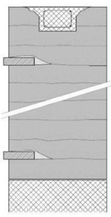
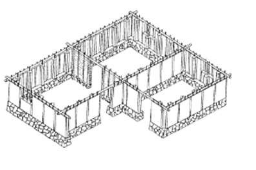
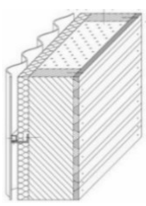
Figure 12 – Different reinforcement systems for raw earth walls [134].

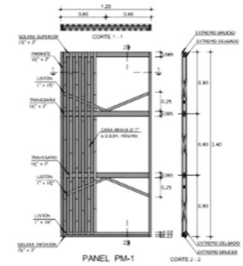
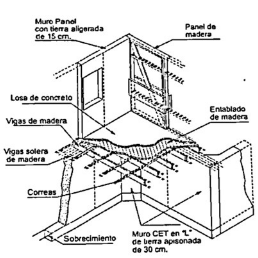
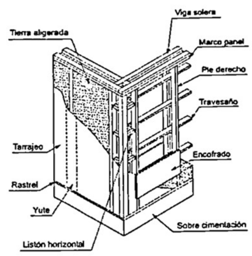
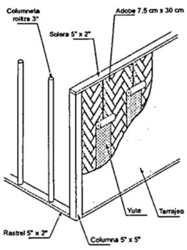
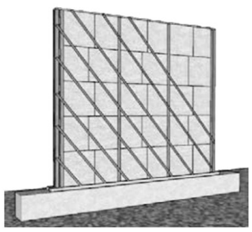
Table 5 - Abacus of earthen reinforced constructive system.

NAME & REF.	PROCESS	SCHEME	CONSTRUCTIVE SYSTEM FEATURES				
			LOADBEARING STRUCTURE	FLOOR	ANTI-SEISMIC DEVICES	THERMAL IMPROVEMENT	CONNECTION DETAILS
HISTORIC CONSTRUCTIVE SYSTEMS							
Baraccata House (Italy, XVIII century) [135-137]	On site		Load-bearing masonry with timber frame reinforcements (coupled, outside the cross section, or single, inside it). The stone are well shaped and placed as if there was not reinforcement	Timber flooring	Wood reinforcements give extra tensile strength to the walls. Structure is stronger and lighter	-	All connections were made by the mortar
Hımış system (Turkey) [140]	On site		Brick masonry with a supplementary timber structure in the horizontal layers, FF with half-timbered walls with bricks	Timber flooring	Masonry reinforced by wooden ring beam at GF, which contrast the earthquake. The upper structure is a timber one, lighter	-	-
Lefkada Islands System (Greece) [139]	On site		Masonry with a supplementary timber structure on the interior face, FF with half-timbered walls with clay bricks	Timber floors rests on the reinforced masonry of the GF.	Reduced horizontal stiffness of the GF timber columns, the masonry which contrast the earthquake. The GF columns are connected to the upper structure and protect this from failure: it's a backup load bearing structure. Reduce the weight at the upper floors	-	The upper floor timber structure is nailed to the supplementary timber structure on the ground floor
Pombalino System (Portugal) [138]	On site		Half-timbered system, with 15 x 30 cm posts in the mezzanine and 10 x 15 cm in higher floor and diagonal bracings (St. Andrew cross). A low-quality masonry is filling the timber skeleton.	Timber flooring in upper floors and arches in the foundations	1.Simple layout per floor and height. 2. Three dimensions connection of structural members. 3. The timber skeleton give ductility to the brittle masonry: the flexibility of wood is limited by the filling. No rigid nodes for wood, to allow energy dissipation in joints and mortar. 4 Lightweight system and redundant: if one structural member collapse, the structure does not.	-	Presence of half lap joints (one element is divided in two to allow easier connection), inlays (where two posts are near to diagonal members), bracing are notched in the vertical members.

Name & ref.	Process	Scheme	Constructive system features				
			Loadbearing structure	Floor	Anti-seismic devices	Thermal improvement	Connection details
			HISTORIC CONSTRUCTIVE SYSTEMS				
Tabique – Adobillo (Chile) [141]	Prefabrication of adobe bricks, On site wooden framing		Mixed adobe - platform frame wood structure. The adobes are interposed each 50 cm between the timber posts, which stops at each floor. There are inclined reinforcements for the bracing of the wood structure.	Timber flooring	The wood structure gives ductility to the adobe masonry, and the structure is well braced because of the diagonal members. Also the adobes work as bracings. Additional surface reinforcements do not allow the drop of adobes during the earthquakes.	Adobe have straw in their mix.	The adobe presents a groove to get fixed with the tongue of the cross-shaped timber posts.
			CODED SYSTEMS				
Reinforced RE wall [31]	On site		Cement stabilized RE wall with vertical steel rebars in weakest points. Rebars are connected to the footing and to upper bond beam (concrete or timber). Horizontal brackets or geogrid nets each RE layer.	Concrete slab	Steel rebars connecting the wall to lower (footing) and upper (bond beam) reinforcement. Horizontal brackets or geogrid to confine the RE wall. Corner reinforcement by rods. Eventually concrete columns each wall ends.	-	-
Canes-reinforced adobe wall [25]	Prefabrication of adobe bricks, On site cane reinforcement		40 cm thick adobe masonry, with canes grid embedded inside, composed by: entire vertical canes and split canes on horizontal layers. Squared adobes with a hole in the centre are also used to incorporate the cane.	Timber flooring	Vertical canes are spaced about 35 - 40 cm and connected to horizontal split canes, embedded in the mortar: they are placed every 4 adobe rows at the bottom of the wall, every 3 at the middle and every 2 at the top. Top timber ring beam.	-	The cane vertical reinforcements go from the foundation beam to the top.
Geogrid-reinforced adobe wall [25]	Prefabrication of adobe bricks, On site geogrid reinforcement		40 cm thick adobe masonry, with an exterior geogrid reinforcement.	Timber flooring	Earth wall is confined by a stiffen geogrid. Geogrid is installed by rope cross connectors. It gives extra tensile strength to the wall. The timbe ring beam has to be connected with the grid.	-	It is foreseen an overlapping of the grid, so it works continuously all over the wall
Nylon rope-reinforced adobe wall [25, 142]	Prefabrication of adobe bricks, On site rope reinforcement		40 cm thick adobe masonry, confined by an exterior nylon rope reinforcement.	Timber flooring	Earth wall is confined by a tensioned rope mesh. Vertical and horizontal ropes are installed by rope cross connectors. The timber ring beam and the footing are connected to the vertical ropes.	-	Rope links are made by knots, tensioning of ropes is made by the eight-knot. More horizontal rope on the upper part of the wall.

Name & ref.	Process	Scheme	Constructive system features: Loadbearing structure	Floor	Anti-seismic devices	Thermal improvement	Connection details
CODED SYSTEMS							
Nylon rope reinforced RE wall [25, 143]	On site		RE wall built with 45° inclined joints between one block and the other (min height 60, maximum length 1.50 m). Surface rope reinforcement.	Timber floor	Earth wall is confined by a tensioned rope mesh. Vertical and horizontal ropes are installed by rope cross connectors. The timber ring beam and the footing are connected to the vertical ropes.	Straw is added to the mixture.	Rope links are made by knots, tensioning of ropes is made by the eight-knot. More horizontal rope on the upper part of the wall.
Reinforced Cob wall [55]	On site		Single storey reinforced/stabilized COB wall built with horizontal and vertical steel reinforcement if needed. Footing and bond beam.	-	Steel vertical and horizontal rods in walls if needed. Wooden or concrete bond beam.	Mass wall with R-value = 0.22. Possibility to add insulation	Metal ties for the connection of the bond beam and the wall.
PATENTED SYSTEMS							
E-logic Wall [144]	On site		Structural wall with a exogenous structure to its longitudinal axis to enable its interior filling on site.	Timber floor	Loadbearing wooden frames, diagonal surface reinforcement system on both sides.	The earth filling is mixed by wood chips and polystyrene.	Nailed.
Habiter 2030 [145]	Prefabrication of CEB and wood members, assembling on site		Platform frame with the filling in compressed earth block, then diagonal wood sheets to close the system.	Timber floor	-	The CEB give thermal inertia to the timber wall.	CEB are shaped to be blocked in between the timber posts.
SIREwall [146, 147]	On site		Cavity RE load-bearing wall, stabilized with cement. Concrete footing. Diffuse steel rebar reinforcement in the RE wythes.	Concrete slab or steel framing	Horizontal brackets between the two rammed earth wythes, connection between vertical steel rebar reinforcement and ring beams.	In the core is included an EPS thermal insulation.	Vertical rebars go from the footing to the ring beam.
S_LOW [148]	Prefabrication of wood members, RE built on site		Mixed timber and RE wall to be realized in situ with a system of removable formworks, anchored to vertical guides. The RE is compacted in continuity with the timber structure.	Timber flooring	While on the interior side a timber panel is maintained, the outer RE façade is left unreinforced.	-	-
Fortified adobe-type construction [149]	On site		Cement stabilized adobe mixture applied to a frame structure having Spaced-apart frame elements and a support structure affixed to form an interior Space.	Timber flooring	Vertical and horizontal frame elements (metal bars) affixed to a concrete footing, and support structure (mesh) to maintain the adobe overlay.	The wall is filled of sagebrush, straw, sheared plastic or a filler-insulating material	-

NAME & REF.	PROCESS	SCHEME	CONSTRUCTIVE SYSTEM FEATURES				
			LOADBEARING STRUCTURE	FLOOR	ANTI-SEISMIC DEVICES	THERMAL IMPROVEMENT	CONNECTION DETAILS
COMMERCIAL AND STUDIED SYSTEMS							
North America reinforced RE [150]	On site		Continuous Rammed earth walls stabilized (usually with cement, percentages between 8 and 10%), with embedded vertical and horizontal steel reinforcement.	Concrete slab.	Concrete beam at the base and at the top of the wall, connected by vertical steel reinforcements.	-	-
RE reinforced with bamboo columns or wood members [151]	On site		Rammed earth made in situ with internal diffuse bamboo reinforcement arranged according to a vertical/horizontal mesh	-	The vertical bamboo reinforcements connect the concrete base and foundation to the upper ring beam (also in concrete)	-	-
Modular RE masonry block [152]	Prefabricated compressed earth block		CEB of very small dimensions (10x20x40 cm, 15x20x40 or 20x20x40cm), with weights ranging from 10 kg to 19 kg. Using CMU technology.	Concrete slab	Steel bars passing through the inside of the soil CMUs connecting vertically the lower and upper ring beams. Bars are then embedded in cement grout.	-	Upper grooved blocks locate longitudinal reinforcement. Vertical holes allow passage of vertical bars.
Modular Building Using RE [153]	Prefabricated wood structure, on site filling		Modular system. Prefabricated wooden boxes with two compartments: on the inner side of the box, earth is rammed, on the outer straw is located.	-	Each wood box module is studied, and different types are defined to best define the bond pattern for the wall.	Outside straw insulation layer is 17.8 cm thick. Timber cladding.	Connections are made by means of wooden nails connecting the various elements.
Prefabricated RE [62, 154, 155]	Prefabricated RE panel, assembled on site		Prefab unstabilized RE panel are installed by use of earth mortar. Usually a concrete or steel structure is coupled to RE wall.	Concrete slab, steel framing.	In seismic areas, longitudinal and vertical reinforcement steel bars are used, which are in special grooves made at the upper edge of the panels.	Gravel cellular glass insulation has been used	By means of steel bars that connect the RE panels to the loadbearingskeleton
RE panel reinforced with bamboo [26]	On site		RE with improved stability (T-shaped compacted elements, 14-30 cm thick) and reinforced with 4 vertical bamboo rods inserted in the wall (2-3 cm diameters).	Timber flooring	Vertical connections through bamboo elements anchored to the lower and upper bamboo ring beam (embedded in the masonry base).	-	A joint between RE panels allow them to move independently during an earthquake. The roof does not rest on the wall.
Prefabricated Wooden-framed panel [156]	Prefabricated wooden panels, earth infill on site		Timber skeleton, 10 x 10 cm columns each 60 cm, fixed to a base board of 18 x 6 cm. Secondary structure with 4 x 6 cm stiffening diagonals screwed to the main elements.	Timber, earth infill.	-	Local soil mixed with wood chips (plastic mixture). Additional Cork insulation panel.	-

Name & ref.	Process	Scheme	Constructive system features				
			Loadbearing structure	Floor	Anti-seismic devices	Thermal improvement	Connection details
			COMMERCIAL AND STUDIED SYSTEMS				
RE reinforced with timber posts [157, 158]	In situ		RE walls with outer timber post reinforcement and wooden ring beam.	Timber or canes flooring.	Timber post reinforcement must be connected to the wooden ring beam.	Straw is used in the mixtures.	This research showed poor connection details (use of iron wire).
Prefabricated Quincha [159, 160]	Prefabricated quincha panels, earth plastering on site		Timber frames are reinforced with a wieving of reeds (canes, bamboo split). Then a plastic mix of earth and fibers is put on the reeds and rendered.	Timber flooring.	The system has a good flexibility and ductility because of the wood. It was traditionally used on the upper floors of earth buildings.	Presence of fibers in the earth mix and empty reeds. Often combined with thermal insulation	-
CET wall: Rammed earth (GF), wood framing (FF) [161]	RE on site (GF), Prefabricated wooden panels, earth plastering on site (FF)		Loadbearing 30 cm-thick RE wall (GF). Sometimes there is an interior wood reinforcement in the walls. Lightweight loam and wattle and daub, 15 cm thick (FF).	Timber, hemidiaphragm mezzanine	Walls are L, Y, T shaped to provide better stability. Timber top ring beam.	-	-
Wooden-framed wall with lightearth infill [161]	Prefabricated wooden panels, earth infill on site		Doubled timber load bearing structure with columns (spaced at 120 cm) , beams and horizontal bracings (spaced at 60 cm). Inside the wall there is a mix of lightweight earth.	Timber flooring.	Lightweight system.	Earth infill is lightened by the presence of barley, wheat and rice straw	Nailed.
Wooden-framed wall with adobe infill [161]	Prefabricated wooden panels and adobes, adobe infill on site		Timber frame (posts each 80 cm) filled with adobes put with a herringbone pattern. Between the main columns (approx.. 12x12 cm) there are smaller ones (ø 7.5 cm).	Timber flooring	Half-timbered system (more ductile compared to an adobe masonry).	Adobes provide thermal inertia to the walls.	Timber connections are nailed, adobes are installed by mortar.
Sistema Mixto [162, 163]	Prefab light earth panels, wood members and earth plastering on site (FF)		Half-timbered structure with prefabricated lightweight earth panels infill.	Timber Flooring.	Half-timbered structure is stiffened by horizontal timber members. An auxiliar diagonal surface reinforcement is added to prevent from panels dropping.	Lightweight earth panels show low thermal conductivities (λ<0.1 W/m K)	Timber connections are nailed.

Legend: GF=Ground Floor, FF=First Floor, RE=Rammed Earth, CEB=Compressed earth block

Among the historical building systems, have been studied also the construction principles of stone masonry reinforced structures as those used in *Baraccate* Houses (Italy), in the *Pombalino* System (Portugal), in the *Hımış* System (Turkey) and in the Lefkada Islands system (Greece). These construction systems, many of which have been developed from the *opus craticium* adopted in Roman provinces [135], have shown excellent resistance to real seismic events. In the last years numerous studies have aimed at their structural modelling. In all historical systems it is possible to identify different anti-seismic strategies such as:

- connections between orthogonal walls (by means of ring beams or ties);
- the lowering of the center of gravity of the building (by using heavier material at the ground floor, and lightweight ones at superior floors);
- the increase of the deformability of the walls (by the addition of high tensile strength materials or reinforcements);
- the reduction of the structure's weight of the structure (by the addition of lightweight materials as aggregates or reinforcements).

As it is well known, the system of the *Baraccata* house, widespread in several Italian regions (Basilicata, Campania, Calabria, and Sicily) consists of a stone or adobe masonry reinforced by a wood frame composed of horizontal, vertical and oblique elements, which are riveted together and act as bracing, with cross section between 10 and 12 cm. This reinforcing system allows for a good box-like behavior of the masonry [137]. This construction system has been subjected to cyclical in-plane tests the framework of research by CNR-Ivalsa and the University of Calabria [136], scientifically demonstrating the validity of this construction scheme in the dissipation of seismic energy and in the acquisition of greater ductility (provided by wood) and resistance (provided by masonry).

A similar analysis was carried out on the *Gaiola Pombalina* system, adopted in Lisbon after the 1755 earthquake, a construction system characterized by the adoption of shear walls made with a continuous wooden frame for all the floors of the building and to which the wooden floors are anchored. The wooden frame is composed of non-deformable triangles that form a three-dimensional stiffening structure, working under static and dynamic loads; the fields between the wooden elements are filled with various material (limestone blocks, bricks, mortar), which give ductility to the structure, increase the energy dissipated in the earthquake event and the cyclical rigidity, as demonstrated by [137, 138].

The construction system developed in the Greek Lefkada islands adopted a masonry ground floor coupled with an auxiliary structural wooden system located on the inner side of the wall; on these two structural systems lies the lightweight wooden-framed structure of the upper floor [139].

Finally, the Turkish construction system follows the scheme of the Ottoman houses, providing a massive stone masonry on the ground floor, interspersed with wooden ring beam, while on the upper floors the lightweight walls are composed by wooden frames filled with bricks and/or adobes [140].

As far as is concerned to contemporary construction, most technologically advanced countries such as Europe, North America and Oceania offer rather homogeneous technological solutions for raw and rammed earth construction, with use of steel reinforcement for the walls, concrete top and bottom ring beam, which guarantees the anti-seismicity of constructions. From a thermal point of view, is usually preferred the combination of earth walls with synthetic insulations like XPS, EPS or PU [133, 150].

Concerning raw earth construction techniques, rammed earth (and its prefabricated variant) and compressed earth blocks constitute the largest slice of contemporary production. Lehm Ton Erde's experience [154, 155] has breathed new life into earth construction in Europe, but it has rarely been adopted in areas characterized by seismic risk and only in combination with metal reinforcement. A similar approach has been used by David Easton in Watershed Materials: compressed earth blocks using concrete masonry unit's technology and reinforced with steel bars [152]. Another interesting solution is the one presented by Sirewall [146, 147], which uses a patented formwork for the realization of a cavity rammed earth wall, cement stabilized and reinforced

with steel rods which are connected by brackets. The two wythes of the rammed earth wall surround a layer of polyurethane insulation, to create a seismic-resistant wall with high thermal performance.
In [164] reinforced rammed earth walls's mechanical behavior under pseudo-dynamic loading is investigated. Rammed earth walls are strengthened with polyester fabric strips in order to exploit the strength potential of rammed earth and to solve its lack of tensile strength. In this research, in-plane cyclic tests were carried out to investigate the shear behavior of unstrengthened and strengthened walls. The proposed strengthening technique requires low-tech equipment and workmanship, uses readily available, unexpensive, and industrially standardized materials. The experimental results were analyzed in terms of stiffness degradation, energy dissipation capacity and equivalent viscous damping. Although the unstrengthened and strengthened walls confirmed a limited ductile behavior, the findings confirm that the strengthening contributes to limit the spread of the diagonal cracks and provide an increase of strength in terms of horizontal load and displacement capacity.
On the other hand, between developing countries and with particular attention paid to the South American context, different building systems, both historical and contemporary, have been analyzed in territories that are among the most seismic on our planet. Reinforced earthen construction techniques are present throughout South America, as evidenced by the research and dissemination activities carried out by the PROTerra network: from the *tabique/bahareque* to the Peruvian *quincha*, to the reinforcement systems for adobe and rammed earth masonries. Concerning adobe and rammed earth walls, reinforcement can be internal or external to the wall thickness, with numerous variations that have been refined over time [24].
In Chile, a historical mixed earth-wood system, called *tabique-adobillo*, was developed from the middle of the 19th century [141], as a result of the increased quantity of timber entering the port of Valparaiso for the construction of boats. This standardized and modular constructive system, present cruciform wooden posts with a reduced cross-section, spaced every 50 cm, as if it were a progenitor of modern platform-frame wood systems. Moreover, it presents diagonal bracing elements. The fields between these cruciform posts are filled with adobes shaped to fit the section of the posts, improving the acoustic and thermal comfort of the construction. It is assumed that the adobes also have a bracing effect in case of earthquake. A surface reinforcement system, made of iron wire, metal mesh or wooden battens, allows to counteract the possible overturning of the adobe.
Still in Chile, work continues on the favorable combination of earth filling and wood reinforcement system even in the contemporary times, as demonstrated by the development of the patented construction system E-Logic Wall [144]. In this system, a raw earth infill (possibly mixed with wood chips, polystyrene or other materials lowering the thermal conductivity) is confined by a wooden structure composed of coupled wooden posts and stiffening elements to which a surface reinforcement system (made with wooden diagonals) is connected. In this way, the structural box behavior of the walls is assured.
Peru, one of the few countries that boasts research in the field of earthquake-resistant earthen construction, deserves a special mention. In 2017, Peru adopted a new construction standard for reinforced earthen construction [25].
This regulation collects the experiences that have been carried out at PUCP [25] on the effectiveness of different reinforcement systems for earth masonry. We already discussed the content of the Peruvian standard in paragraph 2.2.2.

2.2.4.1 Construction process and formwork for rammed earth

The literature review about raw earth reinforced constructive systems showed us the difficulty to actively integrate reinforcement systems in the construction process, both from a technological point of view (*can reinforcements be useful during the construction process?*) and from a practical-constructive one (*can we design the reinforcement to be less invasive during the construction process?).* These questions brought us to widen the research to investigate existing formwork systems and innovations brought in this sector.

Formwork systems for massive raw and rammed earth walls were historically built with wood. In current times rammed earth, the most innovated raw earth technique, has been inspired by concrete industry systems to develop its own formwork system, using steel framed reinforced ones.

In this analysis different processes for rammed earth walls in situ-construction have been studied. The following table 7 lists the rammed earth technologies, the reinforcements to be incorporated during the construction process, the formwork and the construction protocol adopted. For each of them the source and thus the area of adoption is indicated.

The main difference found in relation to the construction process is obviously determined by the geographical and economic context in which this technique is developed. In rammed earth construction, costs increase with the complexity of the architectural design, the availability of labor and equipment and the amount of formwork available.

In Europe, USA, Australia and New Zealand, the rammed earth technique uses formworks inherited by concrete construction, using high-density plywood panels with a smooth surface, covered with a laminated layer that reduces the possibility of adhesion of the wet earth mixture to the formwork surface. The outer face of the formwork is strengthened with a horizontal steel or wooden grid of elements, which reduces the possibility of formwork buckling during the pouring/compaction of the material.

Sometimes formwork from concrete construction is used, such as Symons formwork, which is a vertically continuous formwork system. This type of construction involves building rammed-earth wall vertical panels up to the final height and then build the next wall panel. In seismic areas, this construction process determines the need to insert reinforcements (internal or external) or punctual reinforcing elements that connect the different rammed earth panels.

In these countries it also exists a prefabricated variant of rammed earth technique [154 - 156], with panels being manufactured in factories or on site and then installed adjacent to the reinforcing structure using cranes. Usually, these structures have been adopted in no seismic or low seismic countries, so it was not required the adoption of a specific constructive process for the integration of reinforcements. As mentioned in table 5, these wall systems are usually coupled with an independent structural frame (realized in timber, concrete or steel) to which rammed earth walls are connected (respectively Alnatura Campus, Ricola Herb Centre, Printing Plant Gugler realized by Lehm Ton Erde are perfectly representative of these processes) [155].

In Latin America, Asia and Africa, rammed earth construction process is much closer to the traditional procedure, with progressive construction of the wall by the overlapping of horizontal layers. In this construction process a single wooden formwork is used (with a system of steel, wooden or rope ties depending on the area) which is moved horizontally, following the architectural plan and, once the perimeter of the building is completed, the next layer is built. These constructive procedures tend to respect the staggering joints-rule for successive rammed earth layers, by the respect of the bond pattern.

The historical construction process left the typical imprints of the wooden/metal ties used to hold the two longitudinal sides of the formwork together. In more recent times, these wooden elements have been replaced by ropes holding the formwork struts together, or by pieces of steel bars, nuts, and spacers.

Figure 13 shows the more common construction processes adopted for rammed earth (RE) construction.

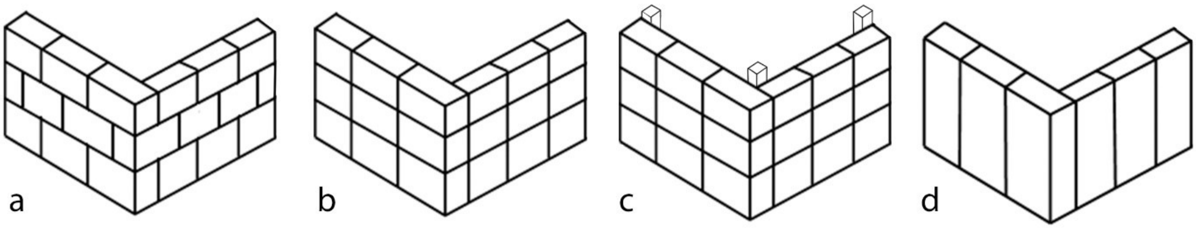
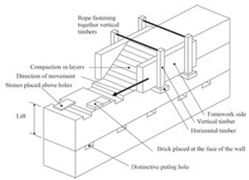
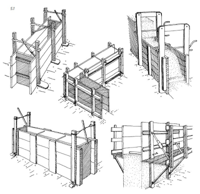
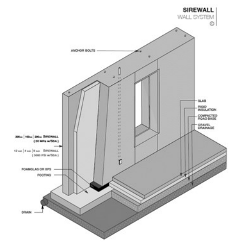
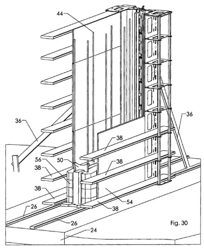
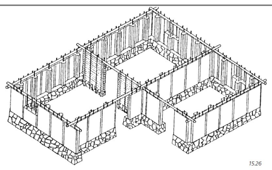
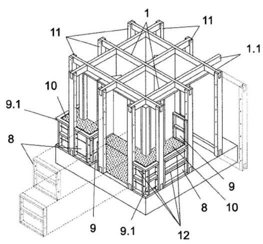
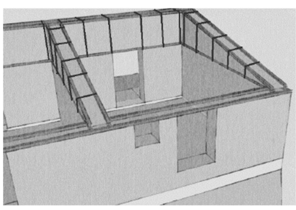
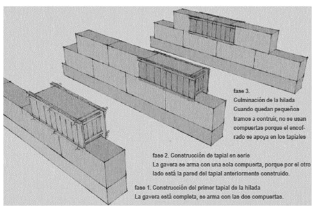
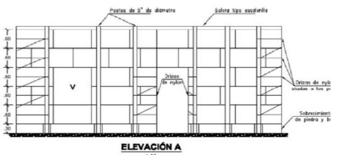
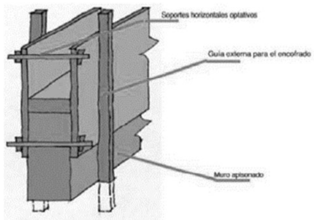
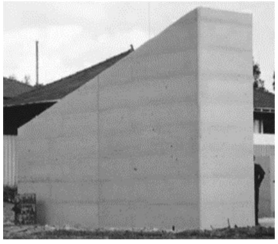
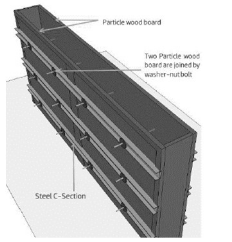
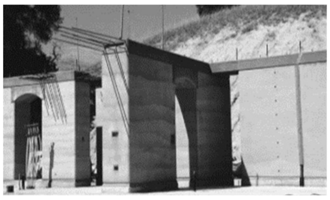
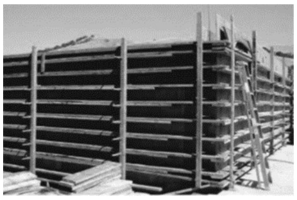
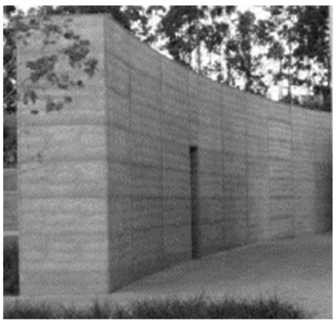
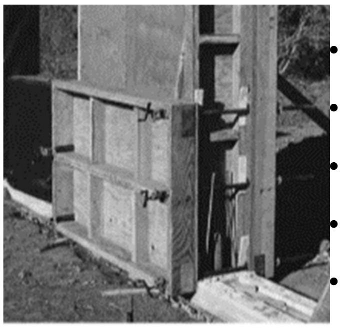
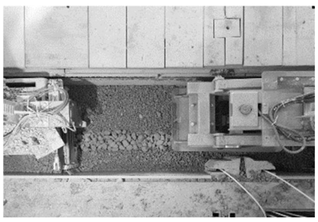


Figure 13 – Staggered RE joint construction (a), aligned RE joint construction (b), aligned RE joint construction with additional loadbearing framing structure (c), vertically aligned RE construction (d)

The integration of the above shown construction processes with mainstream formwork systems has generated years of research in this area and some results in formwork realization are identified in table 6.

Table 6 - Formwork system for rammed earth walls

Reinforced rammed earth technology	System	Formwork	Process
Traditional RE reinforced with canes or wood posts inside the wall [24, 26]			• In situ construction process as in fig. 15a; • Construction of horizontal wall rings with staggered joints, then the wall rises in height. • Wooden ties are used and when removed, they left voids in the walls
Sirewall Cement Stabilized, Insulated and structural (Vertical steel reinforcement confined by horizontal brackets) RE [156, 157]			• In situ construction process as in fig. 15d; • construction of vertical panels till the final height of the wall; • no through holes for tie rods.
Bamboo reinforced RE Internal bamboo reinforcement (2 cm< φ < 3cm) [26]		T-shaped metal formwork, 80 cm tick, 40 cm tall	• In situ construction process as in fig. 15d; • construction of vertical panels till the final height of the wall; • no through holes for tie rods.
S_Low RE wall reinforced with an interior framed timber structure (timber posts and plywood panels) [148]			• In situ construction process as in fig. 15c; • wall sections are erected (1/3 of total height) with reinforced formwork anchored to additional posts and side rails (1/3 of total height); • a plywood panel nailed to the timber posts on the inside serves as a disposable formwork.
Rope mesh reinforced RE Mesh of horizontal and vertical ropes, Timber ring beam with longitudinal and transverse elements **[143]**			• In situ construction process as in fig. 15a; • construction of horizontal wall rings with staggered joints, then the wall rises in height; • ropes connectors are inserted as the material is rammed into the formwork, otherwise holes for ropes have to be drilled once the wall is completed.

Reinforced rammed earth technology	System	Formwork	Process
Timber reinforced RE Wooden posts on the two sides of RE wall (max spacing. 1.5 m, φ=10 cm or section 7.5 x 10 cm) Timber ring beam [157]			• In situ construction process as in fig. 15a; • construction of horizontal wall rings with staggered joints, then the wall rises in height; • installation of timber posts on the exterior sides of the wall; • connection of the timber posts to the ring beam; insertion of nylon ropes at the corners (surface reinforcement).
North America RE RE wall with vertical steel reinforcement [165]			• In situ construction process as in fig. 15d; • construction of vertical panels till the final height of the wall; • use of reinforced concrete formwork, but problems with through-tie-rods.
California RE RE in seismic area, reinforced with (1) concrete frames that incorporate them (to withstand lateral loads), (2) tongue-and-groove shaping at the end of each panel to increase lateral stability, with wall expansion joints, (3) continuous rammed earth walls without joints and in-situ reinforced concrete ring beam [165]			• In situ construction process as in fig. 15d; • construction of vertical panels till the final height of the wall; • to accommodate the reinforcement, the formwork was designed to increase the distance between the ties; • timber formwork (t_{min}=1.9 cm) with horizontal reinforcement elements (Max spacing 40 cm) with 5 x 30 cm cross section, length equal to the distance between the ties (usually 180 - 300 cm) • full-height side rail, resting on foundation.
Australia RE Unreinforced RE (non-seismic area) [165]			• In situ construction process as in fig. 15d; • construction of vertical panels till the final height of the wall; • use of high-density plywood formwork with steel reinforcing frames; • formwork approximately 60 cm high, with ties at top and bottom corners; • full-height side rail resting on the foundation; • subsequent formwork panels are anchored to the panels below and only the top ties are required.
Prefabricated (in situ or not) RE panels Built in place adjacent to the loadbearing structure. [155, 166]			• Prefabricated panels for load-bearing purposes or for cladding of concrete, timber or steel structural frames; • RE wall is made in the factory and then cut according to the basic module chosen. Alternatively, the panel is manufactured on site and then erected with the aid of a crane; • the finished panel rests on steel or wooden profiles to allow it to be moved;

2.2.5 Structural aspects of reinforced raw earth walls

Raw earth load-bearing structures in high-seismic areas present the same structural behavior as masonry ones. The main issue is caused by the first mode collapse mechanism, that is an out-of-plane mechanism causing wall overturning. After the 2007 earthquake which stroke the central coast of Peru (Magnitude 8.0, epicenter 150 km away from Lima), a research group composed by the engineers of the Pontificia Universidad Católica de Peru [167] observed that a big amount of the houses which were destroyed by the seismic event were mainly realized in raw earth technique (adobe). In most of the building, several typical construction mistakes of raw earth/masonry structures were observed:

- High vertical slenderness of earth wall;
- Lack of bonding in perpendicular walls (with cracks in the corners);
- Lack of seismic details;
- Lack of the ring beam.

These construction mistakes cause the typical collapse mechanisms and damages in raw earth buildings:

- In-plane ruptures of the wall ("x" cracks);
- Out-of-plane rupture of the walls with overturning of pieces of wall;
- Roof collapse.

The principal problem of raw earth buildings as adobe and rammed earth (so we are obviously not talking about the weaved solutions as wattle and daub and *quincha*) is the high mass of these walls. High mass means higher weight which is accelerated by the earthquake, and which should be absorbed by some specific designed elements, the so-called anti-seismic devices. That is the reason why a common trait of the reinforced historical raw earth and stone masonry techniques rely in the ability to control the cracking pattern through the interruption of the continuity of the structural members.

As raw earth massive constructions are not able to withstand the inertia stresses generated by the dynamic solicitation of earthquakes [168], buildings get seriously damaged and collapse if no reinforcement system is adopted. Researchers from the PUCP and other institutions have been studying how to improve behavior of adobe and in general raw earth dwellings located in seismic areas for more than fourty years [169]. Recently, a PUCP pilot program presented an adobe-housing scaled model, previously damaged, repaired with mud injections and reinforced with an external mesh of nylon ropes tensed by metal turnbuckles. The structural behavior of the model repaired and reinforced, during a sequence of unidirectional seismic simulations of increasing intensity, was excellent. The external reinforcing mesh helped maintaining the wall's integrity and stability, preventing from the collapse, and keeping the portions of walls together [170, 171]. Rope mesh has great potential to be used as a seismic reinforcement material in self-built homes as it is much cheaper and safer from previously studied reinforcements [172]. In addition, the turnbuckles can be replaced by a small, easy-to-implement knot (the so-called eight-knot) as a low-cost alternative [173].

To introduce the calculation methodologies for ropes reinforcement studied by [174], we will consider a detached portion of wall due to out-of-plane actions.

The central image in figure 14 shows a simplified rigid block model of the interaction between the main structure (Block A) and the detached wall portion (Block B), during the 2014 experimental campaign. Both blocks are joined by a set of n horizontal elastic springs, which prevent the overturning of block B. the rightest image in figure 13 shows the free body diagram of block B, including inertia forces. Block A is fixed to the ground, which moves with absolute displacement x_o. Block B has mass m_B, central moment of inertia I_G, and pivots around ground point O. Relative displacement (with respect to O) of any i-point located on block B at height h_i is noted as u_i.

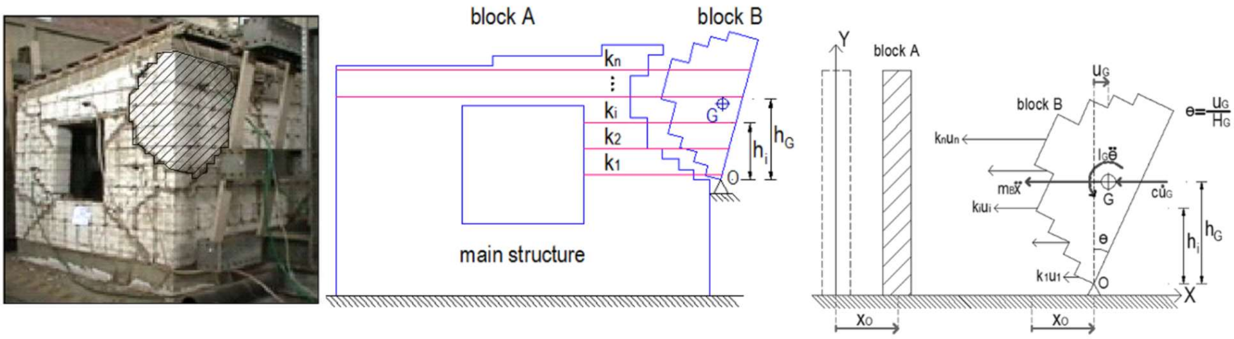


Figure 14 - Interaction between adobe blocks and reinforcement due to seismic motion. (left) Damaged full scale model; (centre) simplified block model; (right) free body diagram of block *B.*

A viscous damper (not shown) with damping factor ζ_B joins block A and the center of mass G of block B. Spring *i* has elastic stiffness k_i and is attached to blocks A and B at a height h_i.

The resulting equation of motion of block *B*, obtained through dynamic equilibrium, is:

$$M_e \ddot{u}_G + C_e \dot{u}_G + K_e u_G = -m_B \ddot{x}_O$$

where the equivalent coefficients for mass (M_e), stiffness (K_e) and damping (C_e) are:

$$M_e = (I_G + m_B h_G^2)/h_G^2$$

$$K_e = (\sum k_i h_i^2)/h_G^2$$

$$C_e = 2\zeta_B \sqrt{M_e / K_e}$$

The natural vibration period of the system is:

$$T_n = 2\pi \sqrt{M_e / K_e}$$

Therefore, if the pseudo-acceleration response spectrum of the ground motion is $S_a(T, \zeta)$, the peak horizontal acceleration of the center of mass *G* of block *B* would be $S_a(T_n, \zeta)$, and the force in the cable *i* is:

$$F_i = \frac{h_i}{h_G} k_i S_a(T_n, \zeta) \left(\frac{2\pi}{T_n}\right)^2$$

This block analysis procedure was applied to estimate the forces on the reinforcement provided to three similar full-scale adobe models tested in different projects on the PUCP's shaking table. The table motion pseudo-acceleration spectrum computed for a damping ratio of 10% [175] is presented in Fig.15. It corresponds to a shaking motion with peak acceleration of 1.53 g, for which an unreinforced adobe model would have collapsed.

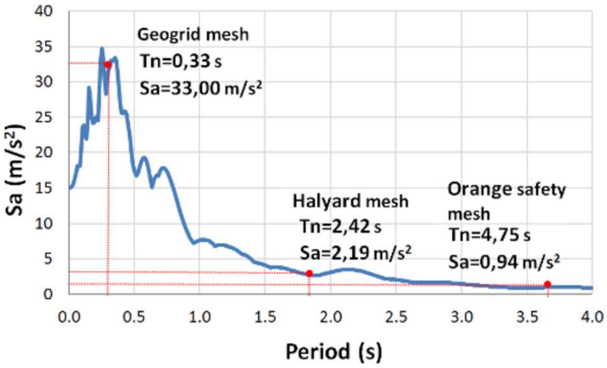
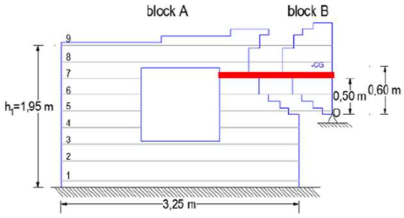
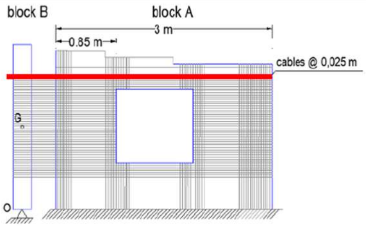
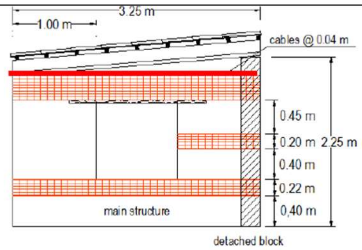


Fig.15 – Pseudo-acceleration spectrum for examples.

Tab. 7 shows the values of the peak load on the most stressed string and the corresponding working load ($f_w=f_u/2$, where f_u is the ultimate load of a single string) calculated for three types of reinforcement mesh: 1) nylon rope mesh; 2) biaxial geogrid mesh; and 3) plastic safety mesh. These calculations predicted correctly the experimental results observed in the laboratory: the forces in the nylon string mesh and the geogrid mesh reinforcement were below their working limit ($f_{max} < f_w$), and the safety mesh failed locally ($f_{max} > f_w$).

Table 7 - Evaluation of maximum forces according to the design reinforcement procedure

Type of reinforcement	Tested model	Most stressed reinforcement strings	String working load
Nylon rope mesh reinforced model			a) Io=320 kg-m2 b) ki =3,00 kN/m c) Tn= 2,42 s. d) *fmax*= 0,83 kN. e) fmax < f*w* = 1,0 kN.
Biaxial geogrid mesh reinforced model			a) Io=2590 kg-m2 b) *ki* =1,80 kN/m. c) Tn= 0,33 s. d) *fmax*= 0,44 kN. e) *fmax* < *fw* = 6,0 kN.
Plastic safety mesh reinforced model			a) Io=2590 kg-m2 b) *ki* =0,12 kN/m. c) Tn= 4,75 s. d) *fmax*= 0,10 kN. e) *fmax*> *fw* = 0.035 kN

These examples are encouraging since their results are consistent with the observed response of different reinforcing meshes. However, it seems that this analysis procedure may not be accurate because it does not consider the observed hammering effect between the adobe wall blocks.

Another interesting contribution given by the PUCP is the research on timber reinforced rammed earth studied in 2016-2018 by [157, 158], after the investigations by ININVI [176]. This reinforcement consists in timber cage composed by vertical post and wood ring beam, embracing the rammed earth wall and connected by wires. This reinforcement creates a composed section, which increase the inertia of wall cross section against seismic actions. As is possible to understand, an earthquake creates two kinds of stress on buildings: walls which are perpendicular to the direction of the earthquake face flexural stresses, and walls which lay in parallel direction to the earthquake one face shear stresses.

The proposed timber reinforcement is located on the outer face of rammed earth wall, so from the composed section (rammed earth wall plus couples of timber posts) it can be calculated a transformed section (fig. 16):

Figure 16 - Transformed section of the wall as for [18].

Where:
a_1 = Dimension of the transformed section
b_1 = Dimension of the timber post which is not to be changed
Ls = Distance between the posts in the section of the wall
t = thickness of the wall
M = Maximum bending moment on the wall
The transformation factor *n* is calculated as the ratio between the Young Modulus of timber and rammed earth:

$$n = \frac{E_{wood}}{E_{rammed\ earth}}$$

So, the dimension a_2:

$$a_2 = a_1 * n$$

The effect of the reinforcement is to change the total inertia of the transformed cross section:

$$I_{wood+ramme\ \ earth} = \left(\frac{a^2 * b_2^3}{12} + \frac{a^2 * b^2 * (b^2 + t)^2}{4}\right) * 2 + \frac{L * t^3}{12}$$

And the maximum normal stress which produce the bending moment *M* in the contact point between rammed earth wall and the timber posts is:

$$\sigma_{rammed\ earth} = \frac{M * \frac{t}{2}}{I_{wood+ramme\ \ ear}}$$

It must be verified that the stress ($\sigma_{rammed\ earth}$) is lower than the resistant stress for flexural tension (f_v) of the rammed earth in the point where there is contact with the timber. If we want to know the effort in the wood at that same point, we multiply to the previous result the transformation factor *n*:

$$\sigma_{wood} = \sigma_{rammed\ earth} * n$$

For a typical structural project of a building using this kind of reinforcement please consult [158]. In this work, the project of a rammed earth house, reinforced with timber posts 5 x 5 cm and spaced 35 cm, is proposed. With this reinforcement, the maximum bending moment (M_{max}) in walls with timber post reinforcements is lower compared to the walls without reinforcement by 35%. Likewise, theoretically, the walls will withstand bending moments approximately three times higher than the walls without reinforcement.
One of the advantages of placing the reinforcement in the walls by connecting it to the wall joints and the foundation is that it allows a greater rigidity to the roof beams. It will therefore ensure that the roof behaves as semi-rigid and the reliability of considering floor beams as edges horizontal braces. Another advantage of including a reinforcement to the walls, wood or otherwise, is that if the walls fail during a severe or rare earthquake, failure is not due to slippage in the joints, but rather to diagonal traction. Also, the rammed earth walls will be confined by the reinforcements thus preventing it from overturning.
When we look at the images of the experimental campaign realized by [157], we realize that poor detail in connections leads to less confinement of rammed earth walls, causing also partial collapses. In figure 17 there are some photos of the rammed earth walls reinforced with timber post where is possible to see the lack of connections between the timber post and the walls. Several problems were seen at the corner, which collapsed for stronger earthquakes, so the authors decided to adopt a supplementary surface rope reinforcement in that point.

These results make us think about the needing of correspondence between the mechanical model and the construction process. The great limit of this system is that the timber post and ring beam are thought as structural members, but they are not intended as part of the building technology and integrated in the construction process. Resolving the connections between vertical posts and ring beam through wires, make us think at the proposed reinforcement as a seismic retrofitting system which is not well solved from a technological point of view. For this reason, we decided to work on the base of these research, trying to improve connections quality and to optimize the construction process, creating a new constructive system where structural reinforcement is actively used during the construction process. The proposed technology will be presented in chapter 4.

Figure 17 - Lack of connections between the timber post and the walls with issues at the corner [147] (Eng. Urbano Tejada Schmidt).

In 2016, some adobe buildings designed by Centro Tierra in Lampa (Peru), following the N E.080 regulation and internally covered with totora mats (a reed that grows on the shores of Lake Titicaca) to improve the insulating properties of the earth masonry and nylon rope reinforcement, were hit by an earthquake equal to 6.3 degrees of the Richter Scale. The buildings (figure 18) have proven to resist effectively, with only minor damages and demonstrating that it is possible to construct earthen construction in a safe manner, using low-cost, environmentally friendly reinforcements, ensuring excellent thermal performance of the envelope [177].

Figure 18 – The upper images show the use of nylon ropes reinforcements in Lampa buildings by the Centro Tierra PUCP [175], the lower images show the minimal damages suffered after the 6.3 earthquake of 2016 [images by Rene Cayo].

2.2.6 Hygrothermal and energy performance of raw earth construction

Buildings must be imagined as systems which consume energy in all their phases: production, construction, use and end-life. This approach is the one corresponding to Life-Cycle description, which provides a wide point of view on the streams of energy which cross the building life-long [178 – 182]. From a thermophysical point of view, the building envelope is obviously involved in this energy exchange, both for the embodied energy during production and construction processes and for its thermal behavior during its use-phase.
Massive envelopes and solar passive design are two choices that can help in reducing costs for heating and cooling in residential buildings. Massive envelopes have proved to have really good performance in Mediterranean climates, because they shift and reduce the thermal waves when they cross the walls thickness. With the aim of reducing energy consumption by contemporary construction, the Italian legislation, following the European and international guidelines, has increasingly adopted a normative apparatus to ensure proper functioning of the building envelope. The intention is to reduce energy consumption and therefore the environmental impact of buildings during the use phase, which has been proved to be particularly incisive (for instance, energy consumption of the residential sector for heating and cooling in Italy is 32.2 Mtoe, a measure expressed in tons of oil equivalent) [183]. It is therefore understandable the great effort directed to the research of construction technologies that can achieve higher energy performance and promote the use of raw materials with lower environmental impact. This interest that has brought back in vogue traditional technological solutions such as the abovementioned earth-based constructions.
Compared to the most common construction solutions, which use reinforced concrete skeletons and Poroton blocks envelopes, the raw earth ones, even when stabilized with percentages of Portland cement around 5%, have an embodied energy of about 500 MJ/m^3, which is only equal to 15 - 25% of the energy incorporated in a conventional brick [184]. Moreover, as mentioned, they have excellent thermal dynamic performance, due to their high inertia, directly improving the thermal comfort in buildings [185].
As is well known, an effective thermal storage mechanism used in construction is based on the latent heat developed by PCM (phase change materials) that accumulate thermal energy at the change of state developed between temperatures of 23 and 20 degrees Celsius: a similar mechanism occurs in the pores of earth-based materials, where thermal energy is used to make the change of state from water to liquid to vapor [129]. In addition to this, it has been shown that thanks to a good bioclimatic design of the building, the earthen envelopes can lead to the reduction of energy used for heating, cooling and humidity control [186].
In this paragraph, we will review the main results related to the thermal performance of earthen buildings in different climates, and their capability to meet the high standards required by international regulations. These works are based on:

1. thermal simulations;
2. measurements on test-box;
3. measurements on existing buildings.

It should be noted that, apart from empirical case studies on existing raw earth buildings, the results obtained from test-boxes and thermal simulations tend to return altered results if not based on experimental data regarding the material and if they neglect the contribution of moisture transport [187].
Concerning the first group of publications, these are thermal simulations carried out mainly in Australia, where the construction sector is called to comply with certain requirements established by the National Construction Code (NCC). For 30 cm-thick rammed earth walls, the minimum thermal resistance required by the NCC impose *de facto* the addition of thermal insulation to the constructions. Alternatively, in Australia

it is possible to comply with the energy legislation through a rating system, the Star Rating Requirement, which sets limits on energy consumption for heating/cooling depending on the climate zone.
This assessment system is used in [186], demonstrating that by varying the type or width of the glazings, their shading system and the thickness of the walls, the rammed earth building achieves an adequate energy load and can be left uninsulated in areas characterized by semi-arid and Mediterranean climates.
Similarly, Hasan and Dutta [188] compare several uninsulated rammed earth construction solutions and show that they are able to meet the annual energy consumption limits in subtropical and tropical climates, while in temperate climates attention must be paid to the quality of the glazings.
Heathcote [189] emphasizes that to ensure effective cyclical performance for raw earth masonry, thicknesses greater than 45 cm must be adopted to level external summer fluctuations and introduce large glazing in the North (the author works in the southern hemisphere) in order to ensure adequate environmental comfort inside the building during the winter season.
A numerical analysis of the summer temperature profile over 24 hours was carried out by [190] demonstrating that a 30 cm thick rammed earth wall can attenuate and stabilize internal temperature fluctuations between 23 and 25 °C.
In [191] several upgraded cob wall constructions are compared, using different cavity insulation like paper, straw, or wool; several sustainable earth wall stratigraphies are found, complying with the restrictive UK thermal regulation. The same authors, in the mark of COBBauge project, have defined an interesting constructive solution which integrates a thick cob wall on the interior side and a lightweight earth with flax or hemp shives on the exterior side of the wall [192], to comply with the mainstream energetic standards respecting the breathability of the cob wall.
Thermal comfort of two sub-saharian buildings located in Burkina Faso, a traditional adobe and an innovative earthbag one respectively, are studied in [193]; annual thermal simulation is run in free-running conditions, and discomfort hours are studied, revealing that design choices on buildings (shape, location of windows) and use of typical bioclimatic strategies (roof shadings elements, night cross ventilation) result in an enhanced comfort for both dwellings (figure 19).

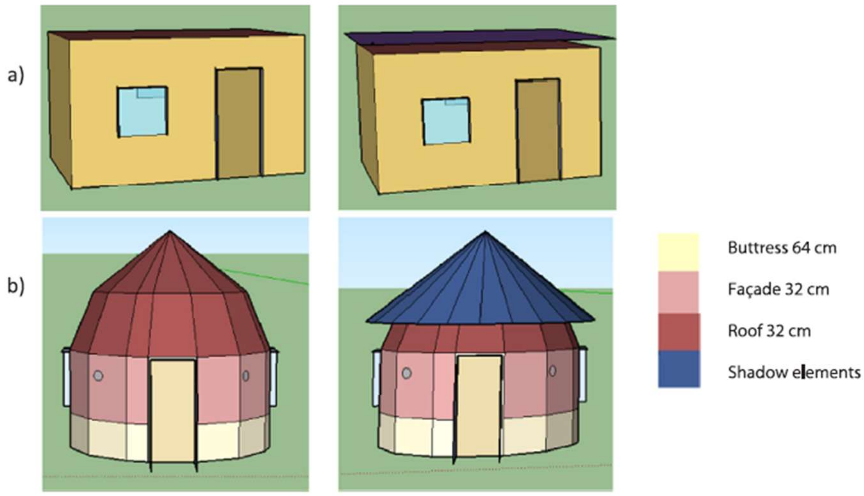


Figure 19 – Modelisation of an adobe (a) and an earthbag (b) building with OpenStudio in [193].

The second group of publications includes measurements carried out on test boxes. In [194] the thermal performance of the south facades of two rammed earth test boxes, with two different thicknesses are compared: the first has 50 cm thick walls and is located in Barcelona, the second uses 29 cm thick walls and is located in Lleida. Both test boxes show to adequately dampen external temperature fluctuations, but the lower

thickness and the more continental climate of Lleida test box determine a significant difference in terms of surface temperatures of the walls and profile of indoor temperatures, producing uncomfortable temperatures in winter. In a later work [195] the authors compare the test box with 29 cm thick rammed-earth walls with a similar one with an extra layer of internal insulation made of wood fiber: the summer performances of both test boxes, with and without the use of HVAC systems, are assessed and it is confirmed that the addition of the insulation allows to obtain a better thermal response, reducing the energy consumption for cooling by 45%.
Allison et al. [196] collected temperature and humidity data from a test room in England (figure 20), and used these data to confirm, by means of a hygrothermal simulation, the improvement in terms of environmental comfort, air quality and reduction of energy consumption determined by insulated rammed earth walls. This work considers the contribution given by vapor transport using the software WUFI Plus v1.2.

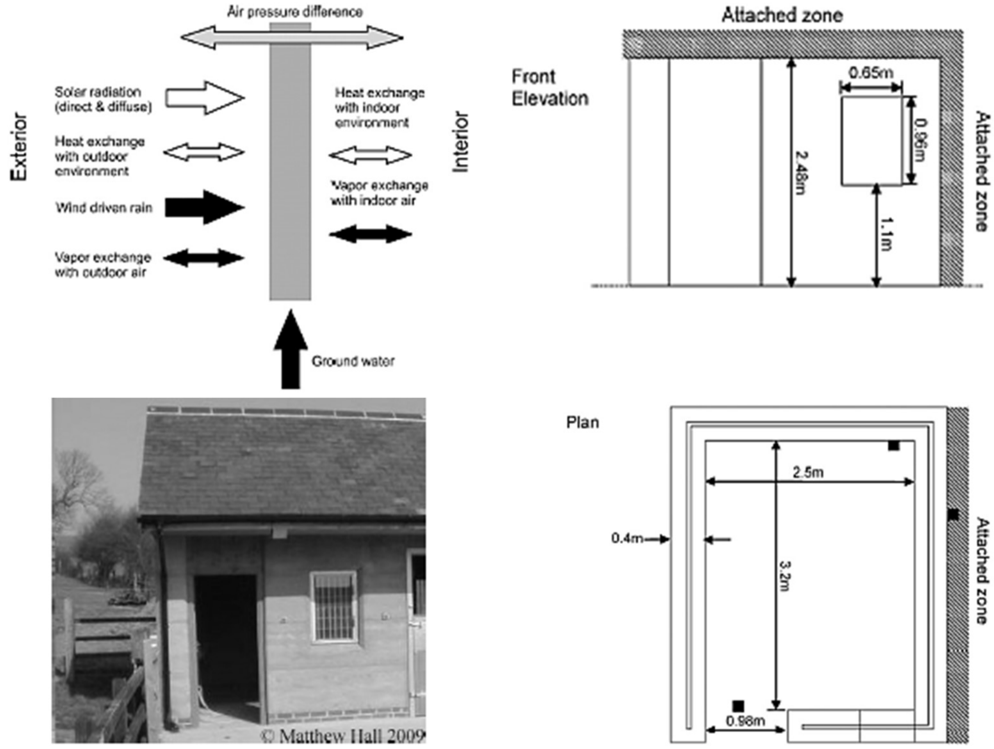


Figure 20 – Hygrothermal behavior of a cement stabilized rammed earth test box [196].

The latest group of publications include direct measurements of indoor temperatures and humidity in earthen buildings. The abovementioned work by Soudani et al. [185] surveys the thermal performance of a rammed earth building with 50 cm thick walls located in the region of Isère, France: the house manages to maintain comfortable temperatures both in summer (with maximum indoor temperatures of 28°C) and in winter (with minimum indoor temperatures around 17°C, occasionally using a wood-burning stove located in the living room).
The importance of associating a correct bioclimatic design strategy with "green" rammed earth buildings is underlined by [197] who analyze a two-story public building in Australia located in Mediterranean climate, finding deficiencies in terms of environmental comfort.
In [198] are listed the positive outcomes of using rigid panel insulations in the rammed earth walls of SIREWALL constructive system, mainly used in cold climates of Northern America; the use of such technology results in mean indoor winter temperatures of 16°C compared to the 7°C outside, while humidity is maintained between 40% and 65%, consistent with comfort values.

In cold climates, the combined use of thermal insulation (natural or synthetic) and rammed earth walls leads to the amortization of heating consumption by up to 70%, as reported by [199] with reference to four residential buildings in Canada.
Measurements on traditional rammed earth buildings, with 50 to 60 cm-thick rammed earth walls, are made by [200] to measure their real thermal performance. The buildings, heated during the winter period, maintain internal surface temperatures between 15.3 °C and 16.6°C, while indoor air temperatures range from 15.7°C to 19.4°C, when outside temperatures are between 3.3°C and 1.5°C. The calculated U-values are between 0.65 and 0.94 W m^2/K, demonstrating the good thermal performance of massive masonry.
The study conducted by [201] illustrates the thermal performance of two identical, uninhabited rammed earth buildings located in Western Australia: one with monolithic rammed earth walls and the other with a polystyrene insulating core. In-situ measurements (figure 21) and simulated thermal behaviors show that the two houses have excellent thermal stability. It is also highlighted how the addition of thermal insulation, in desert climate regions, does not lead to further improvements in thermophysical performance. In [202] the same buildings are studied after the settlement of two families which are queried about the comfort conditions experienced: the opinions expressed by the inhabitants reflect the good thermal performance of the two buildings which, while requiring occasional use of electric heating in winter, tend to perform very well in summer. The authors conclude that these performances can hardly be described by today's environmental comfort assessment systems used in Australia.

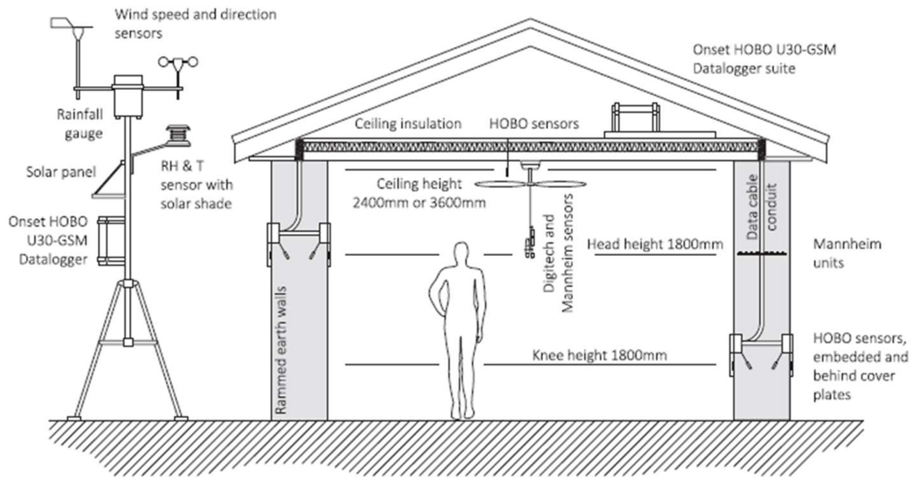


Figure 21 – Representation of instrumentation location in [201].

From the shown literature review, is easy to understand that calibrated thermal simulations must be based on experimental data concerning thermal characterization of the base raw earth material. As in [203, 204] procedures for the assessment of thermal properties of raw earth materials are still being developed and nowadays there is no consensus on standard procedures to be used for the evaluation of dry density, thermal conductivity, and specific heat capacity, especially when considering the influence of moisture content.

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3. Research goals and methodological approach

In this section we will focus on the definition of the research goals and on the methodological approach we used to achieve them.

The analysis conducted on previous research work on contemporary rammed earth construction, showed us that it appears to be characterized by stabilization and reinforcing techniques taken from cement-based construction. Independent research on a sustainable, eco-friendly, and efficient rammed earth technology does not seem to be completely developed (research gap).

For this reason, an umbrella of research goals is presented in the first two paragraphs, and particularly:

- It is defined the statement of aim of the present research, which is the programmatic purpose of the study and consequently, several operative objectives are defined to meet the aim (3.1);

- the research questions on which the research is structured are presented together with the hypothesis on which the current research works and aims to confirm (3.2).

In the last paragraph (3.3) it is presented the methodology used in the design of the research (theoretical level), and the methods used to answer the research questions (practical level). A deepening in the essence of research by design is furthermore provided.

3.1 From the research gap to the research goals

From the background section emerges that in the last few decades, traditional raw earth techniques have been rediscovered and often redesigned in contemporary applications, in different contexts and with various aims. Starting from the classification made by [1], which make a division between these practices putting them in relation with the geographic areas where they rise, in Section 2 we expanded this review adding details about the composition of loadbearing structure, with reference to anti-seismic devices and thermal improvements. This analysis pointed out that in Asia, Latin America, Africa and Middle East Countries, the development of new raw earth technologies is more concerned about social and emergency housing, with strong efforts made in training local communities in self - building practices of low-tech raw earth dwellings [2].
In Europe the focus is the interest on raw earth as a natural sustainable material which can reduce the environmental costs of new constructions. As the topics of reduction of environmental impact of construction sector, in its triple dimension of minimizing embodied energy in base materials, reducing energetic costs for use-phase and eliminating end-of-life waste in construction, have become the *leit-motiv* of the so-called sustainable architecture, raw earth is nowadays living a rebirth.
Among raw earth techniques, some of them like rammed earth are coming into strong modifications in their manufacturing process [3], to improve their mechanical characteristics and speed up their production. As we saw in Section 2 of the present work, traditionally rammed earth is a technique which uses a damp soil that has to be dynamically compacted inside timber formworks with manual rammers (usually realized in wood or steel); in the last decades this production process has been improved using metallic continue formworks (similar to those used for concrete) and pneumatic rammers [3]. Another contemporary raw earth technique is compressed earth block (from now on CEB), small-prefabricated bricks with almost the same composition of rammed earth, which are subjected to a static compression; they can be easily transported and assembled on site in a masonry.
Looking at contemporary rammed earth and compressed earth block production, it is possible to understand that they have been developed in countries which adopted a raw earth construction regulation. *Inter alia*, Australia, New Zealand, New Mexico, Germany, Spain, France are countries with good contemporary raw earth manufacture and complete building codes or guidelines on earth buildings.
Not surprisingly, countries which are endowed of Earth building codes, also show a good amount of raw earth dwellings. For instance, Australia, where rammed earth succeeded in conquering 20% of the building sector. Peru is a leader in anti-seismic earth building standard, because of the experience gained with the recovery plans for high Andean villages affected by strong earthquakes, where was promoted the use of reinforced earth buildings [4].
In the richest Countries of the world, it is noticeable a wide use of raw and rammed earth-based products for cladding and coating purposes [5-7], but only in some cases these have been designed as components inside a new constructive system.
David Easton's Watershed materials have an outstanding mechanical strength, but they have been thought as CMU (concrete masonry unit) blocks to be used inside a concrete based technology [8-9].
The same adaptation to concrete technologies happens in Martin Rauch's Lehm Ton Erde production, in which massive panels have been usually coupled to timber, concrete or steel frames and sometimes used with insulations as granular foam glass [5-7].
In some cases, companies sell a complete constructive system kit: this is the case of the Canadian SIREWALL, which promotes a thermal insulated anti-seismic rammed earth system. This system uses a double wythe of cement stabilized rammed earth, reinforced with vertical steel rebars and horizontal brackets to prevent failure

from earthquakes, with a polyisocyanurate rigid insulation interposed [10-12]. This system represents one of the most outstanding attempts to adequate traditional rammed earth to contemporary construction, but it is affected by the influence of massive use of industrial and high-polluting materials like Portland cement (used in the stabilization process of the soils), steel rebars and synthetic insulations.
Between the review constructive systems, only few of them show the will to innovate raw and rammed earth technologies yet respecting its original environmental sustainability, by the creation of faster constructive process [13-14], by the partial prefabrication of constructive components and the integration of anti-seismic devices [15-18]. Yet, none of the examined constructive systems present the simultaneous optimization for material properties, seismic resistant design and hygrothermal and energy performance, conjugated with the will to innovate and fasten the constructive process.
In conclusion, it is possible to infer that contemporary rammed earth mainstream technology is still deeply linked to concrete - based ones. Methods to improve material properties are based on Portland cement stabilization of soil mixtures. Reinforcements of rammed earth walls are usually made with steel ones. Procedures to enhance thermal performance of rammed earth envelopes consider the use of synthetic insulations, whose production has an elevated environmental impact.
The use of these materials to improve the final performances of rammed earth technology cause a deep discrepancy in the reasons which initially brought to its rediscovery:

- on a material scale, cement stabilized rammed earth is not anymore reusable or recyclable and, for a modest improvement in its mechanical performance, its embodied energy increases dangerously [19];
- on a system level, steel reinforcements enhance structural performance (not concrete framings, which have proved to be too stiff in comparison with raw earth material and really dangerous during seismic events [20, 21]) but present the same increase in environmental costs;
- on a performance stage, use of thinner rammed earth walls as the one adopted in insulated rammed earth cavity walls (total thickness 30 cm) does not seem to be optimal because it reduces the benefit of massive envelopes in the creation of comfortable indoors; moreover, the use of synthetic insulations increases the environmental costs of the technology and there is still no consensus in literature about the compatibility of hygroscopic rammed earth walls and non-breathable thermal insulation.

The gap we found in contemporary rammed earth research and production is therefore referred to the fact that no contemporary sustainable and eco-friendly rammed earth techniques have been developed for high seismic risk countries where strict energy and thermal standards are applied to reduce the environmental impact of constructions. In areas like Europe, North America and Oceania, base materials are demanded to be highly performative to accomplish the requirements of the building sector, and constructive process must be easy and fast to be implemented by labor, in order to be competitive against conventional constructive systems.
As we already said in the Introduction chapter, the aim (A) of the research is to delineate a holistic design approach for rammed earth constructive technology, that combines the advantages of working with natural, healthy, poorly processed and reduced environmental impact materials, with the need to ensure certainty in the structural (in particular, in the seismic resistance), hygrothermal and energy performance of the system. In this work the certainty of performances is pursued by the adoption of semi-industrialized production processes of the rammed earth reinforced constructive system, and more in detail by the prefabrication of the rammed earth material and timber reinforcing elements, and by the definition of a careful construction process.
This programmatic aim has been translated to several practical objectives to be achieved, which are:

1) the design of a premix material for rammed earth masonries, with superior physical, mechanical and thermal performances (O1);
2) the adoption of easy-to-implement seismic-resistant design principles for rammed earth buildings; this involved finding correct design principles for the reinforcements of the constructive system and adapting the constructive process for their integration (O2);
3) the validation of vertical envelope's stratigraphy design by the control of the building system's hygrothermal and energetic performances (O3).

3.2 Research questions and hypothesis

In this sense, a general and programmatic research question arise, concerning the possibility of designing a reliable, sustainable, fully recyclable rammed earth technology which could conjugate efficient structural performances, with high thermal and energy ones and cost-effectiveness.
The aim of this thesis is to answer yes and to reinvent rammed earth technology in a sustainable 21st century version, using design tools of engineering studies, and to make it competitive inside current construction sector. It is possible to identify three research questions connected to the present work:

RQ1: Can we define a rammed earth material which has outstanding and repeatable performances thus being totally recyclable?

RQ2: Can we design a seismic resistant rammed earth technology which is economically, environmentally, and constructively competitive?

RQ3: Can this design approach lead to the definition of rammed earth envelopes and buildings which can meet current energetic standard?

The hypothesis advanced by the author is that rammed earth construction can aim to meet the high-qualitative standards required by construction sector by the adoption of semi-industrialized production processes for the production of the rammed earth material and for the structural reinforcement to be used in the constructive system. Likewise, the structuring of the design and construction process can ensure the sustainability of material choices, construction phases and final thermal and energy performances. In particular:

H1: Innovative stabilization methods for rammed earth material, using agro and non-agro waste in a circular economy vision, can give outstanding physical, mechanical and thermal performances to the material.

H2: A seismic-resistant design for rammed earth walls can be adopted, using natural, low-cost and eco-friendly reinforcements which enhance structural performance thus being integrated in the construction process.

H3: The use of thick rammed earth walls, eventually combined with natural-based thermal insulations, satisfy current energetic standards and sustainability criteria, thus creating comfortable indoors.

3.3 Methodological approach and Methods

As previously introduced, this research is finalized to the definition of a sustainable, seismic resistant and thermally efficient constructive rammed earth system, and its prototyping for the industrial implementation. The methodological approach we followed to reach this objective, is usually known as Research by Design or Design-Based Research [22 – 30]. This kind of methodology has an underlying premise to develop the design of an artefact, a technological tool, or to further a new or an existing theory which can deepen the understanding. This approach is characterized by the need to answer to specific design research questions developed after the analysis of the state of the art which can be fulfil using different methods, depending on the specific questions arisen. Moreover, Research by Design is characterized by an iterative process, where preliminary research is followed by several prototyping and validation phases until a satisfactory answer to the pre-determined research question is reached. For further details on Research by Design methodology please see the explanatory sheet at the end of the paragraph.

To achieve the objectives (O1, O2 and O3) and to answer the specific research questions (RQ1, RQ2 and RQ3) described in the previous paragraphs 3.1 and 3.2, the use of mixed research methods was required. We will now introduce the methods used, but further details will be provided in the specific paragraphs concerning developments on material (4.1), constructive system and process (4.2) and thermal and energy performance of the system (4.3).

Experimental methods (M1) were used for the material design, starting from an analysis of the base materials provided by the industrial partner (Guglielmino Soc. Coop.) and offered by local Sicilian territories. After that, different mix design for rammed earth materials were defined and representative samples were manufactured at the Guglielmino Soc. Coop. and tested at the University of Catania concerning their physical, mechanical and thermal performances. In particular, this stage of the research consisted in:

- a qualitative characterization campaign on different sicilian soils;
- a geotechnical and mineralogical characterization of the soil, fibers and aggregates used;
- a material investigation on physical, mechanical, and thermal characteristics of rammed earth samples.

Significant guidance in the definition of the finally adopted stabilization method for the rammed earth material has been provided by the Centro Tierra advisors, Prof. Arch. Sofia Rodriguez Larraín and Prof. Eng. Julio Vargas Neumann.

Prototyping and validation procedures (M2) were used for the design of the constructive system and process. In this stage of the research, a design-simulation-validation approach, characterized by several design iterations has been carried out. Particularly, the first designs of the construction technique contemplated the use of prefabricated rammed earth panels and were made at the University of Catania. These constructive systems were reviewed during the visiting at the Pontificia Universidad Católica de Perú, where a strong seismic-resistant design approach for raw earth building was acquired on the base of a continuous dialogue with PUCP supervisors. At the end of the visiting, a comparative dynamic test on different scaled rammed earth constructive prototypes was performed, allowing us to understand the correctness of the seismic resistant design adopted, but also the need to simplify the constructive process, especially when referring to the prefabrication of rammed earth panels. To simplify the constructive process, the prefabrication of rammed earth panels was abandoned in favor of the prefabrication of a rammed earth mix as base material for walls to be built on site. Constructive system and processes were optimized at the University of Catania by the construction of several 3D-models. Finally, with the help of the Guglielmino Soc. Coop., a full-scale prototype has been built on the base of the hypothesized construction phases. A patent application has been made on this constructive system by the research group of University of Catania in collaboration with the Guglielmino Soc. Coop. So, to summarize, the second method consisted in:

- the construction of an abacus of reinforced raw earth constructive technologies;
- the design of a constructive model of the technology on the base of [4] and the construction of several prototypes to be tested on a portable shake table;
- the creation of several 3D models (SketchUp) to simulate the integration of the reinforcement during the construction process;
- The validation of the constructive process by the construction of a full-scale wall at the Guglielmino Soc. Coop.

Building physics simulations methods (M3) were used in the last phase of the research, for the assessment of the hygrothermal and energy expected performances of a representative building located in the city of Catania, Sicily. Thermal and energy simulations were run on DesignBuilder software and calibrated on the base of the rammed earth material properties and local weather data. Influence of different bioclimatic strategies to improve summer performances was also investigated. The use of the Optimization tool, allowed for a comparison of thirty-one rammed earth wall insulated and uninsulated stratigraphy which could at the same time minimize energy needs and environmental impact, by respecting comfort requirements. On the base of the last analysis, a first exploratory study on the hygrothermal performances of a wall designed with the innovative rammed earth material was run on Delphin software. The analysis aimed to understand which insulating solutions are more compatible with the rammed earth wall, in Mediterranean climate zone.

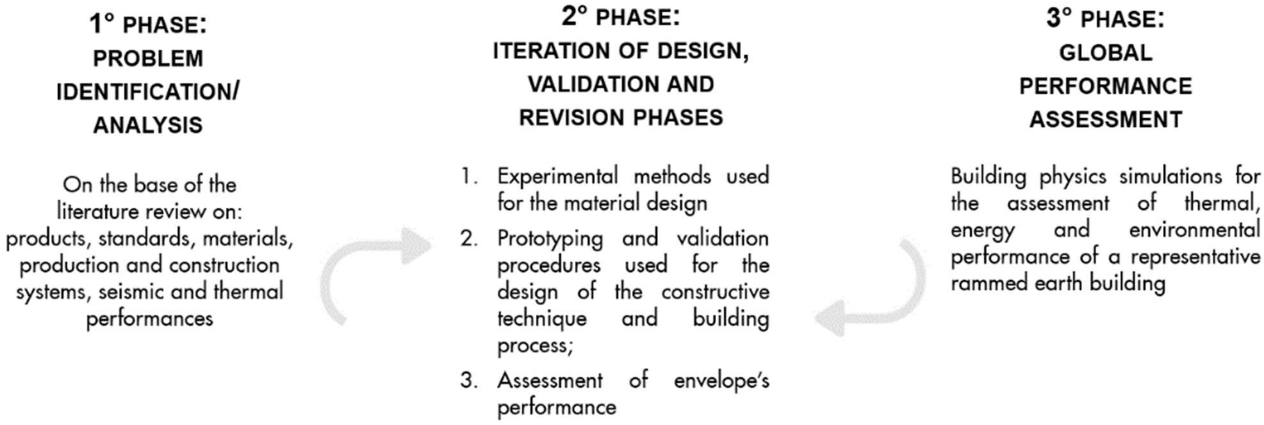

Figure 1 - Research by Design methodology and methods applied to present thesis.

The constructive system has been furthermore subjected to structural performances validation to confirm the efficiency of the designed reinforcement devices. A preliminary simulation carried out on Midas FEA NX software, relating to the structural behavior of a two-story rammed earth building with intermediate timber floors and ring beams, subjected to an earthquake of medium intensity, have given positive results in terms of maximum stress and strain displayed by the building. Moreover, the preliminary investigation considered the pronounced non-linear behavior of rammed earth masonry, and it highlighted the positive effect of the reinforcement system in the increase of final bending stress and in the limitation of cracks in a damage model opportunely adapted from the theory of nonlinear fracture mechanics of concrete. This aspect of the research is currently under development and will not be reported in the thesis.

Research by Design methodological approach

Research by Design has an underlying premise to develop the design of an artefact, a technological tool, or to further a new or an existing theory which can deepen the understanding.
As Schoenfeld [22] explains, « the products of well conducted design experiments are improved interventions and improved understandings of the processes that result in their productiveness » which can have productive effects on the research community.
During the 1960s, design research evolves as an autonomous field of study: the first generations of design theories were enmeshed in technical design, which then evolved in a problem-solving process. We have to wait till 1983 to see the first definition of design as a reflective conversation with a particular situation [23]. This contribution is interesting because it clarifies that design is actively framed by researchers, which decides to improve a precise situation or problem.
Two are the main paradigms in design research:

- Design as problem solving;
- Design as reflection-in-action.

According to Plomp [24], design-based research is « cyclical in character: analysis, design, evaluation and revision activities are iterated until a satisfying balance between ideas » of what was wanted and what has been achieved. Another important aspect of design-based research is that it is often defined as a series of approaches rather than a single one. This variety allows for the flexibility and adaptability of the research design. This point is important because it allows for the use of different approach (experimental, theoretical, simulations) to find an answer to the research question.
Design-based research is characterized by a systematic evaluation of the consecutive research phases or iterations which actively contribute to the theory building [23]. There are some fundamental aspects of this kind of research:

- The research moves in a real context, with active collaborations with practitioners aiming at solving complex problems;
- There is an integration between known and hypothetical design principles and technological advances in order to find solutions to complex problems;
- The researcher has to divide a complex problem into different research questions, which can be answered using different methods;
- The research process is cyclic and iterative.

Usually, research by design studies are characterized by three different stages: preliminary research, prototyping phase and assessment phase [24]. In the preliminary research needs and context analysis is undertaken, a review of the existing literature is conducted, and the researcher/s develops a conceptual or theoretical framework for the study.
The second or prototyping phase is the iterative design phase, where several iterations of the materials and/or approach are undertaken, with each iteration being a micro cycle (microphase) of the research. Mixed - methods of data collection are used allowing a more robust understanding of the learning environment. Each of these micro cycles is a stand-alone study that may focus on fine-tuning a particular aspect of the study with a formative evaluation being the most important research activity at the conclusion of each phase. The formative evaluation aims to improve and refine the materials, the approach, and the theory. The focus on iteration is not just to evaluate an innovation, for example, a hardware or software, but rather to produce and refine design principles that can provide guidance for similar research studies or development endeavours [25].
The final stage is the assessment phase. The purpose of this phase is to conclude how the outcome of the investigation meets the pre-determined specifications of solving the problem [25]. In this phase, recommendation for future work may be generated.
The main difference between the traditional predictive research approach and design research approach is that the latter supports the clarification of the problem and the development of design principles and theory refinement through a cycle of reflection, evaluation, and refinement whereas a predictive approach supports hypothesis development and refinement.

According to [25] « The development of design principles will undergo a series of testing and refinement cycles. Data is collected systematically to re-define the problems, possible solutions, and the principles that might best address them. As data is re-examined and reflected upon, new designs are created and implemented, producing a continuous cycle of design-reflection-design».

As [26] suggest, in a design-based research study, data are analyzed immediately, continuously and retrospectively. Part of this cycle of data collection involves stages, such as a comprehensive literature review coupled with the systematic and purposeful implementation of research methods. This iterative process leads to the development of design principles, which are then reflected upon and evaluated through the refinement of the problem, solutions and methods.

This process of refining and redefinition of the design and the achievement of goals contributes to the development of valid theory [27, 28]. Waderman's generic research design model [28] demonstrates the dual outcomes of design-based research as the practical product and a contribution to theory. Through the cycles of analysis, consultation, development, testing, refinement, reflection and evaluation, the principles and the solution implementation are revised and refined. The use of micro phases or prototyping phases in design-based research is a strategy to ensure reliability of the design before the final field work study.

As design-based research aims to ascertain if and why a particular intervention works in a certain context, micro research phases provide researchers with an opportunity to refine the design and to gain a more informed understanding of why an invention may (or may not) work in that context [24]. Micro phases involve a series of small-scale design studies that result in the subsequent revaluation of the materials before the final product is used in a school-based study. The use of micro phases is part of what [24] refers to as the prototyping stage: « each cycle in the study is a piece of research in itself (i.e., having its research or evaluation question to be addressed with a proper research design) ». Each phase should be presented as a separate study as there may be different research questions, population groups, data samples and methods of data analysis.

A typical framework to be adopted in this kind of research could be the DMADDI: Design, Measure, Analyze, Design, Develop and Implement framework. In addition, to develop the consistency of the approach, the repetition of the phases is encouraged in investigation of "all reasonable areas" to ensure that early closure does not occur, thus reducing the impact of researcher bias [29, 30].

One of the issues that can arise in design-based research by a solo investigator is the occurrence of conflicting researcher roles; that of the designer and developer, the facilitator and the evaluator of research. While playing multiple roles can be beneficial in that a researcher can understand the whole process, there are, at times, tensions between the roles.

The use of multidisciplinary research teams is seen as a strength of design-based research as a greater breadth of understanding can be brought into the research environment that from solo research or mono-disciplinary studies. It is easy to draw the benefit of a multidisciplinary team obtained by the inclusion of several experts in the research group, which evaluate materials and data collection instruments and interrogate the findings providing a degree of rigour that may escape a solo researcher. The nature of design-based research necessitates researcher adaptability. As the research takes place in a real-world setting, often the wishes and needs of partners may influence the study. Given that design-based research takes place in a "real world" context and is based on iterative cycles of design and re-design resulting in ongoing changes, it is necessary to implement a planning framework [24].

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4. Core

In this section we will focus on the core of this research.

In the first paragraph (4.1) considerable attention is given to the study of the construction material. In particular, the choice of the base materials and preliminary operations for their preparation (4.1.1), the definition of several rammed earth mixes (4.1.2), the manufacturing protocols (4.1.3) and test results (4.1.4) are presented.

In paragraph 4.2 it is presented the multiphase prototyping procedure of an innovative constructive solution in reinforced rammed earth based on the design principles provided by the Peruvian Standard NTE 080 [1]. This constructive system presents a combined reinforcement system: a principal timber reinforcement skeleton and an auxiliar rope strengthening to improve the structural behavior in seismic areas. At the same time, efforts have been made to systematize and rationalize the constructive process for an easy-to-implement integration of these reinforcements as part of the formwork system.

Rammed earth walls perform another fundamental role in the system: they work as temperature and humidity regulator to define comfortable indoors [2-5]. In paragraph 4.3, it is investigated the hygrothermal and energy performances of rammed earth envelopes with thickness defined by the structural project, with and without thermal insulations, to assess compliance with energy standards and expected comfort levels.

4.1 Material

4.1.1 Choice of the base materials and preliminary operations

The first step of the research concerned the study of the base material and the optimization of the mix to improve physical, mechanical and thermal properties through a stabilization process.
A qualitative experimental analysis was carried out on 5 different Sicilian soils coming from quarries which are 5 to 150 km away from the processing factory, to find a suitable soil for rammed earth construction.
The variables considered for the choice of the raw material were the dry resistance (which is expression of the internal cohesion provided by clay fraction), the texture (through sieving and a simplified sedimentation test) and the linear shrinkage. The evaluation of the dry resistance of the material is coded by several earth construction manuals, as well as the simplified sedimentation test, but the combination of the information coming from the sieving analysis and the linear shrinkage test were done following the procedure proposed by [6]. These procedures showed that three on the five soils had an interesting amount of clay, suitable for earth construction, but one of these was discarded because the quarry was too far (100 kms away) as the procedure of bringing the material to the factory was not considered economically sustainable.

Figure 1 – The five Sicilian soils tested through the methodology by [6]

The Particle Size Distribution (from now on PSD) of the two remaining soils was determined through laboratory tests [7, 8]. After that, the soil with higher amount of clay and easiest quarrying and preparation process was selected. This soil, from now on called soil F, comes from Floridia quarry, and was subjected to several stabilization process to improve its properties.
As it is known, stabilizing means to change the natural composition of the base material in order to regularize its behavior. Every stabilization process aims to different material improvements: for instance, if we want to improve the mechanical characteristics of the natural soil (such as compressive strength) we could work on its particle size distribution to reduce excessive porosity, or additives could be added, which can improve internal cohesion between the components of the mix. Through these procedures several results can be achieved: improvement of mechanical characteristics and cohesion, reduction of absorption and shrinkage effects, enhancement of erosion resistance to wind and inhibition toward capillarity water.
The soil adopted for optimization is a Sicilian soil quarried in the area of Syracuse and its particle size distribution (compared to fuller curves adapted for rammed earth construction [9]) is shown in figure 2.
The first part of the particle size curve is obtained through direct measurements by sieving, while the second part is deduced indirectly through density measurements, in accordance with the ASTM D7928 – 17.
The F soil is characterized by a comparable amount of clays ($d < 0.002$ mm) and silts ($0.002 < d < 0.006$ mm) and seems to lack in fine fractions. However, considering that different stabilization methods were going to be applied, we decided to continue with this soil.
In table 1 is shown the result of the plasticity test (obtained by Atterberg limits on the fine fraction), to assess the liquid limit (LL), plastic limit (PL) and the plasticity index (PI= LL - PL). In the same table is reported the acceptable limits of these values for rammed earth application, as defined in [9 - 11]. Comparing these results to the reference values, the mineralogy of the clay contained in Soil F is identified as a kaolinite. The kaolinite is a clay mineral, with the chemical composition $Al_2Si_2O_5(OH)_4$. It is a layered silicate mineral, with one tetrahedral sheet of silica (SiO_4) linked through oxygen atoms to one octahedral sheet of alumina (AlO_6) octahedra. Kaolinite has a low shrink–swell capacity and a low cation-exchange capacity (1–15 meq/100 g). It is an earthy, usually white, mineral (dioctahedral phyllosilicate clay), produced by the chemical weathering of

aluminium silicate minerals like feldspar. In many parts of the world, it is colored pink-orange-red by iron oxide, giving it a distinct rust hue.

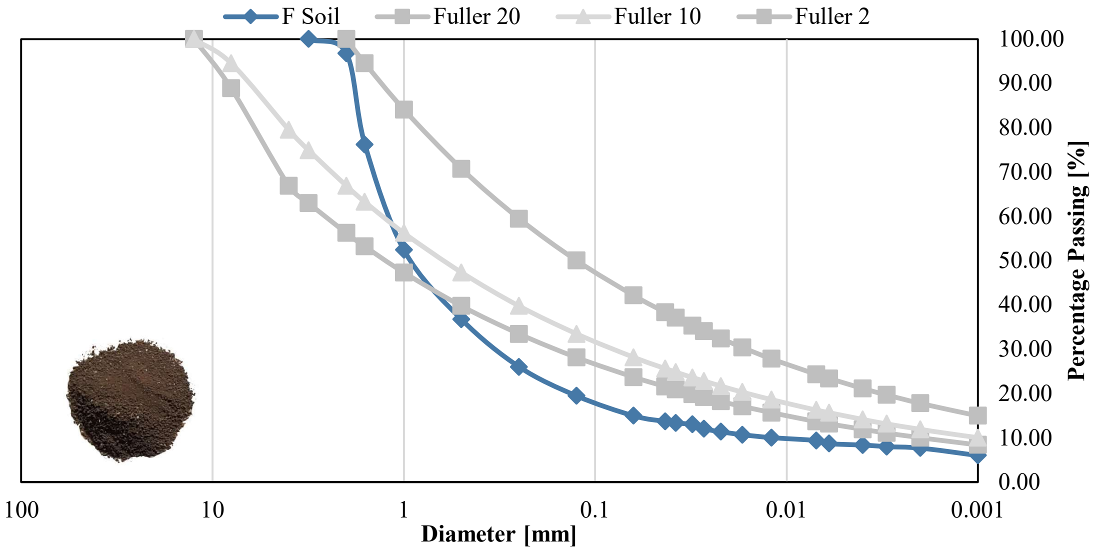


Figure 2 – F soil and its particle size distribution (Giada Giuffrida, 2018)

Table 1 - Atterberg limits for F soil and comparison with values from literature

Reference	Atterberg Limits			Skempton Classification	
	LL (%)	PL (%)	PI (%)	CF	Ia
Houben & Guillaud [9]	25-50	-	2–30	-	-
HB195 [10]	<35–45	-	<10–30	-	-
Walker [11]	<45	-	<2–30	-	-
F Soil [Present study]	47.30	30.68	16.62	51.33	0.324

As we already introduced in previous section, this research wanted to focus on alternative stabilization methods using agro and not agro waste, respecting the principles of circular economy. Chemical stabilization through Portland Cement (less frequently with lime) is nowadays regarded as a common practice in many areas, as Australia and United States, and explicitly recommended in some earth building codes as [12]. As we already said, the addition of Portland cement increases the embodied energy of rammed earth [14], reduce its recyclability, and therefore increase the environmental impact of the material.

For this reason, prior to realize a chemical stabilization with these agents, it would be better to operate a physical correction of the base material and try alternative stabilization methods.

The comparison between these basic information and the current average PSD composition values (found in literature) brought us to elaborate several unstabilized rammed earth (from now on URE) mixes.

Two stabilization philosophy have been followed in this research. In the first-generation mixes (2018 campaign), natural soil has been mixed with increasing amount of gravel and sand, following the methodology indicated by [15]. This physical stabilization is the first experimental step to reach a minimum characteristic unconfined compressive strength of 1 - 2 MPa, in accordance with many standard [1, 10, 12].

Two stabilized mixes, a cement-stabilized and a lime stabilized have been added to this first experimental campaign, to understand the physical and mechanical improvements these binders could add. It is important to point out that the first experimental campaign followed the typical stabilization methods indicated by [15, 16], adopted in Europe in non-seismic prone countries.

In the second-generation mixes (2019 campaign), natural soil has been mixed with the sand, with a filler derived from the cutting of marble and with natural fibers. This stabilization strategy come from a broadening of the literature review to stabilization methods used in seismic countries [1] and by the expected improvement of durability and reduction of capillary water absorption provided by the marble cutting waste. We will now introduce the other base materials used in both experimental campaigns, then we will present the chosen mix designs, the manufacturing procedures and the flow-chart followed to assess their performances.

The particle size distribution of Soil F has been modified through the addition of local aggregates available in whole Etna volcano area. The added aggregates have different sizes: in the first-generation samples, the bigger particles are gravels with diameters ranging from 12.5 mm to 4 mm (gravels in general have 4 < d < 20 mm), while the smaller sand ranges from 4 mm to 0.5 mm (sands in general have 0.06 < d < 4 mm). In the second-generation samples, lava sand diameters range from 4 to 0 mm. The particle size distributions of the two aggregates are shown in figure 3 (in second-generation samples were used diameters smaller than 4 mm).

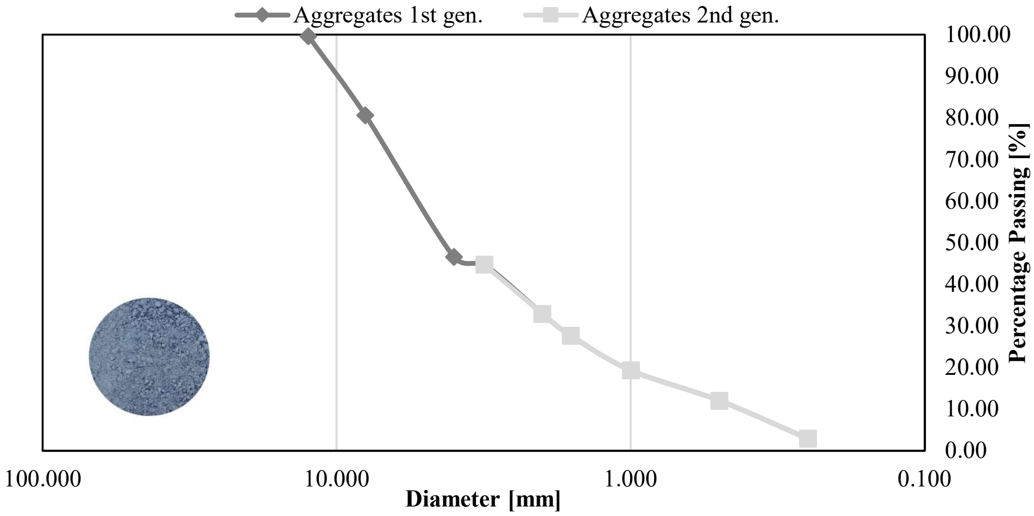


Figure 3 – Volcanic aggregate in two particle size distribution (Giada Giuffrida, 2018-2019)

The chemical composition of this aggregate can be found in table 2.

Table 2 – Chemical composition of lava aggregate

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	S	P_2O_5
Lava Sand	45.9	20.43	1.44	9.99	0.15	4.71	10.22	4.02	1.35	-	0.48

The chemical binders used (Portland cement and Lime) were provided by the Guglielmino. In particular, the Portland cement is a *TECNOCEM 32,5 R* by Italcementi group and lime is a *Calce dei Berici*, a natural hydraulic lime NHL 3.5 produced by the company Villaga. The binder's characteristics are shown in table 3.

Table 3 – Characteristics of the chemical binders used

Characteristics	Italcementi Cement	Villaga Lime
Sulfates (SO3)	≤ 3.5%	< 0.5%
Chlorides	≤ 0.10%	-
Initial Setting (t)	≥ 75 min	5 h
Expansion	≤ 10 mm	-
Rc (2 days)	≥ 10 MPa	-
Rc (28 days)	≥ 32.5 MPa	≥ 3.5 MPa
Rc (56 days)	-	≥ 4.5 MPa

The literature review in Sec.2 helped in the choice of the natural fibers to be used to improve mechanical and thermal performance. As the mechanical improvement was of paramount importance in seismic areas, we chose the sisal fiber, extracted from a succulent plant belonging to the Agavaceae family, genus Agave, native to the Yucatán peninsula in Mexico. The textile fiber obtained from its leaves (sisal) was used in ancient times for making ropes, strings, baskets, carpets, and other handicrafts. In Sicily this type of fiber, was mainly used to weave comfortable fabrics to be used in the seats and backs of wooden chairs and was called "zammara" by inhabitants.

Easy to find because of its rapid growth in all types of soil, the sisal agave can be found in deserts, dry forests, grasslands, roadsides, coastal beaches, dunes and plantations. It appears as a tropical succulent plant of 1.5-2 m in height, with a basal rosette of elongated sword-shaped thick leaves. The base plant is a short trunk (30-150 cm), from the top of which grow spirally arranged leaves that are heavy and persistent, 0.6-1.2 m long, 10.2-20.3 cm wide and 2.5-10.2 cm thick at maturity.

Agave sisalana needs full sunlight and a moderate supply of water to grow. It grows best in regions with an average annual rainfall of 800-1000 mm. The species is drought-resistant; it is morphologically adapted to cope with water scarcity due to its extensive root system and the arrangement and shape of its leaves which, like a funnel, concentrate rainwater on a small area. The maximum temperature should not exceed 32 °C. At temperatures as low as 5 °C the plant is damaged and, in addition, does not tolerate hail or stagnation. In dry and arid conditions or at low average temperatures it forms fewer leaves per year and has a longer life cycle. This species prefers sandy-loamy soils but can grow on a range of soils with a pH between 4 and 6.

The dry weight components of sisal fiber and its mechanical and physical characteristics compared to other fibers [17] are indicated in the following table 4.

Table 4 – Physical, chemical and mechanical properties of sisal fiber

Fiber	Density [g/cm^3]	Cellulose [%]	Hemi cellulose [%]	Lignin [%]	Moisture content [%]	Ash [%]	Microfibril angle [°]	Wax [%]	Tensile strength [MPa]	Young Modulus [GPa]	Elongation at break [%]
Sisal	1.4	67-78	10.0-14.2	8.0-11.0	11.0	-	20.0	-	468-640	9.4-22	3-7

Figure 4 – Agave sisalana plant (left), leaf fiber (center), and cross section of the fiber (right).

The world's largest producers of sisal fiber are Brazil, Kenya, Tanzania and Madagascar. After extraction of the fiber, about 95-96% of the weight of the leaves remains (leaf waste).

In Sicily there are no cultivations of agave sisalana. Joseph Whitaker, in 1909, became actively involved in carrying out his project to create extensive plantations of Sisalana and had the first 400 seedlings planted in Motya, laying the foundations for a modest plantation. Unfortunately, this initiative had to come to terms with several limitations at that time, such as the cost of renting land and labor, which was much higher than what compatriots paid in the colonies to obtain the concession of a plot of land and to maintain the necessary workforce. Nowadays, the improvements made in the fiber extraction processes and the favorable local climate seems to be good incentives to the development of a Sicilian sisal cultivation and extraction chain.

As part of the research, characterization tests were carried out on Sisal fibers. The average length of the agave filaments is around 2 cm. The specific weight, obtained by means of a precision balance and a standardized metal cylinder, is about 612 Kg/m^3. Sisal was bought by PANneto supplier, in packages of 1 kg.

Marble cutting waste is a suspension of fine marble particles in water, generated during processing and polishing. The material was provided by the Amato Marmi company in Biancavilla (CT). Originally, the work was assigned to the stonemason, but today are used powerful, precise numerically controlled machines.
The spindles can be fitted with different drills or cutters, depending on the job and the type of marble, as well as special polishing discs or, when the machine is set to cutting mode, diamond discs that make precise and fast cuts. As the processing of any marble slab creates very fine and volatile dust, it is nowadays preferred to carry out these operations by spraying the cutting area with water. A pump pressurizes a certain flow of water in a system that diverts it to flexible nozzles, which reach the spindle head and send continuous jets of water to the surface to be machined, to the cutter or the diamond disc. In this way, in addition to preventing dust from being dispersed into the environment, the discs are constantly cooled by jets of clean water, as they are mechanical parts are always subjected to sudden overheating due to friction with the material being machined. The jets of water transport the marble dust, i.e., the very fine particles of marble, to drains that lead to settling tanks (50x80x100 cm). The Amato company has three settling pits placed in succession; this arrangement serves to collect all the mud from the processing in the first pits. Once the sludge has settled to the bottom, the clean water that has remained on the surface is free to overflow into a collection tank. From here, the clear water flows back to the spray nozzles to cool the cutters and discs, and to transport more dust. Periodically, workers empty the pits, collecting the mud saturated with water and placing it in industrial polypropylene bags, approved for construction site waste and debris.
The MCW consists mainly of CaO with minor percentages of other oxides and traces/minor contents of chloride ion, alkalis, and iron oxide [11]. The pH of the MCW is slightly alkaline. The X-ray diffraction of the marble cutting waste used is shown in figure 5. The pattern confirms that the waste is mainly composed of calcite mineral ($CaCO_3$), and traces of plagioclase (Na,Ca)(Si,Al)4O_8.

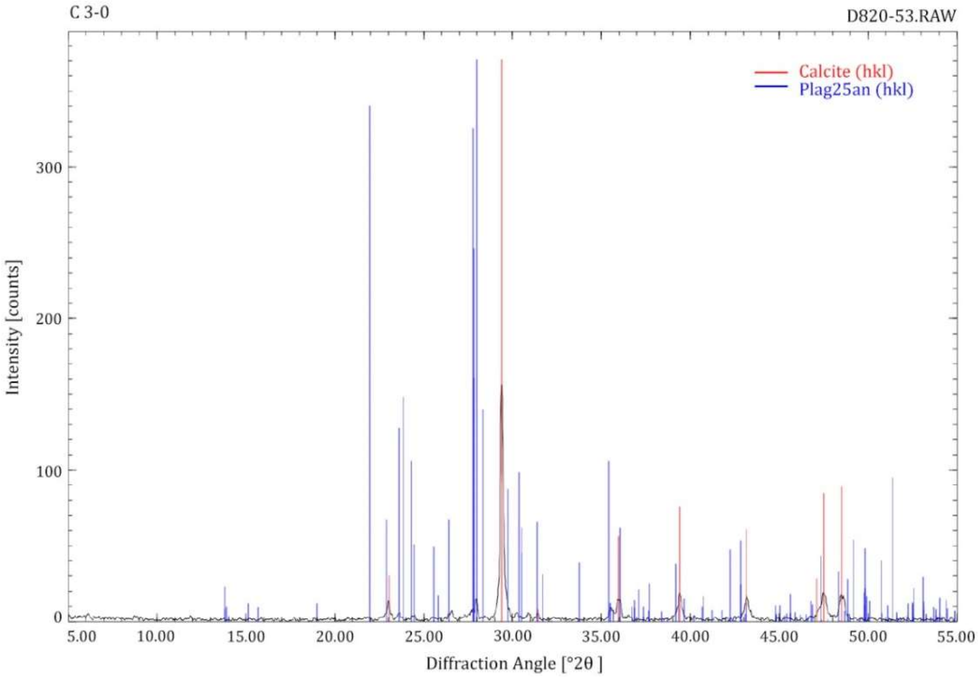


Figure 5 - X-ray diffraction (XRD) pattern of the MCW used

Figure 6 – Teorema SB Numerically controlled machine of the Amato Marmi company (Daniele Calderoni, 2019)

In the literature review are cited three contributes using marble cutting waste to reduce porosity of earthen base materials, thus minimizing the water absorption of these composites [18-20].
During the material testing campaign, 30 kg of sludge were collected (June 2019). The material samples were subjected to natural drying for a period of seven days, by placing the material in small portions or clumps on a sheet and placing it outside (no rain fell during this time).

Figure 7 – Marble cutting waste natural drying process (Daniele Calderoni, 2019)

At the end of the seven days, the marble cutting waste is now dry. The next stage was the grinding of the chunks of material: inside a container and with the help of a mixer the chunks were crushed into smaller portions. Marble dusts are very fine particles, in the micrometer range. The main fraction, about 90% of the material, has particle sizes of less than 20 μm [20]. Therefore, the dry chunks obtained can be ground several times until all the coarse grains have reverted to microscopic, impalpable dust.

Figure 8 – The dried material is mixed and then sieved in diameters < 2 mm (Daniele Calderoni, 2019)

4.1.2 Mix Design

The base materials introduced in the previous paragraph and used in the elaboration of different mix design for rammed earth material are shown in figure 9.

Figure 9 – The base material of the experimental campaigns in 2018 and 2019.

As abovementioned, two stabilization philosophy have been followed in this research. In the first-generation mixes (2018 campaign), the soil F, in its granulometry 0-2 mm, has been mixed with increasing amount of gravel (4 – 12.5 mm) and sand (0 – 4 mm). The first five unstabilized rammed earth samples, with different amount of these three compounds are indicated in table 5 (URE 1, URE 2, URE 3, URE 4, URE 5).
Two stabilized mixes, a cement stabilized (CSRE 3) and a lime stabilized (LSRE 3) have been added to this first experimental campaign, to understand the physical and mechanical improvements these binders could add to the best performing unstabilized rammed earth sample (URE 3).
In the second-generation mixes (2019 campaign), the soil F (0-2 mm) has been mixed with the same sand (0-4 mm), eliminating bigger aggregates to reduce the possibility to create local concentration of stresses in the material (mix design: URE 6) [1]. This unstabilized mix has been improved by the addition of sisal fiber (FSRE 6), lime (LSRE 6), marble cutting waste (MSRE 6), marble cutting waste and lime (MLRE 6) and finally with sisal fiber and marble cutting waste (MFRE 6).
The percentages of the mix components and their codes are shown in table 5.
A design density of 1930 kg/m^3 has been used for the calculation of the mass of components to be added. This density is consistent with data found in literature for rammed earth materials.

Table 5 – Mix designs adopted in this investigation

Sample	Batch	F soil [%]	Sand [%]	Gravel [%]	Cement [%]	Lime [%]	Sisal [%]	Filler [%]
URE 1	1	85	0	15	0	0	0	0
URE 2	2	70	0	30	0	0	0	0
URE 3	3	50	20	30	0	0	0	0
URE 4	4	40	30	30	0	0	0	0
URE 5	5	30	40	30	0	0	0	0
CSRE 3	6	50	20	30	5	0	0	0
LSRE 3	7	50	20	30	0	6	0	0
URE 6	8	50	50	0	0	0	0	0
FSRE 6	9	50	45	0	0	0	1	0
LSRE 6	10	50	45	0	0	5	0	0
MSRE 6	11	50	35	0	0	0	0	15
MLRE 6	12	50	35	0	0	5	0	0
MFRE 6	13	50	35	0	0	0	1	15

Note: Percentage are given by weight

4.1.3 Samples manufacturing

In order to test the innovative rammed earth material, eight cube-shaped samples for each mix design (with dimensions 150 * 150 * 150 mm) were manufactured at the Guglielmino Soc. Coop. plant. The number of samples corresponds to the required ones for the tests which we performed:

- Unconfined compressive strength test (3 samples), following the NZS 4298:1998 [12];
- Capillary absorption test (3 samples), following the HBE 19-2002 [10];
- Thermal conductivity test (1 sample, three testing points), following the ASTM D5334 – 14 [13];
- A qualitative check for volumetric shrinkage (1 sample), following the NZS 4298:1998 [12].

Sizes, manufacturing process and curing process are done in accordance with [1, 12].
Two manufacturing protocols were adopted during the two experimental campaigns in 2018 and 2019.
The 2018 protocol comprises the manual compaction of the samples, according to the following phases:

1. A quantity of material corresponding to the percentage required by the mix design is weighted;
2. the components are dry mixed in a bucket with an electric mixer PROTTOL MXP 1000 ES;
3. addition of the stabilizer (lime, cement);
4. addition of a percentage of water (8 – 13% by the total weight of the mix), confirmed by [12];
5. 20-40 minutes rest for samples not using chemical stabilizers (as cement and lime) to hydrate clays;
6. a controlled amount of mix is weighted for manufacture of one sample;
7. formwork is covered with oil (to help the formwork removal);
8. a 10 cm height of mix is put into the formwork and its corners are compacted with 10 strokes of a 300-gr hammer, with the help of a wood stick;
9. compaction of the mix surface with a 3.5 kg rammer until it reaches half of its initial height;
10. the same procedure is repeated until the formwork is fully filled;
11. flattening of the upper part of the sample;
12. cement-stabilized samples have to be compacted within 45 minutes in order not to make them set;
13. formwork removal and curing for at least 28-days (wet and dry curing for stabilized samples as [12]);
14. controlled temperature and humidity conditions before testing.

The 2019 protocol comprises the pneumatic compaction of the samples according to the previous steps, with only exceptions made for phase 3 (when the sisal fiber is added, it had to be spread uniformly inside the mix) and phase 8 (the compaction of the rammed earth material is made with a pneumatic tool realized modifying a SIMBI 10r). Some images of the manufacturing procedures are shown in figure 10.

Figure 10 – Different manufacturing phases numbered as in the text.

4.1.4 Testing protocol and results

The optimization of rammed earth mixes comes through the analysis of several properties, related to the mechanical, physical and thermal performances of the material. In order to define these properties, a testing protocol was defined to economize production of useless samples and first assess the most important performance for a material to be used as loadbearing, the unconfined compressive strength.
Samples were first visually checked to assess their right consistence and presence of cracks. Then, qualitative measurements revealed that no major shrinkage phenomena happened, being the volumetric shrinkage always minor to 0.05%. Samples were then tested concerning their unconfined compressive strength and Young's modulus.
For samples which satisfied the safety objective (i.e., samples having more than the minimum compressive strength as for [1, 12]), a new testing procedure regarding comfort properties was set up. Samples were then tested concerning their capillary absorption and dry thermal conductivity.
If thermal conductivity was found to be less than 0.80 W/ mK and samples were consistent, they were then tested regarding the specific heat capacity by a DSC scanning calorimetry, which allowed for the calculation of thermal effusivity, thermal diffusivity, thermal lag and decrement factor.

Table 6 – Testing protocol adopted in this investigation

RAMMED EARTH WITH IMPROVED MULTIFUNCTIONAL PERFORMANCE		
SAFETY	• Compressive strength test • Determination of Young Modulus	
IF fc ≥ f min, as for standards		
HYGRIC AND THERMAL PERFORMANCE	• Absorption Test • Moisture dependent Thermal Conductivity Test	
IF Thermal Conductivity λ ≤ 0.80 W/ mK (typical values) AND Samples are consistent		
COMFORT	DSC Scanning Calorimetry	• Specific heat capacity • Thermal Effusivity • Thermal Diffusivity • Thermal Lag • Decrement factor

The aim of the first tests is to determine the behavior of the material with regard to compression stresses, i.e., the resistance offered by the material to vertical loads. The test was carried out on 4 samples for each mix produced. Material testing was performed at the Test Material laboratory of the University of Catania, with a mechanical press CONTROLS with a 100 KN load cell and initial load speed of 0.5 KN/s.
This press was useful to determine the modulus of elasticity of all the specimens and the compressive strength (until failure of the specimen) of the specimens without fibers only. For the fiber-reinforced specimens, the compressive strength was obtained by using another CONTROLS press available in the laboratory with a 500 KN load cell.
The test operations firstly involve setting the parameters (specimen area, specimen height) to be entered in a software connected to the press. Then, the test is started by activating the hydraulic pump.
Young's Modulus was determined for the best samples by submitting them to load-unload cycles at one-third of their expected final resistance. To obtain the corresponding deformation at each stress, an electric transducer is set up to record the individual displacements. This is useful for subsequently obtaining the stress-strain diagram.

The specimens are accepted if their compressive strength is comparable with the data found in specific raw earth standards [1, 12]; specifically, the objective is to ensure that all the specimens reach 1 - 1.3 MPa.
In addition, a correction coefficient of 0.5 was applied to the compressive strength (f_c) values obtained, to evaluate design compressive strength (f_{cd}). Tests were accompanied by photographic data, while the measurements were noted in a notepad and then transferred to an Excel spreadsheet.
Compressive strength results against dry density for first- and second-generation batches are shown in figure 11 and 12. In these figures the measured compressive strengths are compared with limits indicated by the abovementioned standards.

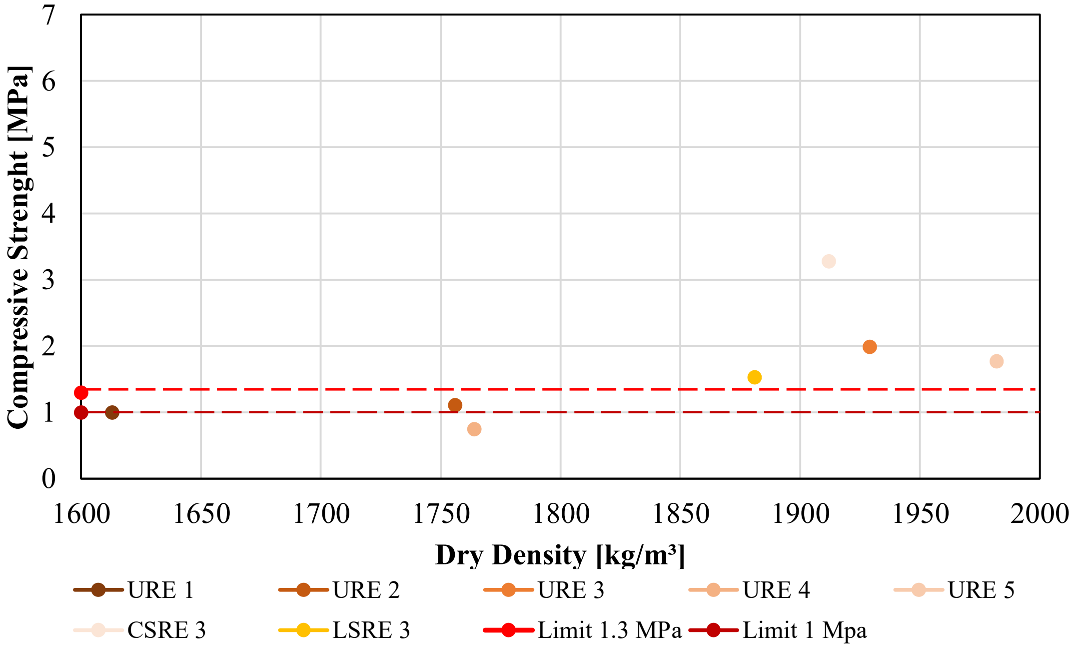


Figure 11 – Compressive strength vs dry density of first-generation batches.

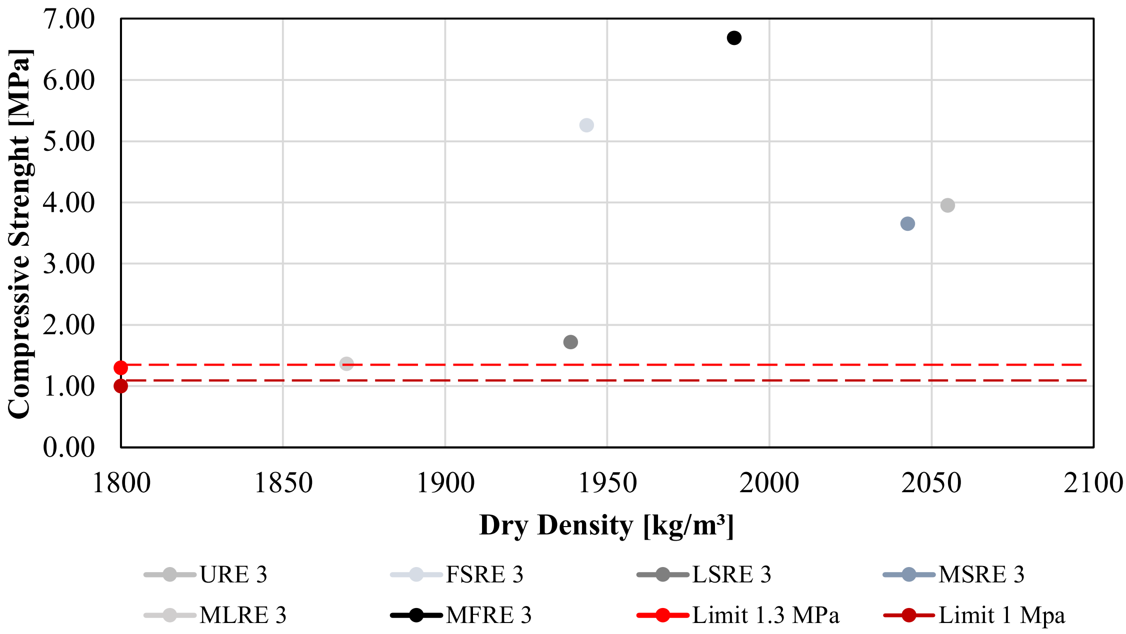


Figure 12 – Compressive strength vs dry density of second-generation batches.

Table 7 show the results of the mechanical characterization campaign on samples.

Table 7 – Dry density, Compressive strength, Young Modulus of tested batches.

	URE 1	URE 2	URE 3	URE 4	URE 5	CSRE 3	LSRE 3	URE 6	FSRE 6	LSRE 6	MSRE 6	MLRE 6	MFRE 6
Dry density [kg/m³]	1613	1756	1929	1764	1982	1912	1881	2055	1944	1939	2043	1870	1989
Compressive strength [MPa]	1	1.11	1.99	0.75	1.77	3.28	1.53	3.95	5.26	1.72	3.65	1.36	6.69
Young's Modulus [MPa]	-	-	-	-	-	-	-	285	254	160	290	184	264

As only the URE 3, the LSRE 3 and the CSRE 3 of the first experimental campaign satisfy the inferior limit as for [1, 12], it was considered not to follow with the conventional stabilization methods. The following tension-strain graphs in figure 13 have been useful for determining the elastic modulus of the second-generation specimens, and to have a direct comparison between different mix designs.

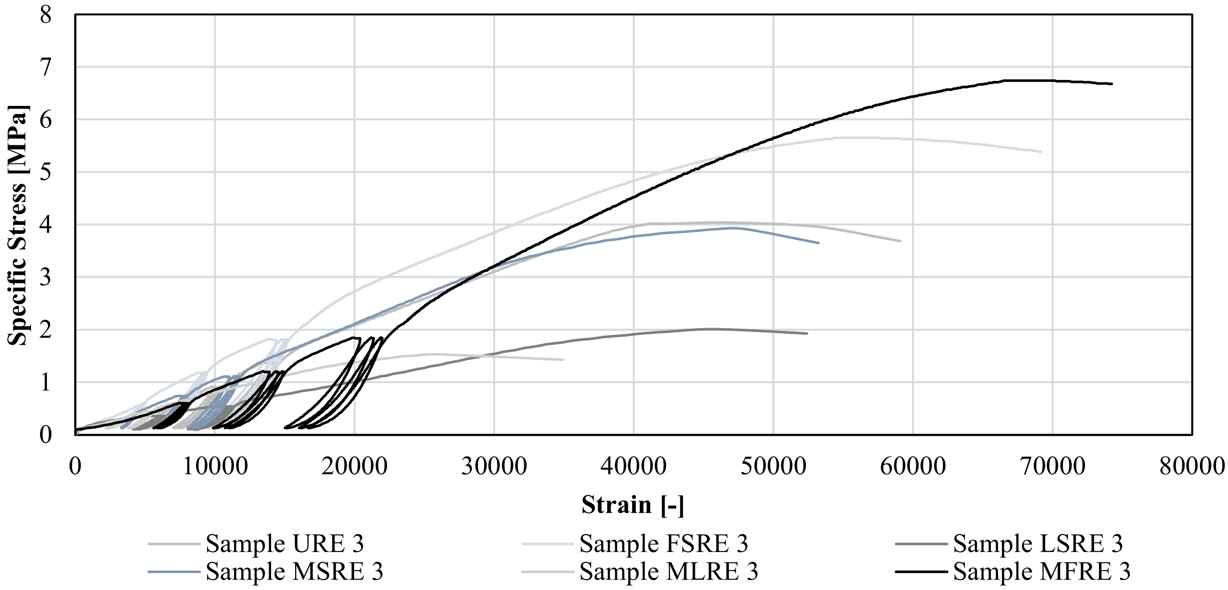


Figure 13 – Compressive behavior of the second-generation batches.

For these samples, Young modulus was calculated as the average of the angle coefficient of the load-unload cycles secants and it is always around 200 MPa, consistent with data found in literature.
Some images of samples subjected to mechanical strength test and Young's modulus assessment can be found in figure 14. Discussion of results will be made in the following section 5.


Figure 14 – Compressive behavior of the second-generation batches.

The purpose of the absorption test is to establish the behavior of the material in relation to the phenomenon of capillary rising water, with reliable indications of the speed of flow. This test is important because gives indications about the durability of material immersed in water and is performed in accordance with [10]. Rising heights are measured at predetermined time intervals over a 12-hour period on 3 samples for each mix following this procedure:

- the cubic specimen is placed on the perfectly smooth bottom of a container
- check of the work surface and the container to be perfectly levelled;
- enough water is poured to immerse samples to a height of 3 cm;
- the height reached by the liquid through capillary rise is measured at pre-established time intervals.

Height measurements are taken as follows: every 15 minutes for the first three hours, every 30 minutes for the next three hours, every hour for the last six hours. At the end of 12 hours, the maximum frontier of capillary rise is measured. In addition to the water basin, a ruler with millimeter accuracy, a camera and a notepad are required for the measurement.
The data collected is noted and archived and then transferred to an Excel calculation software to determine the value of the rising velocity and total water absorption.
The test specimens can be defined as acceptable if the height of the water does not exceed the regulatory limits shown in the table 8 highlighted in grey. In any case, at the end of the test, the sample must be almost intact and with slight loss of material at the base. Table 8 also shows the test results, the speed of rising water and an estimate of the water absorbed.

Table 8 – Absorption test results

	URE 3	CSRE 3	LSRE 3	URE 6	FSRE 6	LSRE 6	MSRE 6	MLRE 6	MFRE 6
Weight (t_0) [kg]	6.5	6.6	6.5	6.3	6.4	6.4	6.5	6.2	6.5
H of absorbed water after 3 h [cm]	12.9	8.4	7.1	13.7	6.6	6.8	5.1	7.2	6.0
H limit after 3 h [cm]	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
H of absorbed water after 6 h [cm]	14.6	10.7	8.8	15.0	8.2	9.03	6.6	9.4	7.6
H limit after 6 h [cm]	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6
H of absorbed water after 12 h [cm]	14.9	13.8	10.8	15.0	12.2	12.9	8.9	12.3	10.5
H limit after 12 h [cm]	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Weight (t_{fin}) [kg]	7.3	6.9	6.8	7.5	6.9	6.9	6.8	6.7	6.9
Average water absorption [%]	12.9	4.1	4.4	20.4	7.6	6.7	5.9	9.2	6.9
Rising water rate [m/s]	3.54 E-05	1.20 E-05	1.02 E-05	3.94 E-05	2.36 E-05	2.56 E-05	1.87 E-05	2.58 E-05	2.15 E-05

In the following figures from 15 to 16 are shown the results of these tests on the various batches.

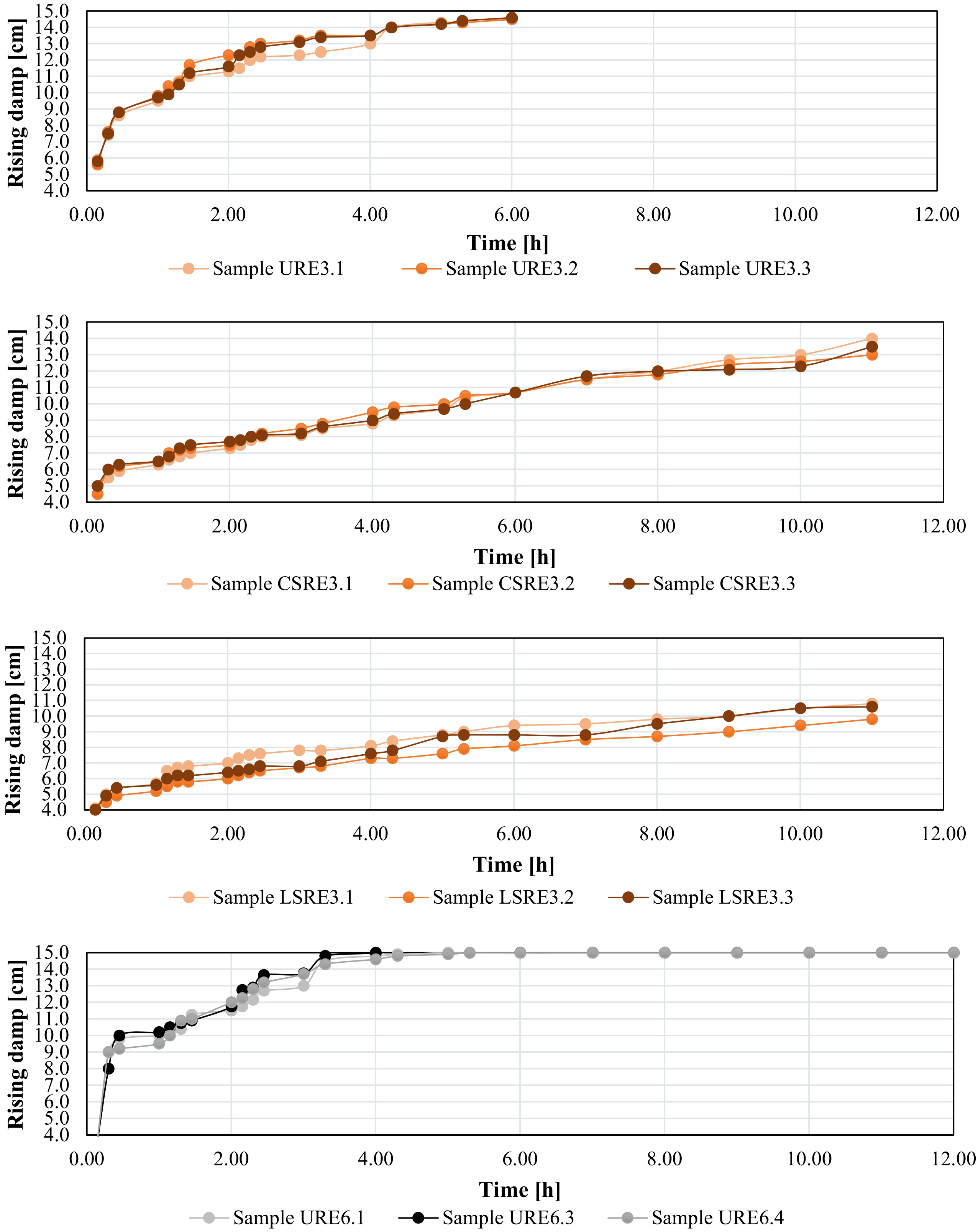


Figure 15 – Absorption test values for URE 3, CSRE 3, LSRE 3 and URE 6 samples

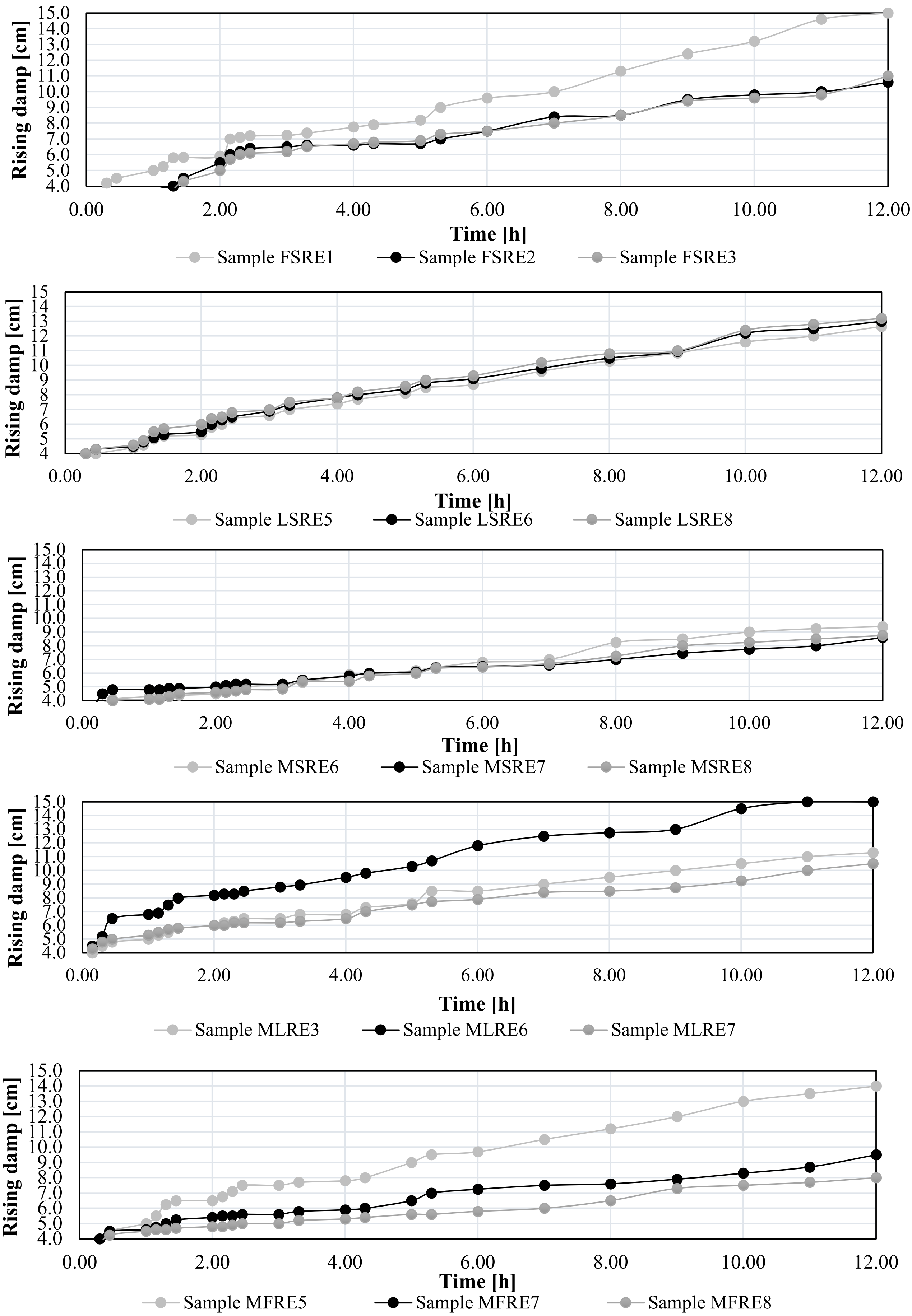


Figure 16 – Absorption test values for FSRE 6, LSRE 6, MSRE 6, MLRE 6 and MFRE 6 samples

Figure 17 - Different batches at the end of the absorption test

An experimental campaign was also addressed to assess the basic thermal properties of the innovative rammed earth material developed. Thermal properties assessments were made on the specimens with higher mechanical properties, which correspond to the second-generation batches, which resulted in having also enhanced thermal properties compared to data found in literature [14].

We will now present the methods used to assess the moisture-dependent thermal conductivity and the specific heat capacity of the rammed earth reinforced material. Once samples were prepared, they were immediately removed from the formworks and allowed to dry slowly to avoid cracking, in a laboratory where the average temperature and relative humidity during the curing were 20°C and 60% respectively. The samples cured for at least one month.

Once cured, samples were put in a climatic chamber, at a temperature of 20 °C and with growing percentages of relative humidity, respectively 15% (assumed as dry condition), 30%, 50% and 70%. The samples were measured concerning their dimensions to evaluate their volume. Then, the weight of the samples was assessed for each of the abovementioned environmental conditions and four thermal conductivity measurements per samples were realized. This procedure allowed for the registration of the moisture accumulation inside the sample, which gives an estimation of the volumetric humidity in the sample, an important property required by many hygrothermal simulation softwares.

Thermal conductivity measurements were carried out on the samples using a ThermTest conductivity meter. It is a portable thermal conductivity meter used to measure thermal conductivity and thermal resistivity. Transient Line Source (TLS) follows the ASTM D5334 standard [63]. The sensor needle consists of a thin heating wire and temperature sensor sealed in 50-mm steel tube. During the test, the sensor is completely inserted into the sample: this means that the samples need to be drilled and cleaned from dust and powder; then, to minimize any contact resistance between the sensor needle and the sample, a thermal paste of $\lambda > 4$ W/mK is applied on the TLS-50 needle (a 5 cm long and 5 mm thick needle, ideal for material of higher density as RE). Once the needle is inserted, heat is delivered to the sample using a constant current source and the temperature rise is recorded over a defined period. The slope from a plot of temperature rise versus the logarithm of time is used in the calculation of thermal conductivity λ. In figure 18 are shown the results of thermal conductivity measurements at different relative humidity, while in figure 19 is shown where volumetric moisture content is expressed as a function of relative humidity.

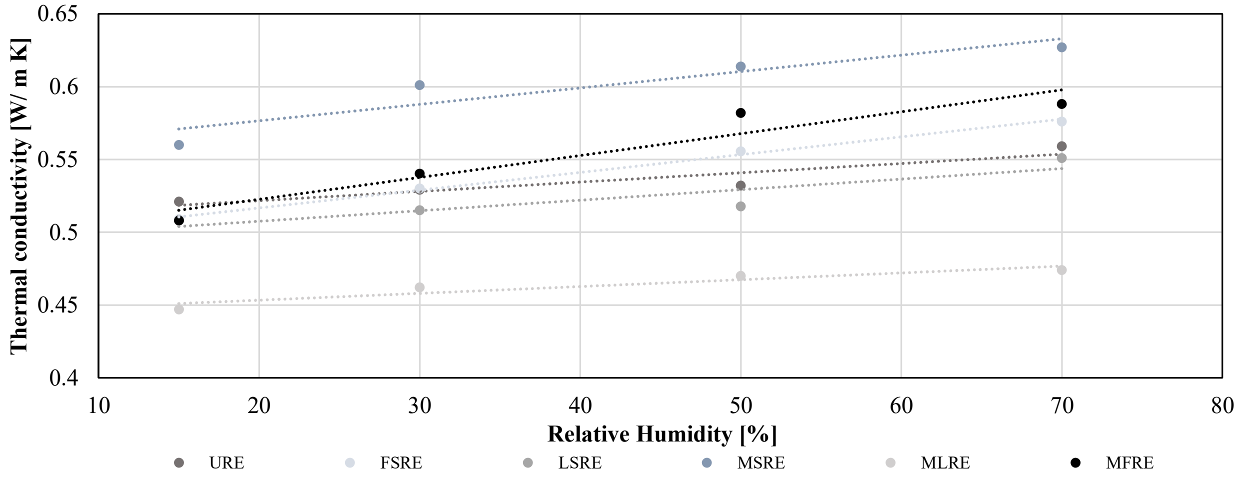


Figure 18 - Thermal conductivity measurements at different relative humidity.

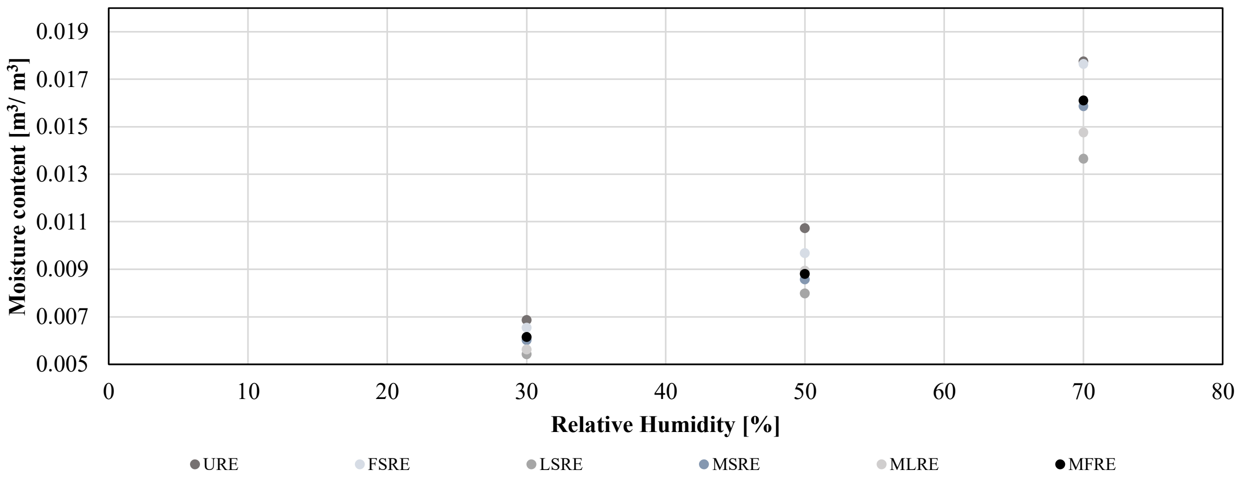


Figure 19 - Volumetric moisture content measurements at different relative humidity.

The specific heat capacity tests were performed on representative crushed samples of the six second-generation rammed earth mixes. Measurements were performed with a Shimadzu DSC-60 apparatus for the calorimetric characterization. Enthalpy and temperature calibrations of the equipment were made according to the procedure suggested by the manufacturer using as standard materials: indium (NIST SRM 2232), tin (NIST SRM 2220) and zinc (NIST SRM 2221a) for temperature; indium (NIST SRM 2232) for heat flow. Samples were held in sealed aluminum crucibles, and a heating rate of 10 °C/min were used for measurements. Differential scanning calorimetry (DSC) scans were carried out from room temperature to 300 °C. Once DSC curves were obtained, we converted heat flux to specific heat capacity, through (1):

$$Q = m \times c_p \times \Delta T \qquad (1)$$

Considering a Δ T of ten degrees.

DSC curves per mix are shown in figure 20, while a comparison of these values is shown in figure 21.

By the assessment of the specific heat capacity, it was possible to calculate the volumetric heat capacity *C*, the thermal diffusivity *a*, and the thermal effusivity *e* with the equations mentioned in the section 2.2.3. A resume regarding these properties for the different analyzed mixes is shown in table 9.

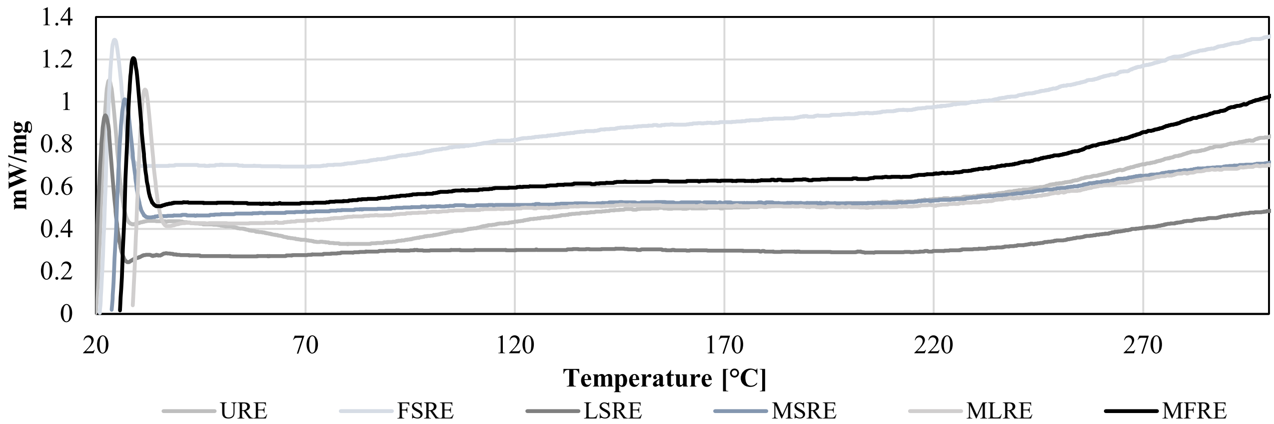


Figure 20 - DSC curves for the rammed earth material

Figure 21 - Shimadzu DSC-60 apparatus

Table 9 – Thermal properties of second-generation rammed earth mixes

	URE	FSRE	LSRE	MSRE	MLRE	MFRE
$\lambda_{dry\ (15\%RH)}$ [W/mK]	0.521	0.509	0.508	0.560	0.447	0.508
$\lambda_{30\%RH}$ [W/mK]	0.529	0.530	0.515	0.601	0.462	0.540
$\lambda_{50\%RH}$ [W/mK]	0.532	0.556	0.518	0.614	0.470	0.582
$\lambda_{70\%RH}$ [W/mK]	0.559	0.576	0.551	0.627	0.474	0.588
c [J/kg K]	1045	1760	907	690	1430	757
C [MJ/m^3 K]	1.954	3.423	1.703	1.384	2.466	1.459
a [m^2/s]	2.666 E-07	1.487 E-07	2.982 E-07	4.046 E-07	1.812 E-07	3.481 E-07
e [J/m^2 K^1 s$^{1/2}$]	1009	1320	930	880	1050	861

4.2 Constructive system and process

The design of the constructive technique and the building process are deeply connected and together define the technology. We already introduced that the focus of this research was the definition of a holistic design approach to rammed earth construction which could make it reliable and competitive (in terms of final performances) in the current construction sector thus respecting the requirements of sustainability, non-pollution and low embodied energy. This aim has been pursued by the hypothesis of semi-industrializing the production process (of base materials, of constructive components).
But before this, it was required to define a correct design approach which could conjugated answers to different issues, as:

- seismic resistance;
- adaptability to thermal insulations;
- simplification of the construction process.

Several prototyping and validation procedures were then used at different stages of the research, using a design-simulation-validation approach, characterized by four design iterations. Each design phase was followed by simulations of the constructive process (by means of construction of physical or modelled prototypes) and validation of the accuracy of the seismic-resistant design (mainly based on the compliance with the Peruvian code on reinforced earth construction [1] and corrections by the partner PUCP).

4.2.1 First Prototyping

The first designs of the construction technique contemplated the use of prefabricated rammed earth panels and were made at the University of Catania. To pursue a performance-oriented design, it is necessary to ensure the reliability of materials, the stability of performance and the control of production processes. Keeping this in mind, at the beginning of the research it was considered appropriate to investigate and develop a low-tech prefabrication process for rammed earth panels to be used in addition to a reinforcing timber structure which could have represented the main loadbearing structure (to respect the Italian building code which does not allow load bearing raw earth constructions [23]).
Some examples of the first ideas on the technology can be found in figure 22.

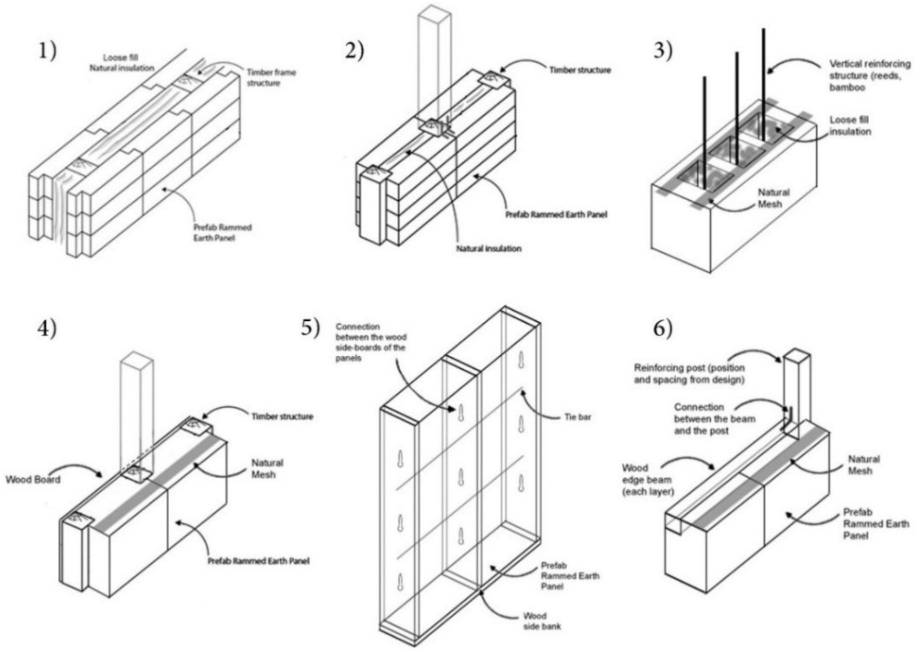


Figure 22 - First sketches on the mixed rammed earth - timber technology.

The main features of these first attempts were the use of internal (solutions number 1, 2, 3) or one-side timber reinforcing structure (solutions number 3 and 5), the design of the rammed earth panel as a big modular "block" to be solidarized to the others by the juxtaposition of meshes on the horizontal joints which could serve as weak surfaces as in [24] to locate energy dissipation in case of earthquakes. The main issues of these designs were the difficulty and the uncertainty of the connection between the rammed earth panels and the timber structure (the idea was to connect these elements by metal connectors, as in [25, 26]), the interface issue between these elements (is there an interaction between the surface of the timber posts and the blocks?), the needing of bracings, the effectiveness of the horizontal meshes to create weak joints for the dissipation of energy and finally, the installation of these heavy panels, which was impossible to do manually and so needed the use of machines.

4.2.2 Second Prototyping

These constructive systems were reviewed during the visiting at the Pontificia Universidad Católica de Perú, where a strong seismic-resistant design approach for raw earth building was acquired on the base of an in-depth study of the Peruvian standard [1] and a continuous dialogue with the Centro Tierra supervisors. Engineering Department of the PUCP has more than thirty years of research activity behind on the integration of seismic resistant design to raw earth construction. With the creation of the Centro Tierra in 2013, this aspect was combined with the adaptation of construction to various climates, and with the development of innovative construction processes [27, 28].

The Peruvian Standard [1] shows how in seismic areas it is necessary to design reinforced earthen buildings with specific geometrical features. The construction system defined during the visiting consists in a prefabricated rammed earth wall, composed by 40 cm thick modular rammed earth panels (the modules is the length of panel, 70 cm). The preliminary design of a representative rammed earth building, resulting from the application of this standard, is shown in table 10, while the explanation of data column is in section 2.2.2.

Table 10 – Verification of the preliminary design according to [1]

Data	Symbol	Value [cm]	Condition	Verification
Raw earth wall thickness	e	40	-	-
Buttress Thickness	e_0	40	I) $e_0 \geq e$	OK
Raw earth wall Height	H	256	-	-
Spacing of loadbearing elements	L	380 (five modules)	-	-
Voids width	a	70	II) $a \leq L/3$	OK
Distance void-buttress	b	155	III) $3e \leq b \leq 5e$	OK
Horizontal slenderness	$\lambda_h = L/e$	9.5	$\lambda_h \leq 10$	OK
Vertical slenderness	$\lambda_v = H/e$	6.4	$\lambda v \leq 6$ or 8 if IV) it is verified	OK
Check horizontal/ vertical slenderness	-	-	IV) $L + 1{,}25H \leq 17{,}5\ e$ V) $\lambda_h + 1.25\lambda_v \leq 17.5$	$700 \leq 700$ OK $17.5 \leq 17.5$ OK

Concerning the rammed earth wall reinforcements, it was thought to use the timber reinforcement cage as in [29, 30] to improve the overall strength. While the earthen masonry responds mainly to vertical loads, the timber elements would have absorbed the bending and shear stresses caused by any earthquakes, increasing the inertia of the cross section. The design of the constructive system required several iterations in this phase. Several hypotheses were designed and discussed with the tutors Eng. Julio Vargas Neumann (concerning structural behavior aspects) and Arch. Sofia Rodriguez Larraín Degrange (concerning technological aspects).

For the sake of brevity, we will now detail only the final version of the constructive system, but the previous versions included:

- version 1: a timber-framed structure with coupled timber posts (tied by spaced connectors) and horizontal crosspiece to connect them. The spaces between each post were filled with the rammed earth panels. An additional rope reinforcement was weaved between each timber posts;
- version 2: a timber-framed structure with coupled timber posts (tied by spaced connectors), with spaces between each post filled with the rammed earth panels. An exterior horizontal rope reinforcement was installed and blocked on each timber post, each rope being spaced every 25 cm for the first third of the wall, every 20 cm for the second third and every 15 cm for its last third;
- version 3: prefabricated rammed earth wall reinforced with a timber structure composed by coupled timber posts (tied by a lower and an upper connectors). An exterior horizontal reinforcement composed by ring of ropes is installed alternatively on different layers of rammed earth panels;
- version 4: a prefabricated rammed earth wall reinforced with a timber structure composed by coupled timber posts (tied by a lower and an upper connectors). The posts present holes were an exterior horizontal reinforcement composed by ring of ropes can pass (spaced every 25 cm for the first third of the wall, every 20 cm for the second third and every 15 cm for the last third of the wall);
- version 5: a prefabricated rammed earth wall reinforced with a timber structure composed by coupled timber posts (tied by a lower and an upper connectors). The posts penetrate deeper in the rammed earth wall composed by panels with tongue and groove shape. The angular panel is drilled to install the reinforcement composed by rings of ropes (spaced every 25 cm for the first third of the wall, every 20 cm for the second third and every 15 cm for the last third of the wall);
- version 6: a prefabricated rammed earth wall reinforced with a timber structure composed by coupled timber posts (tied by a lower and an upper ring beam). The timber posts are connected by fragment of ropes spaced every 30 cm on their height. The angular panel is drilled to install the reinforcement composed by rings of ropes (spaced every 30 cm for all the height of the wall) and these are blocked by the fragment of ropes coming out from the posts;
- version 7: a timber-framed structure with coupled timber posts (tied by a lower and an upper ring beam), with horizontal rafters connecting the two sides timber posts. Each rectangular area comprised between these two reinforcements is filled by a rammed earth panel with a groove on the upper face to locate the horizontal rafter.

The final version of the constructive system defined at the PUCP is based on the version 6 and uses a timber reinforcement which is composed by a system of timber posts and, differently from [29, 30], they are coupled in the thickness of the wall, aligned with the external surfaces of the wall face, and connected by fragments of ropes. This design was preferred both to realize an easier connection of the timber posts with bottom and upper timber ring beams and for the possible integration of successive insulation layers (both on the interior and the exterior face of the wall) or plumbing/electrical installations. In this system, the horizontal joints between the panels could act as preferential sliding surfaces for the dissipation of seismic energy in the case of in plane-stresses [24]. Another difference from [29], is the use of an additional horizontal reinforcement for all the surface of the wall. This reinforcement was deemed to be necessary to create a three-dimensional mesh that confines and "pack" the wall against possibility of collapses [31, 32]. This surface reinforcement consisting of several horizontal nylon or polyester ropes, solidarized to the timber structure, and tensioned to confine the earth panels. It counteracts any out of plane mechanism of the panels and acts has a backup reinforcement that connects all the elements of the system (panels, posts). This construction system (shown in figure 23) has been refined concerning its dimensions, shapes, etc. together with the Pontifical Universidad Católica de Peru.

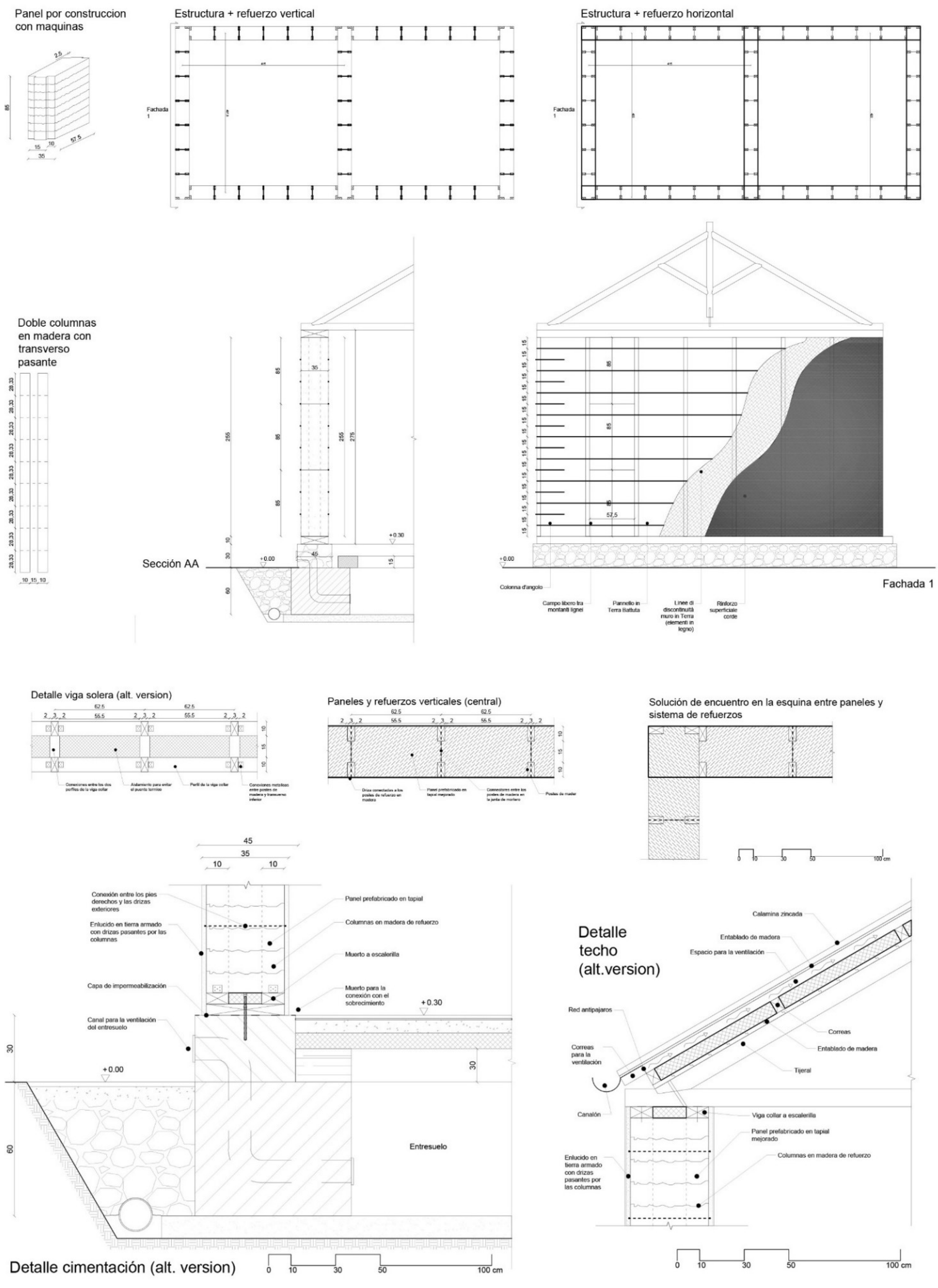


Figure 23 – Study of the version 6 constructive system during the visiting at the PUCP: technical plans, section, façade and connection details.

Under the version 6 of constructive system hypothesis, we started the study of the construction process (figure 24) which was furthermore analyzed during the preparation of the comparative dynamic test on different scaled rammed earth prototypes, a test performed to confirm the correctness of the structural design adopted.

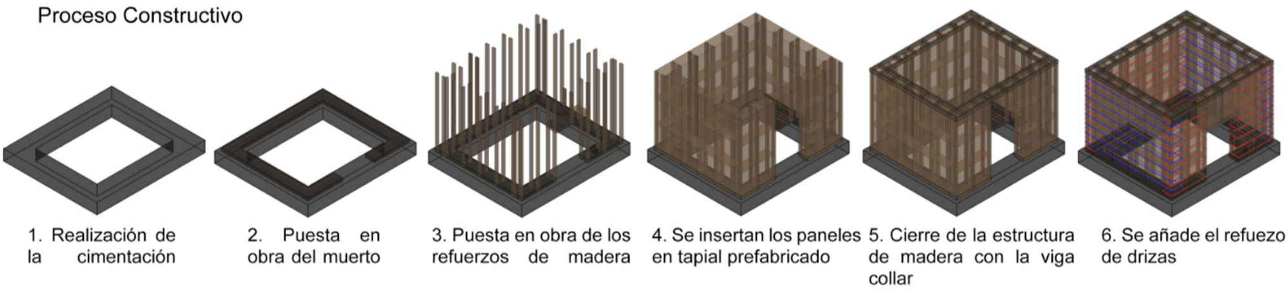


Figure 24 – First studies on the construction process with prefabricated rammed earth panels.

The objectives of the comparative dynamic test were:

1) to show and compare the seismic behavior of reinforced and unreinforced rammed earth models by the use of a portable shake table;
2) to compare the effectiveness of natural and low cost reinforcements to industrial ones;
3) to study the production process of the prefabricated rammed earth panels;
4) to identify the weaknesses of the constructive process.

The method which was used was already implemented by [33, 34] and consists in the simulation of the effect of an earthquake on scale models of typical Andean raw earth buildings.

During the test, three constructive solutions have been compared: the traditional and unreinforced rammed earth system realized in situ, the contemporary concrete-reinforced rammed earth system realized in situ and the low cost reinforced prefabricated rammed earth solution defined in this research. The three modules have been realized in scale 1:10 in order to be tested on a portable shake table activated by a bike (figure 25).

- Platform 600 x 600 mm
- Vibration frequency: 1 - 3 Hertz
- Horizontal displacement: 50 mm
- Vertical displacement: 15 mm
- Maximum model weight: 80 kg
- Energy: Generated by man
- Mechanical system: Like a bicycle
- Ergonomic shape, easy to maintain, easy to use and silent

Figure 25 – Portable Shake table activated by the bicycle and technical data [34]

The step followed for the design of the test and the manufacturing of the models (figure 26) were:

1. Definition of the geometry of the models;
2. Definition of the number of rammed earth blocks to be produced for the traditional model and for the new constructive system;
3. Design and realization of the formworks for the panels;
4. Design and realization of the concrete slab and lintel;
5. Definition and realization of the timber reinforcement elements (posts, ring beams, lintels, and a wood board to simulate the roof in the traditional and innovative system);
6. Definition of the section of the nylon rope.

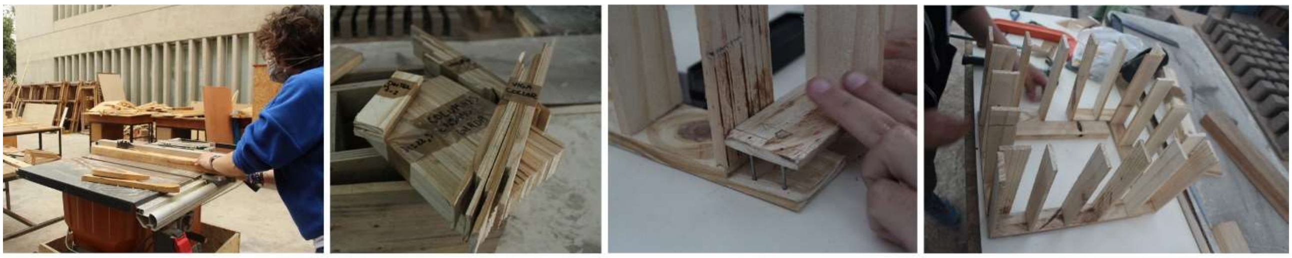
The construction of the three prototypes has been realized with the collaboration of the Masters' Degree students Barbara Bruno, Victor Sakata, and the Arch. Silvana Loayza, in the Centro Tierra laboratory which provided al the facilities and base materials.

The portable shake table adapted to the setup of the test

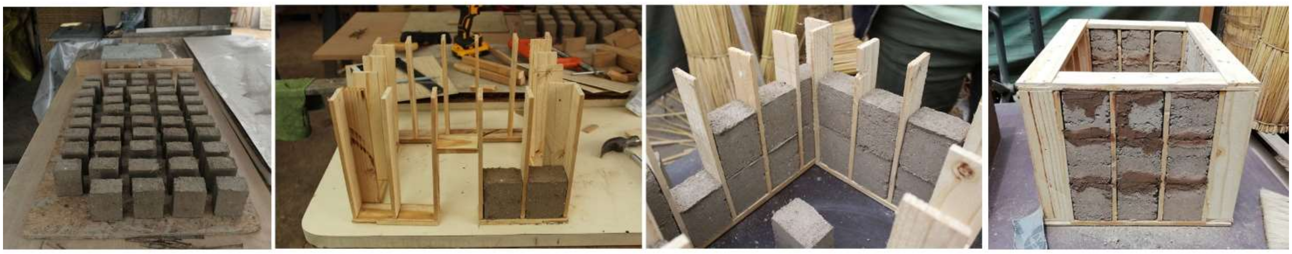
The construction of the unreinforced rammed earth prototype

The construction of the concrete-reinforced rammed earth prototype

The prefabrication of the timber reinforcing structure for the innovative semi-prefab constructive system



The installation of the prefabricated rammed earth panels in the innovative constructive system



The installation of the horizontal rope reinforcement in the innovative semi-prefab constructive system

Figure 26 – Some construction phases of the tree scaled prototypes.

Figure 27 – Phases of the comparative dynamic test.

In phase a) of the test shown in fig. 27, the three modules were put on the top of the portable shake table and tested simultaneously (small impulses were given to the table through the pedals).
In phase b), the unreinforced rammed earth model collapsed right at the beginning of the test, even if a small layer of earth mortar had been put between one rammed earth piece and the other to simulate the construction process made in situ. For the intensity of the movement, the other two models moved rigidly, without experiencing ruptures or collapses. In order to follow with the test discouraging the rigid body movement, wood pieces were nailed on the shake table at the base of the two reinforced system, in order to stop movement towards the "earthquake".
In phase c) in the concrete reinforced rammed earth, concrete slab experienced a higher acceleration and was projected out of the table. The compatible reinforced prefabricated rammed earth showed cracks in mortar joint, but not collapses.
The results of this test showed the correctness of the seismic resistant design of the innovative constructive system, but it was also observed the need to simplify the constructive process, especially when referring to the installation of rammed earth panels in a reinforced system. The simplification of the constructive process was pursued by abandoning the idea of the prefabrication of rammed earth panels in favor of the prefabrication of the rammed earth mix as base material for walls to be built on site, and prefabrication of the timber elements (posts, ring beams, lintels).

4.2.3 Third Prototyping

Constructive system and processes were optimized at the University of Catania during the SARS-CoV-2 pandemic. The impossibility of constructing full scaled model at that time, forced us in simulating the in-situ constructive process by the construction of several 3D-models.
Keeping in mind the seismic-resistant design defined during the visiting at the PUCP, efforts were made to optimize and simplify the construction process by the integration of the seismic-resistant reinforcement during the construction process. The presence of the timber posts and the fragments of horizontal rope connectors were integrated in the formwork installations and totally embedded in the rammed earth walls during the construction.
Concerning the construction of the rammed earth walls, it was first considered to be done by constructing horizontal rings of rammed earth, respecting the traditional constructive process. Then the construction of vertical walls of rammed earth was preferred because this process allowed the construction of different parts simultaneously, by the creation of sub-building sites which help in the rationalization of building site logistic and in the reduction of construction times. As discussed in Sec. 2, constructive process adopted by the newest rammed earth technology prefers to build vertical walls of rammed earth instead of horizontal rings. The system is suitable to be realized also for horizontal rings, foreseeing the staggering of wall sections.
An in-depth description of the constructive system and process phases will be now presented, which is at the base of the patent application titled "Anti-seismic construction system: technology and production process" [35] forwarded by the research group of University of Catania and the company partner to the competent ministry. The key points of the proposed innovation are:

- the definition of a mixture of fiber-reinforced rammed earth and filling material that reduces its porosity (and therefore increases resistance to capillary water);
- the definition of a modular rammed-earth construction system that integrates the seismic resistant reinforcement system with the modular and reusable formwork.

This construction system is characterized by a fiber-reinforced rammed earth wall and a reinforcement system made of timber posts (vertical) and ring beams (horizontal, arranged longitudinally at the base and at the top of the wall) together with nylon/polyester ropes (horizontal, arranged transversely and parallel to the plane of the wall) which integrate the formwork system during the construction process. The constructive system has been verified for a type of single-story building, but the first simulations carried out on the Midas FEA NX software, relating to the structural behavior of a two-story building, with intermediate timber floors and ring beams, have given positive results. This aspect will be further investigated in future works. Figures 28 and 29 show the basic technical characteristics of the innovative constructive system.

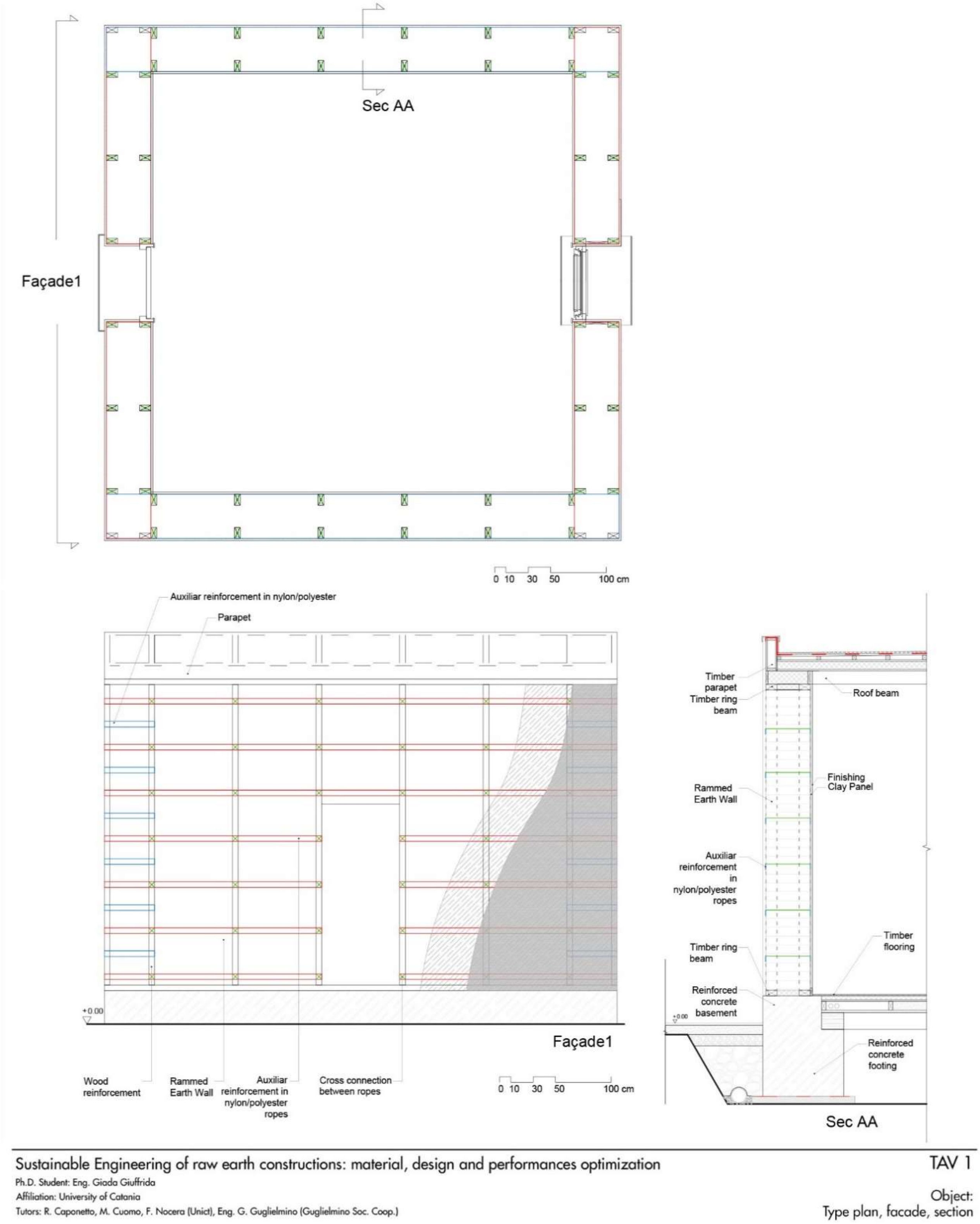


Figure 28 – Type plan, façade and vertical section of the innovative constructive system.

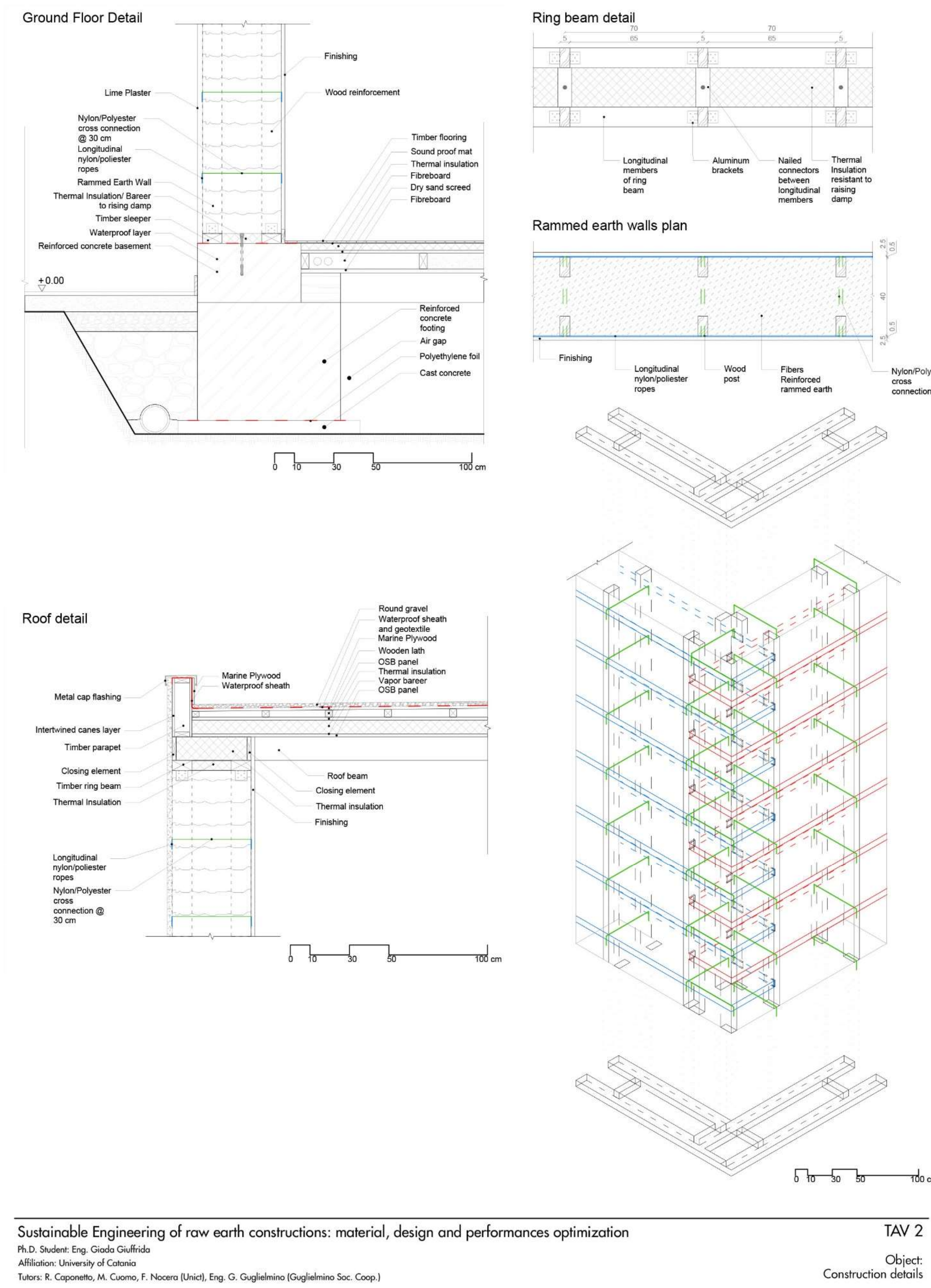


Figure 29 – Construction details of the innovative constructive system.

In the following, the operational phases of preparation of the base material and its implementation within the proposed construction system will be detailed, as well as the integration between the formwork system (used to place the material) and the structural reinforcement system.

4.2.3.1 Preparation of the material

The preparation of the soil mixture can be done using a premix material (first hypothesis) or by using on-site quarried soil. In the following we will explain both procedures.

Preparing the soil mixture: use of premix material (I hypothesis)

The basic materials are prepared in the factory: inorganic clayey soil and sand (volcanic or carbonate) are crushed to 0 - 2 mm and 0 - 4 mm respectively.

The natural fibers used, which must have a high tensile strength (they may be sisal fibers, or alternatively straw, hemp, flax, jute or kenaf fibers, such as to ensure adequate tensile and flexural strength in accordance with the specifications of the structural design). Fibers are cut to a length of approximately 3 cm. As indicated above, the natural fiber is used to provide ductile fracture behavior for the earth material.

The filler from the stone cutting industry is known as marble cutting waste and has a grain size of less than 0.625 mm. As mentioned above, it serves to reduce the sensitivity of the sand material to rising damp.

The materials are stored in a cool, shady, and ventilated area, protected from rain and moisture.

Consistent with the proportions of the mixture components, the base materials are weighed and prepared for dry mixing. The percentage of fiber, for a technique such as rammed earth, should never exceed 1% by weight of the total components. The materials must be mixed dry using a horizontal mixer.

Once the premix has been made, it should be placed in closed, heavy-duty bags for handling.

The addition of water will be done on site, using an axial mixer: a progressive amount of water will be added to the premix to bring the mixture to a wet state. The amount of water to be added is indicated on the bag and depending on the wanted workability it can be between 10 and 13% by weight. The wet state can be considered to have been reached when the material can be squeezed into the hand without leaving traces, or when, by performing the Drop Test [12], the ball of material hitting the floor breaks into 2-3 pieces.

The mixture, once well mixed and moistened, must be left to rest under an impermeable cloth to favor a more uniform hydration of the material, for at least 24 hours.

It is advisable not to mix quantities greater than the volume of soil applied in a single day.

Preparing the soil mixture: use of on-site quarried material (II hypothesis)

Notwithstanding the use of a percentage of filler from the stone and natural fibers industry to optimize resistance to absorption and increase the ductility of the material, it is possible to consider using soil quarried in situ for the construction of the structure, reformulating the mixtures to obtain physical-mechanical performance of equivalent value to that obtained with the premix. This can only be done if the local soil has characteristics that make it suitable for this purpose; for this reason, certain conditions must be verified. The operations to be carried out to verify the soil are all defined by a detailed protocol, which is summarized below.

First, it is necessary to verify that the soil material has an adequate percentage of stable, non-swelling clays, i.e., it must have good cohesive capacities that allow it to bind together the other components of the mixture without coagulating into lumps that are difficult to break. To do this, the soil must essentially consist of a fine earth fraction, including diameters of less than 2 mm, i.e., medium and fine sands, silts and clays, with percentages of clay (representing the fraction with binding properties) ranging from 5 to 15 % of the total. In order to verify the type of clays present in the soil matrix, it will be necessary to carry out a preliminary assessment of their quality by determining the Atterberg limits and the Skempton index, indices that assess

their plasticity and activity; in general, kaolinite and illite type clays will be accepted, while montmorillonite type clays will be discarded.
The soil must not contain gravel or aggregates larger than 3 mm, which would cause localized stresses in the wall continuum, a very dangerous aspect in seismic areas. For this reason, some field tests could be performed (dry strength test, simplified sedimentation test) [37]. If the sandy fraction is missing, it has to be added in a percentage corresponding to the missing fraction in the soil.
The basic mixtures (inorganic soil only) and the additive mixtures (inorganic soil, fibers, filler according to mix designs defined from time to time depending on the type of inorganic soil used) must then be tested.
Five cubic specimens per mixture are to be prepared and these are to be subjected to a compression test; to confirm the suitability of the material, the specimens must guarantee compressive strengths greater than 1.3 MPa [12] and ductile breaking behavior (the use of fiber will have beneficial effects in this respect).
Once the mixture to be used to make the construction material has been defined, it will be prepared as defined in the paragraph on premixed material.

4.2.3.2 Constructive Process

The Constructive Process has been structured in all its phases distinguishing the solid ground floor, the wall, and the roof construction.

Construction phases of Solid ground floor:

1. Creation of the excavation for the reinforced concrete footing (or masonry made of squared stone blocks);
2. installation of the layer of cast concrete to level the ground;
3. possible application of a waterproofing layer, e.g., made of polyethylene sheets (in the case of particularly humid soils or soils close to aquifers);
4. creation of the reinforced concrete L-shaped foundation; it must protrude from the ground level by at least 30 cm, to protect the rammed earth wall from flooding phenomena and from rebound of rainwater. At the top, on the inner side, there will be a fold at least 20 cm deep which will provide a support for the beams of the horizontal base closure;
5. creation of a drainage crawl space on the external side of the foundation and realization of a screed, possibly reinforced (if the external space is to be made accessible to vehicles), in order to facilitate the subsequent construction of the wall;
6. installation of the beams of the horizontal base closure (after waterproofing the ends of the beams);
7. installation of the floor excluding the finishing layer;
8. fixing of a pair of timber members to the plinth by means of concrete anchors (like SKR and SKS anchors or expansion ones). These two members present a rectangular cross-section, joined together by means of transversal connectors (placed in correspondence with the vertical stiffening posts of the wall, which will subsequently be positioned, according to the spacing determined by the structural project). Together they create the bottom timber ring beam of the wall;
9. filling of the space between the connectors with a water-resistant material or a water-resistant thermal insulation.

Construction phases of the rammed earth wall:

1. Connection of the timber posts to the base ring beam using steel L-squares. The spacing and cross-section of the wooden posts are fixed, as mentioned above, by the structural project. It is possible

to increase the cross-section of these posts to provide additional strength. These posts have slots along their entire height, spaced vertically by approx. 30-40 cm, for the passage of nylon/polyester type 1 ties;

2. installation of three high-strength nylon/polyester type 1 ties for each pair of posts, starting from the lower part of the wall. These ties will be passed inside the slots of the posts and will protrude from them by a length of at least 20 cm, necessary for the subsequent positioning and locking on the formworks;
3. installation of the two longitudinal panels of the formwork. The formwork has horizontal, exterior metal reinforcements which prevent the formwork from buckling during the pneumatic compaction procedure. In addition, the panels are perforated at the points where the nylon/polyester ties pass through, and the ties are secured in the immediate vicinity of these points by means of clamps and/or buckles;
4. insertion of the type 1 ties into the holes of the formwork, stretching and locking on the two longitudinal panels of the formwork by anchoring the ties in the cleats/ buckles.
5. installation of two type 2 ties in the vicinity of the last couple of posts near the corner post X. This type of ties is offset by 15-20 cm in relation to ties type 1; they are used to complete the binding of the wall confinement system that will be carried out later, to improve the bonding between the walls at the corners and wall intersections;
6. installation of the side rail of the formwork, exteriorly reinforced, in a position outside the posts. Each side rail is held in place by anchor bars placed transversely to the wall and fixed to the longitudinal formwork by means of nuts; alternatively, the clamping system can be used (see Framax universal clamp patent). Special care must be taken when plumbing the side wall. The formwork covers the field between four pairs of posts (including the corner post);
7. solidarization of the pairs of timber posts, at their upper ends, by means of a flat ring consisting of a polypropylene strap with a fastening buckle (see Dunlop patent) to prevent them from tipping over during the compaction phases;
8. pouring and ramming of the ready mixed rammed earth material into the formwork by means of an electric or pneumatic compactor, to be carried out in layers of approx. 15 cm in height; compaction will be carried out until the rammed earth reaches a height of approx. half the height of the material poured into the formwork. This procedure must be repeated for the subsequent layers until a height of 90-100 cm is reached. Particular attention must be paid to the areas close to the ties during compaction. After compaction, the ties will be well confined by the rammed material;
9. completion of the first section of rammed earth masonry;
10. installation of ties type 1 and 2 for the above rammed earth masonry section;
11. lifting of the formwork for the block above, checking the plumbness;
12. repeat steps 6 to 9 for the construction of the next rammed earth wall section. To realize the entire height of the wall, three layers of formwork will have to be superimposed;
13. completion of the second rammed earth masonry section;
14. removal of the solidarization ring connecting the posts at the top, before completion of the last section;
15. completion of the rammed earth wall (Wall A) with the last masonry section, according to the procedure described above;

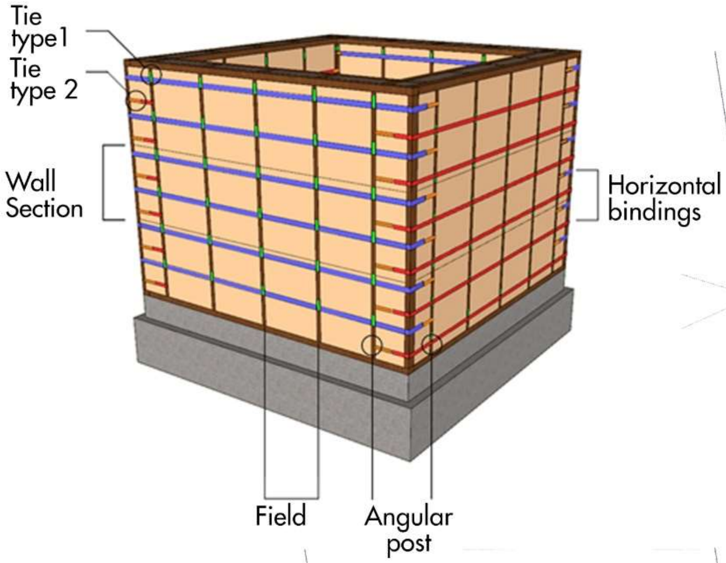
16. steps 2 to 15 are repeated for Walls B, C and D. The formwork system can be either have different dimensions (with a standard formwork for the width corresponding to the spacing between three posts; an extended formwork to cover the width of the corner; a raised formwork to compensate the offset in height of the slots of the posts in walls B and D) or holes made at different heights in order to be crossed by the tie ropes 1 of orthogonal walls;
17. installation of horizontal nylon/polyester ties and anchorage to type 2 ties;
18. tensioning of the ties by means of turnbuckles (later removed) or by means of sliding knots and fastening to the type 1 ties;
19. repeat steps 17 - 18 for walls B, C and D. The corner will then be confined by a double system of horizontal ropes from the two orthogonal walls.

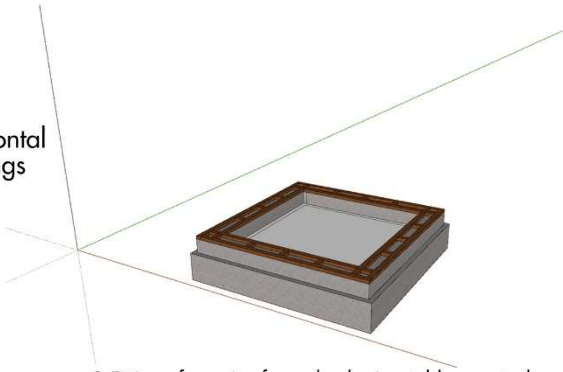
Roof Horizontal Closure

1. Once the vertical earthen wall has been completed, the top ring beam is installed. This element is shaped and sized like the bottom ring beam. It consists of two longitudinal members of rectangular cross-section, joined together by transverse connectors. The ring beam is fixed to the head of the posts by nailing or laterally by means of a straight plate;
2. filling of the space between the connectors with a thermal insulation with low resistance to the passage of vapor;
3. the ring beam is effectively connected to the wooden reinforcement system of the masonry and represents an effective support for the load-bearing elements of the roof (horizontal wooden beams). In the case of a sloping roof, the top ring beam would be the connection system between the wooden roof trusses and the load-bearing walls;
4. fixing of the load-bearing beams of the floor by means of metal brackets to the ring beam: in particular, the beams will be set back a few centimeters (2-3 cm) with respect to the external edge of the wall, to allow the fixing of an external frame (made up of wooden boards) aimed at restoring the vertical continuity of the wall plane;
5. on the inner side of the wall, another sideboard will be positioned (again, made of wooden boards placed between the ceiling beams) to mark the inner edge of the wall;
6. installation of thermal insulation with low resistance to the passage of steam in the cavity between the two closing banks;
7. for the stratigraphy of the horizontal/inclined closure of the roof, it is recommended to use an insulation with low resistance to the passage of vapor, in line with the breathable characteristics of the rammed earth envelope. For the horizontal closure of the roof, solutions that project slightly from the vertical plane of the wall, ventilated roofs or green roofs are preferred.

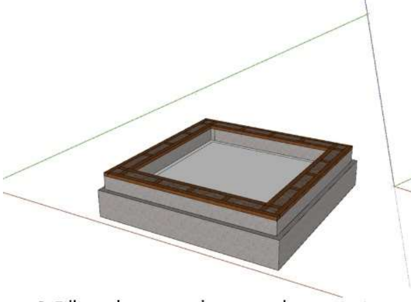
Finishing can be carried out with dry or wet processing.
The vertical scanning (timber posts) of the rammed-earth masonry allows for the easy application of an internal counter-wall that allows for the passage of the plant engineering equipment and the insertion of a possible thermal insulation layer, to be applied either loose or in panels, outside or inside the wall (depending on the final use of the building), eventually by the creation of a cladding wall.
If plastering is preferred, it is advisable to use an earth-based or lime-based plaster, with fibrous body plaster in order to incorporate and protect the surface reinforcement system in polyester/nylon bands. The finishing layer should be made of a breathable material.
Figures 30 and 31 show the main construction phases of the innovative constructive system.

Construction phases

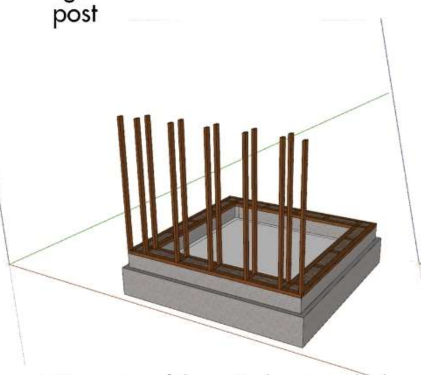




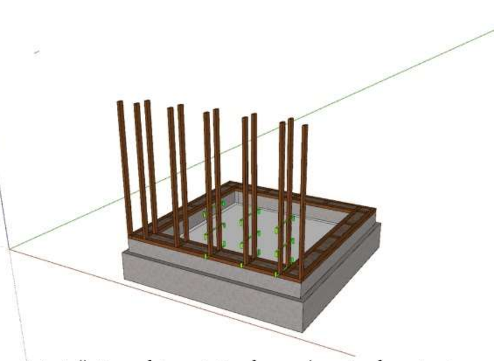
2. Fixing of a pair of wooden horizontal beams to the foundation by means of screwable concrete anchors. The double horizontal beams consists of two longitudinal beams (aligned with the outer sides of the wall) of rectangular cross-section, joined together by means of cross-pieces.



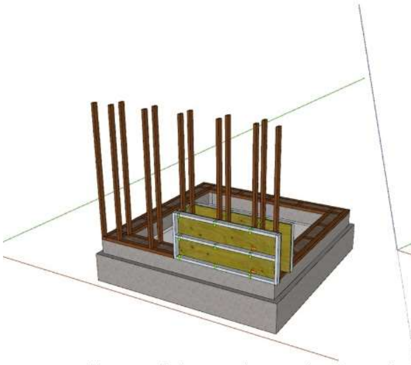
3. Filling the space between the crosspieces with water-resistant material or water-resistant thermal insulation.



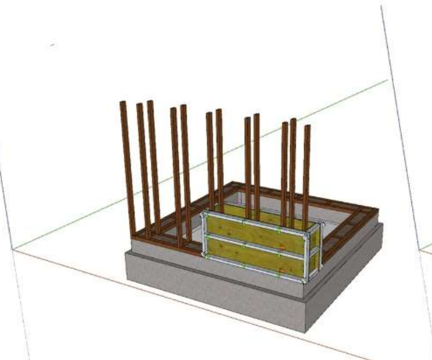
4. Connection of the vertical posts to the base beams using L-shaped steel angle brackets. The posts have slots along their entire height, spaced vertically about 30-40 cm apart, for the passage of nylon/polyester type 1 ties.



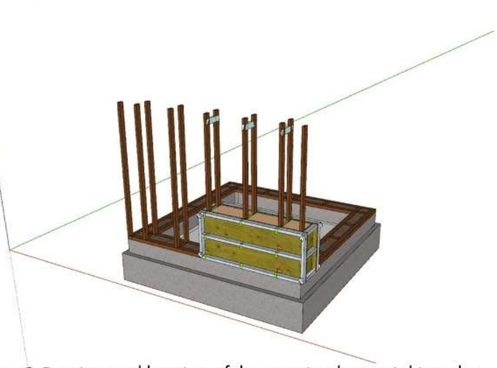
5. Installation of type 1 ties for each pair of posts, starting from the lower part of the wall. These tie-rods will be passed inside the slots in the posts and will protrude from them by a length of at least 15 cm, which is necessary for the subsequent positioning and locking of the formworks.



6. Installation of the two longitudinal panels of the formwork. Insertion of the type 1 tie-rods into the formwork, stretching and locking by anchoring the type 1 tie with the cleats.



7. Installation of type 2 ties (offset by 15-20 cm from type 1 ties), side formworks, bars and nut anchor for formwork fixing.



8. Pouring and beating of the premixed material into the formwork by means of a pneumatic compactor, in layers of approx. 15 cm in height, until the soil has reached half of the original height.

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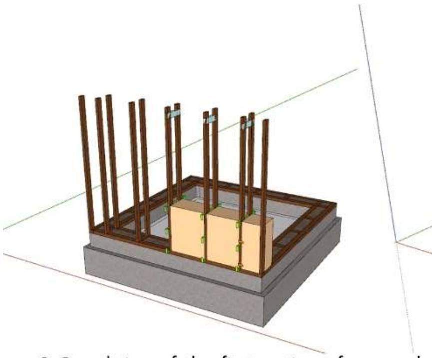
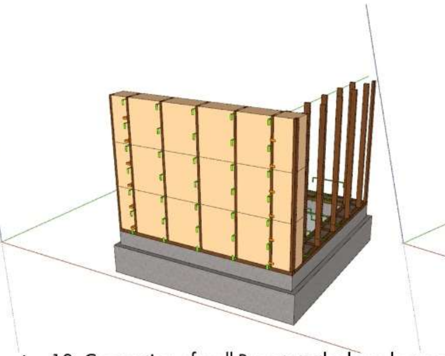
TAV.4.1
Object:
Construction phases

Figure 30 – Construction phases for wall construction.

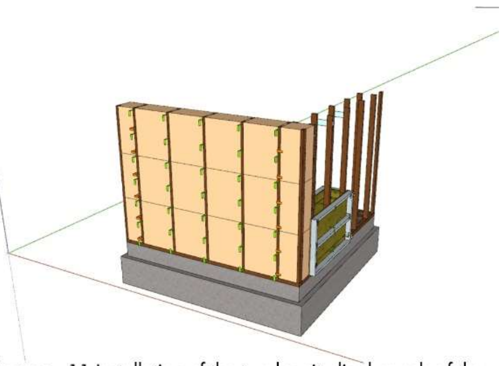
Construction phases



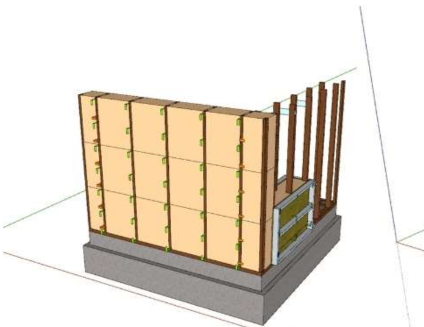
9. Completion of the first section of rammed earth masonry (on wall A) to a height of 90-100 cm.



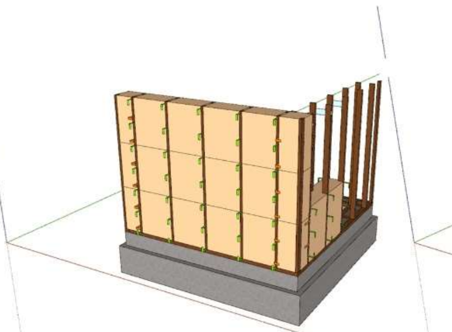
10. Connection of wall B posts to the base beams using L-shaped steel angle brackets. Installation of type 1 ties for each pair of posts, starting from the bottom of the wall.



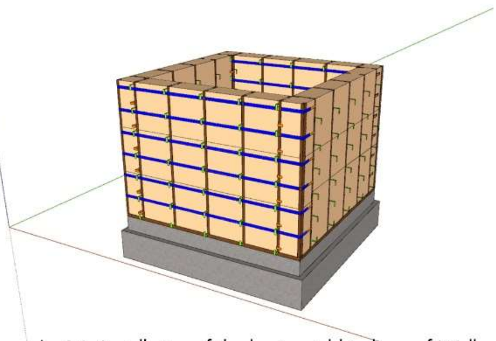
11. Installation of the two longitudinal panels of the formwork and insertion of the ties type 1, stretching and securing by anchoring them with the cleats. Installation of the type 2 ties (offset by 15-20 cm from the type 1 ties), side formworks, bars and nut anchor for formwork fixing. The other side of the formwork is held in place with the three type 1 ties.



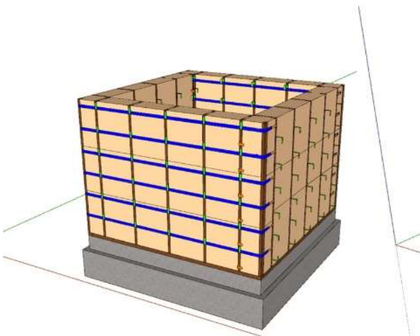
12. Pouring and beating of the premixed material into the formwork by means of a pneumatic compactor, in layers of approx. 15 cm in height, until the soil has reached half of the original height.



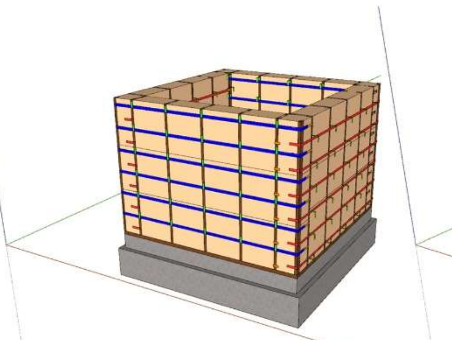
13. Completion of the first section of rammed earth masonry (on wall B) to a height of 90-100 cm.



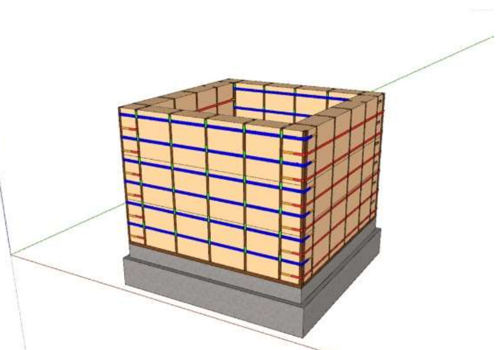
14. Installation of the horizontal bindings of Wall A and anchorage to the type 2 ties protruding from Wall B.



15. Tensioning of Wall A ties (using turnbuckles or a eight knot) and attachment to the type 1 ties projecting from Wall A using a simple knot.



16. Installation of the horizontal bindings of Wall B and anchorage to type 2 ties protruding from Wall A.



17. Tensioning of Wall B ties (using turnbuckles or a eight knot) and attachment to the type 1 ties projecting from Wall B using a simple knot.

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TAV.4.2

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Object:
Construction phases

Figure 31 – Construction phases for wall construction.

4.2.4 Fourth Prototyping

With the help of the Guglielmino Soc. Coop. and the financial support of Unict funding (Linea di intervento 2 del Piano per la Ricerca 2016/2018, Person in charge: Prof. R. Caponetto), a full-scale prototype was built to validate the hypothesized construction phases. The prototype was built in the Guglielmino Soc. Coop. plant, which also provided the base material and most of the equipments necessary for construction.

With the industrial partner, effort have been made to estimate the cost of the premix rammed earth material which can be commercialized in addition to the construction system. Table 11 show the cost analysis of a 25 kg bag of premix material, excluding the profit for the company, which gave as a result a cost of 10 euro/25 kg of material, which is equal to 0.40 €/kg.

Table 11 - Cost analysis for the premix material (Guglielmino soc. Coop.)

ANALISI COSTO: MISCELA TERRA BATTUTA STABILIZZATA E RINFORZATA

	COMPONENTI AL SACCO 25 Kg	**Kg.**	**E/Kg**	**euro**
1	TERRA FLORIDIA 0-2 mm	12.50	0.175	2.1875
2	IINERTE LAVICO 0-4 mm	8.75	0.015	0.13125
3	LIMO DI MARMO 0-2 mm	3.75	0.175	0.65625
4	CALCE IDRAULICA VILLAGA	0.00	0.400	0
5	FIBRA SISAL	0.010	25.00	0.25
	TOT	25.01		4.28
6	**INCIDENZA MANO D'OPERA PER PRODUZIONE 25 Kg**	**min.**	**E/min.**	**euro**
	(stima produzione giornaliera= 8 h. per 6.000 Kg) = 750 Kg/h	1.50	0.83	1.25
		Kg	**E/Kg**	**euro**
7	**STIMA COSTO ENERGIA ELETTRICA 0,01 €/25 Kg**	25.00	0.01	0.25
		Kg	**E/Kg**	**euro**
8	**AMMORTAMENTO IMPIANTO (stima) €/25 Kg**	25.00	0.042	1.05
	(costo stimato euro 550.000/10 anni = 55.000 euro anno)			
	kg. 6.000 x 20 gg x 11 mesi = Kg. 1.320.000 anno			
	euro 55.000/ kg 1.320.000 = 0,042 euro per Kg.			
		Kg	**E/Kg**	**euro**
9	**INCIDENZA SPESE MANUTENZIONE(stima) 0,010 €/25 Kg**	25.00	0.01	0.50
A	TOTALE COSTI 25 Kg.			7.32
B	**SPESE GENERALI 15%**			1.10
	TOTALE COSTI + SPESE GENERALI			8.42
C	**UTILE D'IMPRESA 0%**			0.00
	PREZZO DI VENDITA (A+B+C) Kg.			10.10
	PREZZO DI VENDITA SACCO			**10.102**

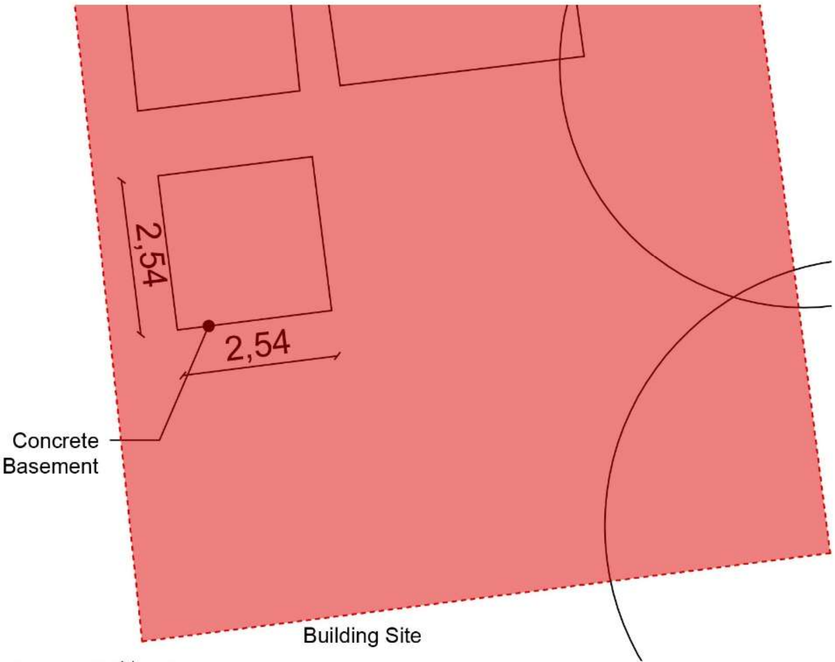
In the following, figures from 32 to 36 show the executive plans realized to facilitate the prototype construction. Finally, figure 37 show various building phases of the prototype.

The preparation of the building site started in September 2021. The marble cutting waste provided by the Amato Marmi company required a preparation prior to the mixing phase (figure 36 A), as explained in section 4.1. Indeed, it arrived in a wet state, so the material was poured on metal platforms to allow drying. After few days, the material was deemed to be dry and collected in buckets. It was then sieved through a 2 mm mesh and collected in smaller buckets to protect it from humidity and rain.

Building Site Plan

Orthophoto of Guglielmino Soc. Cooperativa Area
Scale 1:2000

Prototipe Building Area
Scale 1:1000



Prototipe Building Area
Scale 1:100

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TAV. 1
Object:
Building Site Plan

Figure 32 – Building site plan.

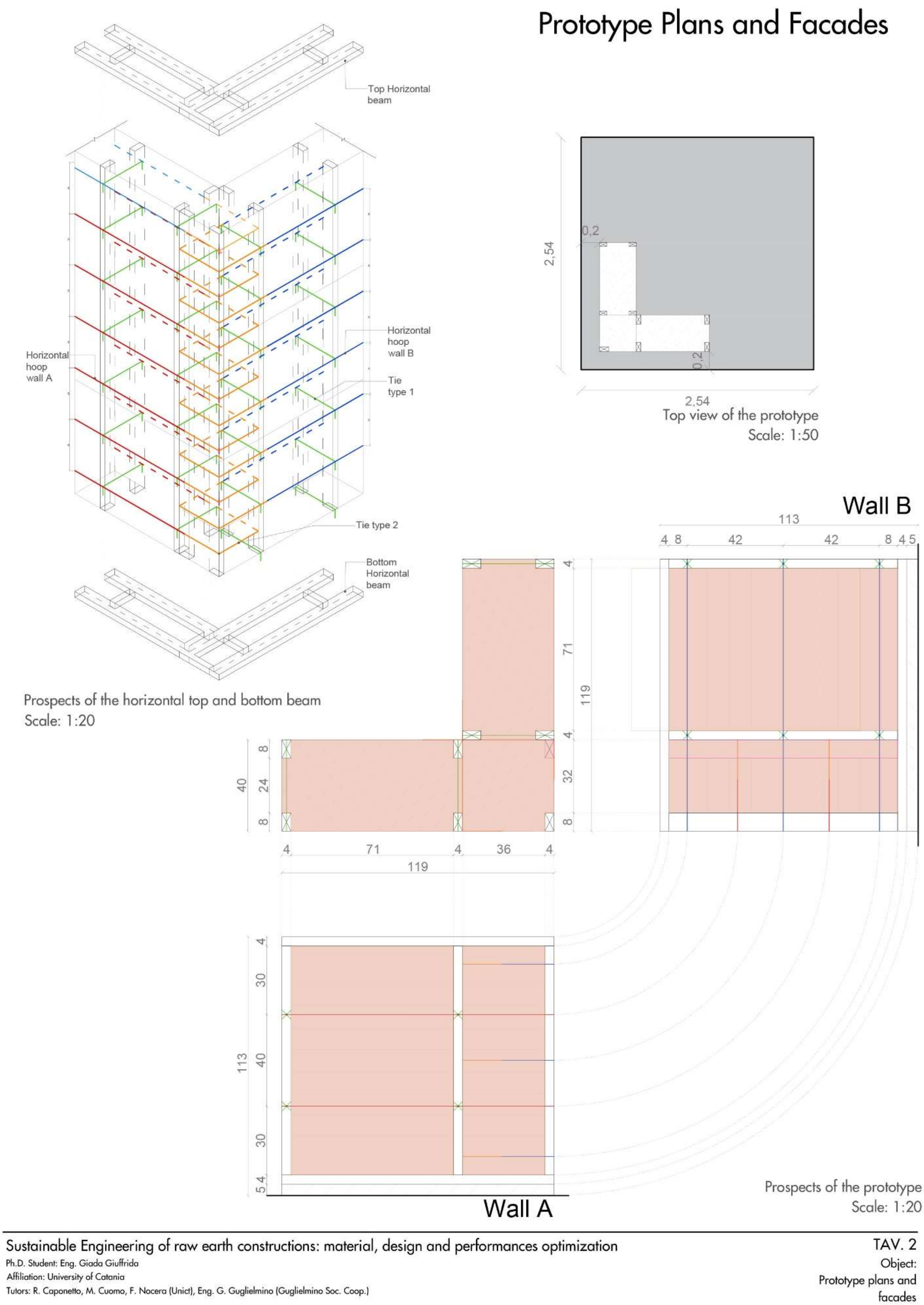


Figure 33 – Prototype plans and facades.

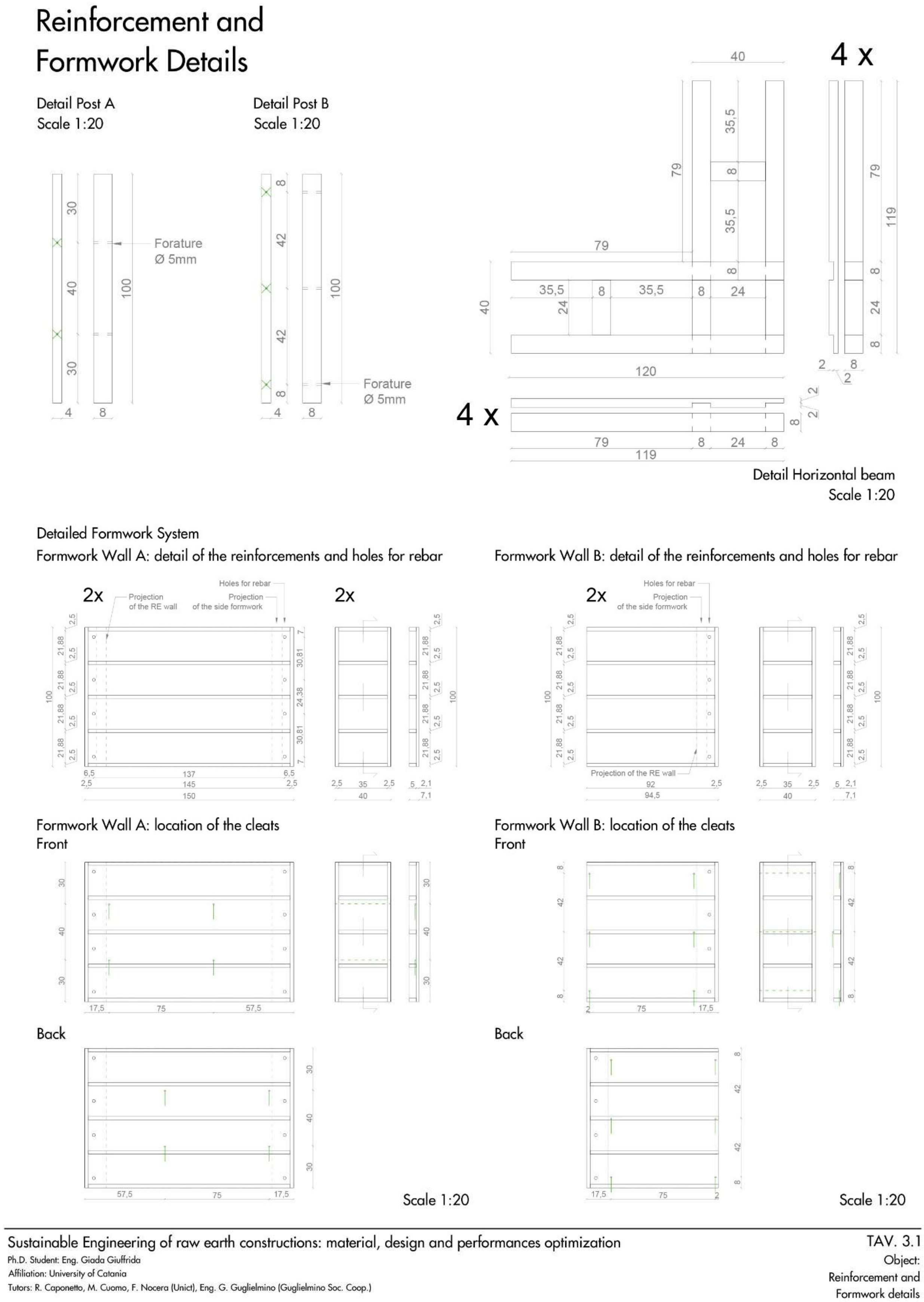


Figure 34 – Reinforcement and formwork details.

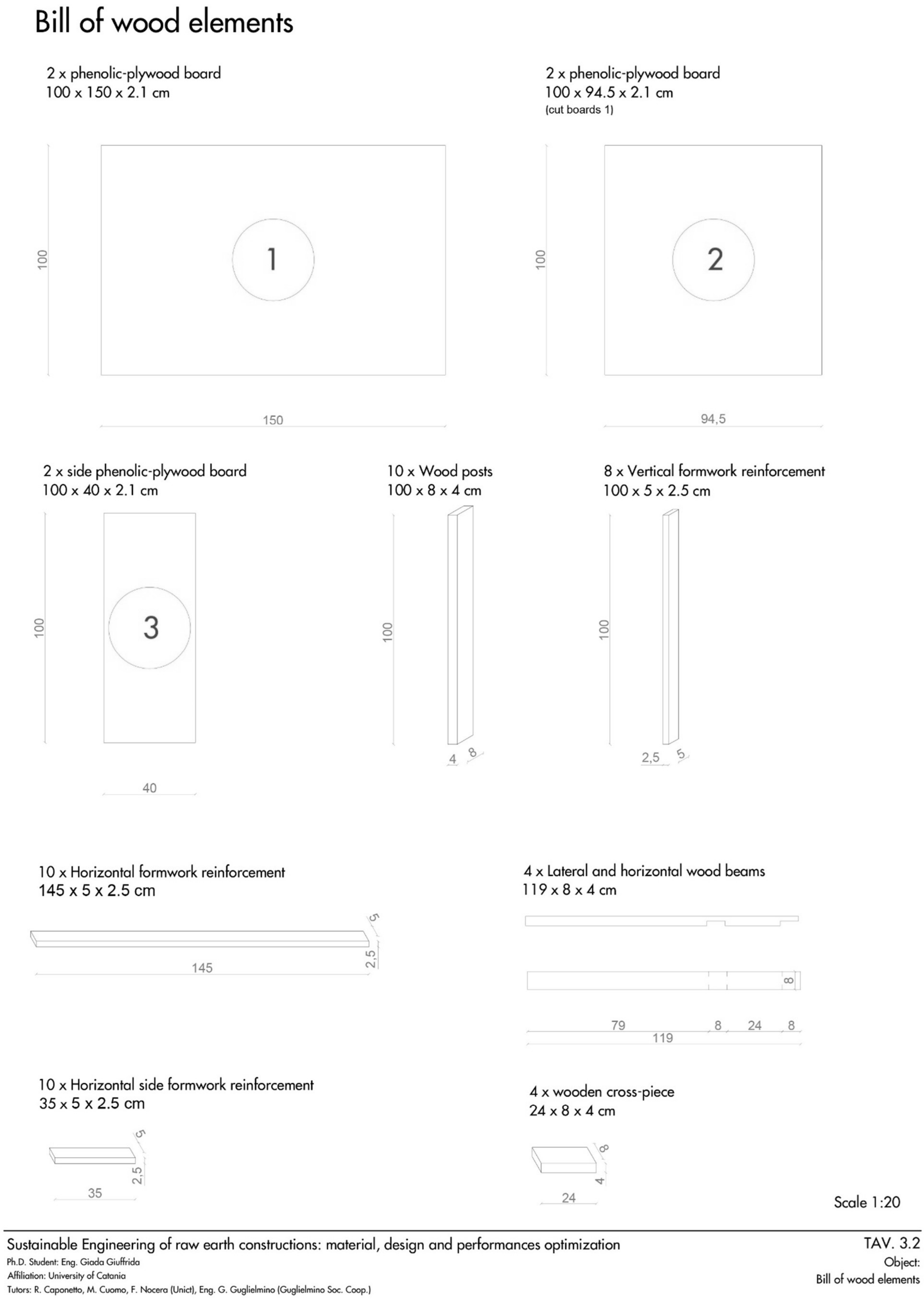


Figure 35 – Bill of wood elements.

Figure 36 – Full scale prototype construction phases (A-E).

Figure 37 – Full scale prototype construction phases (F-I).

Figures 36 B show the preparation of the timber formworks for the full-scale prototype, which was done with the help of a carpenter. These formworks were previously designed by the author (figures 34-35) in such a way to be adapted to the incorporation of the timber and rope reinforcements. For the commercialization, this formwork system could be further improved.

Timber reinforcements elements (figure 36 C) were realized with the help of table saw and jigsaw (for the cuts), carpenter's chisel (for the carvings of the composed ring beam) and drill (for the realization of the posts' slots).

The bottom ring beam was installed by means of concrete anchors on the reinforced concrete footing, after the application of a waterproofing layer. After that, timber posts were installed on the bottom ring beam by angular brackets (figure 36 D).

After the installation of the timber reinforcement elements, it was possible to install the ties type 1 and the formwork previously realized. Attention was paid to the application of the ropes pieces and anchoring on the formwork longitudinal panels by the use of fixed cleats, were ropes ties 1 were allowed to pass and be blocked.

After the blockage of the ropes, the two side rails were installed and blocked by means of four anchor bars and nuts at each side (figure 36 E).
Once the formwork of the first side of the wall was mounted, we started to prepare the rammed earth material in a mixer. Controlled amounts of the material were first dry mixed, and sisal was defibrated to avoid formation of clumps. After that, water was progressively added, and once the material was deemed to be wetted, it was stock in a metal tipper and covered with a plastic sheet (figure 37 F).
The rammed earth material was then poured and compacted by means of hand and pneumatic rammers inside the formwork. The manual rammed was used for the corners, while the pneumatic one facilitates the fast and efficient compaction of the rest of the wall. Layers of 15 cm of material were deemed to be compacted when they reached a final height of 9 – 10 cm (controlled by means of a flex meter). During the compaction, the ties ropes 1 did not negatively affect the execution of the wall, as they are flexible. The final layer of the wall was manually compacted to compensate exactly the heights of the timber posts (figure 37 G).
For the construction of the second wall, the formwork was adapted to the new length (80 cm) by moving the side rail and drilling new holes for the anchor bars passing through the wall. As it was done for the first wall, the timber posts were installed by means of metal connectors on the bottom timber ring beam. The fragments of ropes were installed in the posts' holes and anchored on the exterior part of the formwork by cleats.
The void spaces inside the timber ring beam were filled with expanded clay and then the construction of the rammed earth wall was started as indicated in figure 37 G. Particular attention was paid to the compaction of the joint between the first and second wall. Figure 37 F show some construction phases of the second wall.
The formworks were then removed, and some adjustments were made on the surface of the wall were irregularities of compaction occurred. The adjustments were made by filling the voids on the surface with a wetter rammed earth mix, with the help of a wood board and a hammer.
Finally, the system of horizontal bindings was installed by tying the tie ropes 2 (the angular ones) with fragments of ropes with the same diameter (figure 37 H). These horizontal ropes were then tensioned by a the eight-knot used by [38, 39] creating the bindings. Finally, bindings were connected to tie ropes 1 by mean of simple knots. In this way the rammed earth wall is totally confined by two orders of horizontal rings.

Figure 38 – External and internal view of the prototype wall.

The construction of the full-scale prototype not only helped in the validation of the constructive process, but also allowed for an estimation of construction times and costs. For the construction of the prototype were employed one common and one skilled worker. Construction times comprise all the procedure described in the construction process including installation of timber reinforcement elements (posts and ring beams), assembling and dismantle of formworks, installation of ropes reinforcements, pouring and ramming of rammed earth material.

On the base of the production process times, local and national database were used to calculate the cost of the labor, of materials and equipments used, thus finally estimating the cost of the whole constructive system per m^2.

It is estimated that with the proposed construction system, to realize 1 m^2 of 40 cm-thick reinforced wall, with the help of pneumatic tools for compaction and including the time of installation of the anti-seismic reinforcing devices, about 3 h are required. This is in line with construction times of common contemporary rammed earth constructions (according to current literature, for the realization of 1 m^3 of rammed earth, it takes about 6 h/man operating according to evolved mechanized procedures and 10 h/man for handcrafted procedures).

The estimated costs for this technology are around 700 €/m^2 for a 40 cm thick rammed earth wall, consistent with costs provided by common rammed earth construction enterprises but with the advantage of installing, at the same time, the wall, and its reinforcing structure (integrated with the formwork system) made with sustainable, recycled, recyclable and natural building materials. It has been estimated that if the second option is chosen, that is using the on-site soil mixed with the designed aggregates, costs could be reduced by at least half.

4.3 Building system's hygrothermal and energetic performances

4.3.1 Thermal and energy optimization of rammed earth buildings

In this paragraph are presented the results of the thermophysical characterization of the innovative rammed earth technology able to reduce the energy demand for cooling space and the improvement of the wellbeing conditions of occupants. The effectiveness of the innovative material was analyzed not just through experimental investigation of the material but also through a building energy analysis. Indeed, the energy simulations have been performed with the aim of identifying the best bioclimatic design strategies which include the use of the rammed earth material.

The methodological approach which is adopted to assess the best design optimization choices for future Mediterranean rammed earth buildings is organized according to the following steps:

- Thermal characterization of an optimized local rammed earth material (shown in 4.1 paragraph);
- Calibration of thermal and energy simulations on the rammed earth material's properties (we assumed to work with mix MFRE 6);
- Search for the optimal design choices for rammed earth buildings in a Mediterranean climate.

The following paragraphs will consider these different aspects in greater depth.

Since the introduction of a new constructive technology must be supported by effective convenience of its adoption, a careful analysis must be carried out in order to assess its possibility of improvement compared to conventional building technologies, concerning the reduced environmental impact (in production, construction, use, and dismission phases), its indoor thermal comfort, its increased structural and energetic performances, and economic accessibility.

Thermal loads of a building and consequently its indoor thermal comfort strongly depend on the building's thermal inertia, which is a passive method to store heat energy and to delay its restitution [40–42]. The thermal inertia of the building envelope depends on the thermal properties of materials [41-43]. However, other parameters that may affect the thermal inertia of the building are the air change rate, the orientation of the building, and internal gains [43–46].

The higher the thermal inertia of a building, the slower is the rate at which its indoor air temperature rises and drops [41]. The propagation of temperature profiles on the wall exposed to cyclical solar radiation and variable outdoor air temperature is assumed to be sinusoidal. In the passage from outdoor to indoor surface of the wall, the sinusoidal temperature wave reduces its amplitude gradually [43,47-48]. This phenomenon is associated with the thermal mass of building components and analyzed through two dynamic parameters, the time lag (TL) and the decrement factor (DF) [44, 47, 49].

As explained in Section 2.2.3, time lag (TL) is defined as the time required for a temperature wave to be transferred from the outer surface of the wall to its inner surface [45,47] and is expressed as follows:

$$TL = \tau_{T_{si,max}} - \tau_{T_{so,max}} \quad (3)$$

where τ is time, in s; T_{si} is inner surface temperature, in °C; T_{so} is outer surface temperature, in °C.

Similarly, the decrement factor (DF) is defined as the ratio between the amplitude of inner surface temperature fluctuation and that of outer surface temperature fluctuation [45].

$$DF = \frac{A_{si}}{A_{so}} = \frac{T_{si,max} - T_{si,min}}{T_{so,max} - T_{so,min}} \quad (4)$$

where A_{si} is the amplitude of the heat wave on the inner surface, in °C; A_{so} is the amplitude of the heat wave on the outer surface, in °C.

As many authors point out [50–53], the thermal performance of buildings and the influences of thermal mass and passive strategies can be assessed only through dynamic thermal simulations. Consequently, the detailed

dynamic thermal behavior of a representative rammed earth building in compliance with the in-force building energy regulation standard was analyzed.
Design Builder Version 6.0 [54], based on the Energy Plus calculation engine, was used to carry out the dynamic simulations of the selected building.
Different configurations of the simulated building model have been proposed to investigate the effects of different bioclimatic strategies (summer night cross-ventilation, use of overhangs, and combined effects). Analyzed scenarios are Base, Base + N.V.50, Base + Over, and Base + N.V. 50 + Over, respectively.
The thermal analysis was performed considering two operating regimes, i.e., in free-running conditions and in the presence of an air conditioning system, respectively. Therefore, two cycles of annual simulation referring to the year 2019 were carried out using a calculation frequency of 12-time steps per hour.
Under free-running conditions, an assessment of the thermal response of massive rammed earth envelopes to outer forcing conditions and an evaluation of the thermal comfort in indoor spaces were carried out in the summer period. The indoor and outdoor superficial temperature profiles of the walls facing east and west were determined in order to calculate the time lag and decrement factor according to Equations (3) and (4).
The indoor thermal comfort was assessed by means of the adaptive model considering categories I, II, and III, according to the standard UNI EN 15251: 2008 [55]. The percentages of the analyzed period in which the indoor operative temperature of the investigated scenarios allow comfort conditions (within categories I, II, and III, respectively) to be calculated. The equations used for the definition of upper and lower limits of comfort categories are (5) and (6):

$$T_{under,cat\ ijk} = 0.33\ T_{rm} + 18.8 - i, j, k \quad (5)$$

$$T_{over,cat\ ijk} = 0.33\ T_{rm} + 18.8 + i, j, k \quad (6)$$

Where T_{rm} is the running mean temperature and is defined as an outdoor temperature obtained from the weighted average of the temperatures of the previous seven days. The index i, corresponding to category I and a limit of 2 °C, with high level of expectation, recommended for spaces occupied by very sensitive and fragile persons with special requirements such as the differently abled, the sick, infants and the elderly; the index j, corresponding to category II and a limit of 3 °C, with normal level and expectation; should be used for both new buildings and renovation; the index k corresponding to category III and a limit of 4 °C, with an acceptable, moderate level of expectation that may be used for existing buildings.
In the presence of the air conditioning system, the specific cooling energy needs per year were calculated considering the building equipped with the air conditioning system to maintain a temperature of 26 °C during the cooling season in indoor spaces. Proposed configurations were compared in terms of normalized cooling energy saving with respect to the cooling energy needs of the basic model (Base).
Furthermore, an optimization analysis has been run to efficiently search and identify the design options for the constructions to best meet key design performance objectives. Design Builder Optimization works using genetic algorithms (GA) to search for optimal design solutions, in a trade-off analysis on different design variables aiming at two objectives: the best design options are the ones which combine the minimum values for the two objectives, outlining a Pareto Front along the bottom-left part of the data point cloud graph.
The energy saving deriving by the adoption of proposed interventions is calculated for each i-th scenario through the difference among the thermal energy of the base case (PET)Bs and thermal energy of the current scenario (PET)i:

$$(ES_T)_i = (PE_T)_{BS} - (PE_T)_i \quad (5)$$

Moreover, with the aim to compare the different scenarios, the energy savings (EST)i are normalized with respect to the max values of the baseline scenario (PET)BS:

$$(ES_T)_i = \frac{(PE_T)_{BS} - (PE_T)_i}{(PE_T)_{BS}} \qquad (6)$$

Where:

$(PET)_{BS}$ is the absolute maximum values of building energy demand;

i-th =1,4 are the possible system configurations (Base, Base + N.V.50, Base+ Over, Base + N.V.50 + Over).

The base design of the case study has been developed on the basis of the Peruvian Standard NTE E.080 [1]. In order to comply with this earthquake-resistant raw earth constructions standard, raw earth walls must be at least 40-cm-thick, to counter the risk of overturning; moreover, they must be equipped with horizontal (floors and roofs) and vertical (buttresses and transverse walls) stiffening elements; finally, the density of the walls in the two main directions must be homogeneous.

Fundamental aspects concerning seismic resistant design of [1] have been explained in Section 2.2.4 and are applied to the current building model, which also use the innovative technology defined in Section 4.2.

The designed rammed earth residential building consists of a rectangular box, with three rooms on the south exposition and two rooms on the sides. All loadbearing rammed earth walls are 40 cm thick, while partitions are made with lightweight materials. Geometrical features of the building are reported in Table 12.

Table 12 - Geometrical data of the rammed earth case study building

Building Characteristics	h (m)	Total Envelope Surface (m^2)	Total Gross Volume (m^3)	Shape Factor (1/m)	Net Floor Area (m^2)	Glazing Area (m^2)	Glazing Surface/ Total Envelope Surface (-)
	3.3	825.9	261.4	3.16	58.92	4.9	0.0059

The basic constructions used for the building components, their thermal transmittance, and superficial mass values are shown in Table 13. Concerning the rammed earth walls, they were first considered uninsulated to investigate the single effect of using thick earth walls with higher thermal inertia. The thermophysical properties of the implemented constructions were deduced by archival data, except for the experimental campaign carried out on the innovative rammed earth material used for wallings. Windows are realized with a 5-cm oak wood frame and a double 6-mm glazing and 13-mm air gap. The overall thermal transmittance value of the windows is 3.00 W/m^2 K, and the solar heat gain coefficient (glass g-value) is 0.75.

Table 13 - Basic constructions of the building components

Solid Ground Floor (U = 0.347 W/m ^{2} K, Ms = 1743.45 kg/m ^{2})							
Layer	Material	t (m)	ρ (kg/m^3)	c_p (J/kg K)	λ (W/m K)	R (m^2 K/W)	Ms (kg/m^2)
	Interior	-	-	-	-	0.170	-
1	Timber Flooring	0.01	650	1200	0.14	0.071	6.5
2	Polyethylene	0.003	980	1800	0.5	0.005	2.45
3	Cork Board	0.05	160	1890	0.04	1.250	8
4	Fiberboard	0.015	300	1000	0.06	0.250	4.5
5	Dry Sand	0.08	1700	1000	0.6	0.133	136
6	Fiberboard	0.02	300	1000	0.06	0.333	6
7	Air Layer Unventilated floor	0.15	-	-	-	0.210	-
8	Reinforced Concrete	0.6	2300	1000	2.3	0.210	1380
9	Cast Concrete	0.1	2000	1000	1.13	0.210	200

Table 13 - continues

Layer	Material	t (m)	ρ (kg/m³)	c_p (J/kg K)	λ (W/m K)	R (m² K/W)	Ms (kg/m²)
	Exterior	-	-	-	-	0.040	-

Roof (U = 0.332 W/m ² K, Ms = 81.4 kg/m ²)

Layer	Material	t (m)	ρ (kg/m³)	c_p (J/kg K)	λ (W/m K)	R (m² K/W)	Ms (kg/m²)
	Interior	-	-	-	-	0.100	-
1	Fiberboard	0.015	300	1000	0.06	0.250	4.5
2	Cork Board	0.07	160	1890	0.04	1.750	11.2
3	Fiberboard	0.015	300	1000	0.06	0.250	4.5
4	Cavity Unventilated	0.05	-	-	-	0.180	-
5	Fiberboard	0.02	300	100	0.06	0.333	6
6	Asphalt Roll Roofing	0.002	-	-	-	0.027	-
7	Loose Fill Powder Gravel	0.03	1840	840	0.36	0.083	55.2
	Exterior	-	-	-	-	0.040	-

Wall (U = 0.98 W/m ² K, Ms = 812.25 kg/m ²)

Layer	Material	t (m)	ρ (kg/m³)	c_p (J/kg K)	λ (W/m K)	R (m² K/W)	Ms (kg/m²)
	Interior	-	-	-	-	0.130	-
1	Lime Sand Render	0.025	650	1200	0.8	0.031	16.25
2	Rammed Earth Wall (MFRE 6 mix)	0.4	1980	1000	0.508	0.787	792
3	Gypsum Plaster Mortar	0.025	160	1890	0.8	0.031	4
	Exterior	-	-	-	-	0.040	-

In the Design Builder model, all rooms of the reference residential building were considered as occupied zones. The internal loads are characterized by occupants, electrical devices, and cooking and lighting systems for a total of 928 W with a density of 16 W/m². The power density of occupancy is 7.00 W/m² for a crowding of 0.05 people/m²; the power density of electrical devices and lighting are 5.00 and 4.00 W/m², respectively. The same internal heat loads are fixed for all the proposed configurations of simulations.

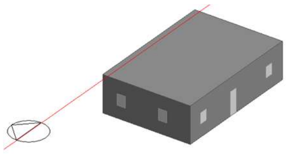
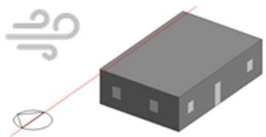
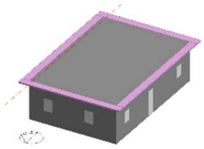
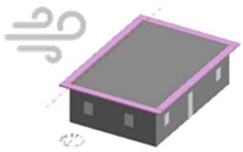
For infiltration of outdoor air, a constant of air change of 0.5 vol/h was set up.

Under the AC system scenario, the building is equipped with a heat pump (HP) system that supplies both heating and cooling. A HP system with a coefficient of performance (SCOP = 3.50) and energy efficiency ratio (EER = 2.50) when it operates as chiller was used. The calculation of the overall thermal energy needs of building was carried out considering two operation programs as established by Italian laws [55] for heating and cooling season, respectively. The conditioning system operates with a set-point temperature of 20 °C during heating season and 26 °C in cooling season.

The meteorological data of the Energy Plus Weather (EPW) file for the city of Catania updated to the year 2019 were used as weather input for dynamic thermal simulations.

Different scenarios of the analyzed building model were set in Design Builder to assess the single effect of every optimized strategy (both bioclimatic and constructive). A basic model (Base) was first developed to investigate the effect of highly massive material for vertical envelopes, as rammed earth is. Design optimization choices were first made applying different traditional bioclimatic strategies to the base model, and then comparing different insulated solutions for the walls using the Optimization Design Builder tool, which allow for comparison of different variables (in this case, the external wall constructions) against two main objectives (i.e., minimization of energy needs, capital costs, embodied carbon, and discomfort hours). Starting from the results of the annual dynamic simulations, it was possible to assess the optimized design solutions to obtain optimal thermal stability to ensure a satisfactory level of comfort and minimize energy needs, costs, and environmental impact. The different simulation cases are codified and described in Table 14.

Table 14 - Codification for the simulated cases.

Code	Building Model	Description of Case
Base		Base model: uninsulated rammed earth walls, insulated roof and ground solid floor. No natural ventilation, no overhang solutions for shadings
Base + N.V. 50		Base model + natural ventilation by the 50% opening of windows
Base + Over		Base model with 60-cm overhangs
Base + N.V. 50 + Over		Base model with 60-cm overhangs + natural ventilation by the 50% opening of windows
Opt. + N.V. 50 + Over		Optimized insulated models (comparison of 31 insulated constructions) with 60-cm overhangs + natural ventilation by the 50% opening of windows

For the sake of brevity, it was extrapolated and analyzed the thermal behavior of the rammed earth building in a representative summer period (28 July–2 August) to study the best design options to be applied on massive earth walls in a hot temperate climate as the Mediterranean one.
Furthermore, it was extrapolated also the winter behavior in free-running conditions in the period 7-11 December. Winter behavior of massive walls in hot-temperate climate is not interested by the bioclimatic strategies used to mitigate summer heat waves; for this reason, typical winter temperature profiles will be discussed only in the last part of the paragraph, where the uninsulated case is compared to an insulated rammed earth wall.
Use of natural night cross-ventilation has been considered in the Base + N.V. 50 coded analysis. In this configuration, 50% of the glazed surface in the building was kept open from 00:00 a.m. to 06:00 a.m. according to a specific schedule to investigate the effectiveness of night-time natural ventilation [56–58].
In Base + Over coded analysis, a 60-cm-deep coronation of the roof was used to analyze their shadowing effects on walls. These overhangs, inherited by traditional Mediterranean bioclimatic strategies and typically used in contemporary rammed earth constructions (the "great hat" which raw earth buildings must be

provided with [9]), were implemented as an independent component in Design Builder. An equivalent conductivity of 0.043 W/mK for this component was set.
The coded analysis Base + N.V. 50 + Over shows the combination effects of the night cross-ventilation (at 50% of windows opening) and use of overhangs.
The last part of the analysis (Opt. + N.V. 50 + Over) is a set of five optimization simulations, focusing on the use of several types of thermal wall insulation aiming at minimizing costs, embodied carbon, and discomfort hours in the building, while minimizing energy needs for heating and cooling. The optimized constructions for the earth walls consist of the use of thirty-one combinations of internal or external thermal insulation (figure 39), all resulting in a final thermal transmittance below 0.43 W/m²K, which is the limit value of Italian standard regulations for climate zone B (in which the city of Catania is located) [59–61]. The main thermal and physical characteristics of these types of insulation are reported in Table 15.

Figure 39 – Optimization options for the rammed earth envelope (Opt. + N.V. 50 + Over analysis)

Table 15 - Type and thermophysical properties of the insulation used in the optimized cases.

Type of Insulation	Origin	t (m)	ρ (kg/m³)	c (J/kgK)	λ (W/m²K)	Cost [GBP/m²] [GBP/kg]	Embodied Carbon [kg CO2/ kg]
Expanded Polystyrene EPS board	Synthetic	0.06	15	1400	0.04	7	2.50
Polyurethane PU board	Synthetic	0.04	35	1590	0.028	35	3.00
Aerogel	Synthetic	0.02	150	1000	0.015	149	4.32
Rockwool	Mineral	0.05	100	710	0.033	10	1.05
Glass cellular sheet	Mineral	0.07	140	840	0.048	40	0.85
Perlite	Mineral	0.07	65	840	0.046	1	1.21
Rubber	Composite	0.12	1200	1000	0.15	30	3.51
Cork board	Vegetal	0.06	160	1890	0.04	35	0.19
Jute felt mat	Vegetal	0.10	330	1090	0.067	50	0.96
Coconut fiber board	Vegetal	0.09	520	1090	0.06	30	0.51
Flax shive board	Vegetal	0.04	500	1880	0.012	35	0.51
Thermal plaster hemp lime	Vegetal	0.12	400	1500	0.085	45.07	0.20
Recycled vegetal fiberboard	Vegetal	0.08	290	1300	0.055	25	0.35
Straw	Vegetal	0.09	310	1300	0.057	15	0.51
Sheep wool mat	Animal	0.05	18	1720	0.037	7	0.96

The thermal behavior of a non-conditioned building is strongly affected by the façade orientation, as well as the thermal inertia properties of its envelope components. For the sake of brevity, considering that the façades facing east and west have rather similar behavior, especially with respect to midday, only the hourly profile of the surface temperatures of the wall facing east during period (28 July–2 August) is shown in Figure 40. Afterwards, the maximum and minimum values of inner and outer surface temperatures of the west-oriented wall are reported next to values of the surface temperatures of the façade facing east in Table 16.

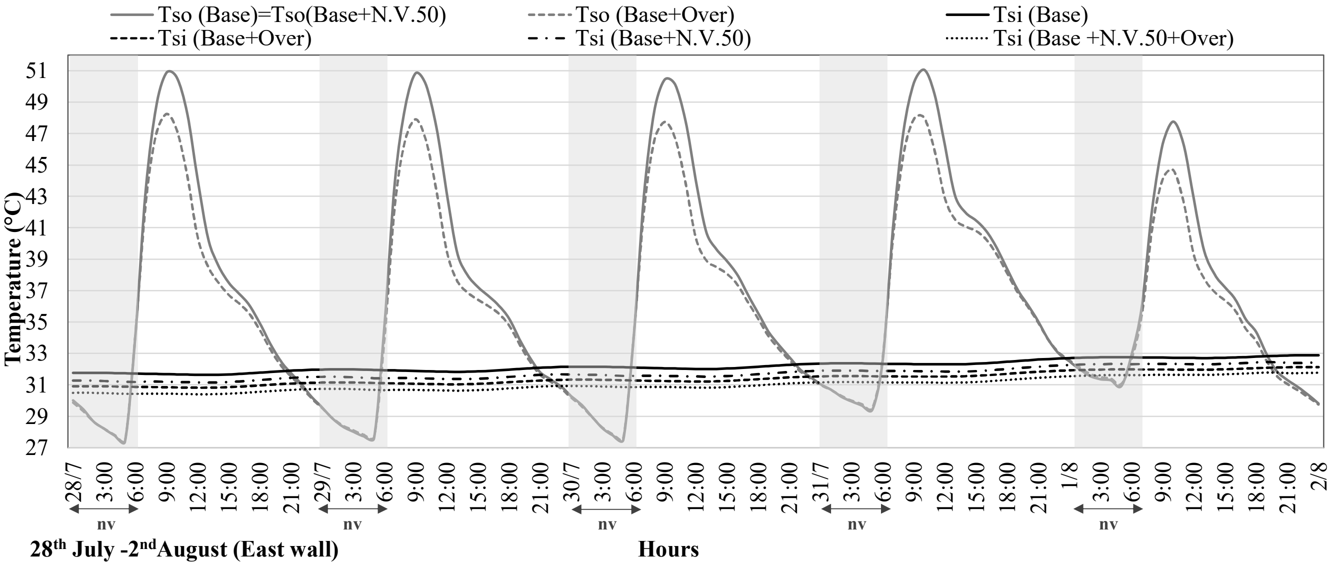


Figure 40 - Outdoor surface temperature (T_{se}) vs. indoor surface temperature (T_{si}) in the investigated cases from 28 July to 2 August.

Figure 39 depicts the hourly variation in inner surface temperature (T_{si}) and outer surface temperature (T_{so}) of the wall facing east for all investigated configurations. Under the base case, the hourly path-line of T_{si} ranges from a minimum of 31.8 °C to a maximum of 33 °C considering the entire selected period against a variation in T_{so} from a minimum of 27.8 °C to a maximum of 51.0 °C.

It should be highlighted that the inner surface temperature is kept almost constant with respect to the curve of outer surface temperature in all investigated scenarios. The daily amplitude of the trend of T_{si} is, on average, 1.0 °C, which is very small if compared to that of Tso. This behavior is confirmed by a very low value of decrement factor, DF = 0.0045 and DF = 0.0253, for walls facing east and west. The peak of T_{si} is delayed by 17 h with respect to the maximum value of T_{so}. This reveals that the fiber-reinforced rammed earth walls behave as a thermal flywheel and remarkably dampen the incoming heat wave.

Under the night-time natural ventilation scenario (Base+N.V.50), the trend of T_{si} is approximately 0.4 °C lower than that of the base case.

The addition of the overhangs to the base case (Base + Over) produces a decrease of 3 °C in the peak values in the outer surface temperature. Against the decrement in the maximum value of T_{so}, a reduction in the inner surface temperature of 0.8 °C for the wall facing east and 0.5 °C for the wall facing west were obtained during the analyzed period.

The best results are achieved under the combined effects of night ventilation and overhangs (Base+N.V.50+Over). Combined strategies succeed in lowering indoor surface temperatures by more than 1.0 °C, in the maximum and minimum values of T_{si} both on east and west walls, the bioclimatic strategies using overhangs being more effective compared to that using only night ventilation.

Table 16 - Thermal inertia of the envelope in the studied cases for east and west exposure.

Scenario °C	East Wall						West Wall					
	$T_{so,max}$	$T_{so,min}$	$T_{si,max}$	$T_{si,min}$	$\Delta T_{so,max}$	$\Delta T_{si,max}$	$T_{so,max}$	$T_{so,min}$	$T_{si,max}$	$T_{si,min}$	$\Delta T_{so,max}$	$\Delta T_{si,max}$
Base	51.1	27.50	32.76	31.8	23.33	0.16	49.92	27.89	32.9	31.5	21.33	0.71
Base + N.V.50	51.1	27.41	32.33	31.4	23.37	0.10	49.87	27.83	32.5	30.8	21.32	0.79
Base + Over	48.3	27.59	31.99	31.0	20.57	0.12	47.64	27.96	32.4	30.9	18.45	0.72
Base + N.V.50 + Over	48.1	27.54	31.64	30.7	20.49	0.08	47.59	27.88	32.0	30.3	18.49	0.76

Indoor surface temperatures decrease less in upgrading interventions using night cross-ventilation, while the use of overhangs has significant consequences for the reduction of indoor surface temperatures.
The analysis of the thermal dynamic responses of the wall facing west leads to analogous considerations of those observed for the wall facing east. It has to be highlighted that, as a result of the orientation of the building, the west wall shows a peak in indoor surface temperature the next day with respect to the action of external forcing agents (T_o and solar radiation).
Figure 41 displays the thermal dynamic parameters calculated for the walls facing east and west.

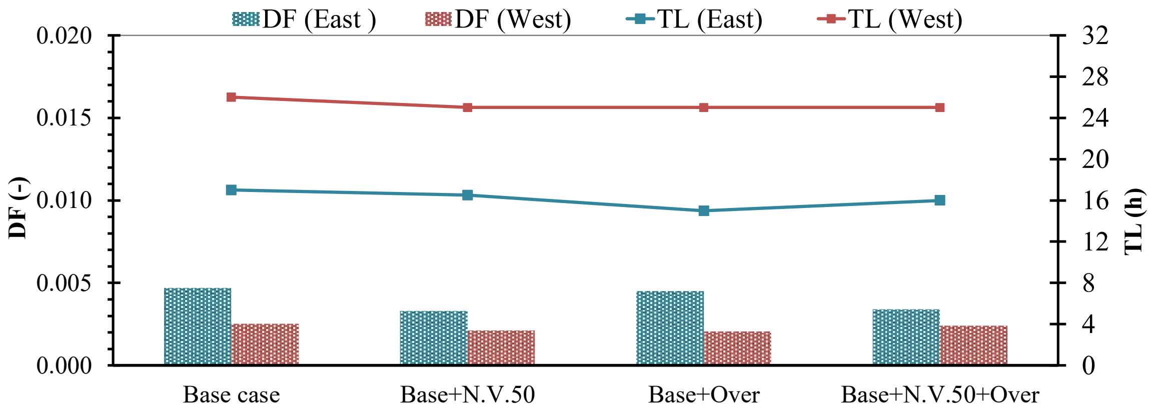


Figure 41 - Decrement factor (DF) and time lag (TL) of east- and west-facing walls.

It has to be highlighted that the basic configuration shows appreciable thermal dynamic behavior, TL = 17 h, DF = 0.0045 for the east wall and TL = 26 h, DF = 0.00253 for the west wall. From the comparison of the TL and DF values of the investigated cases, it can be observed that time lag remains almost constant in the various upgrading scenarios, while the decrement factor tends to decrease in combined and more complex design solutions.
An evaluation of the thermal conditions in indoor spaces under the investigated scenarios was conducted analyzing the trend of indoor air temperature. In the presence of internal heat gains, the hourly profile of air temperature from 28 July and 2 August is plotted in Figure 42. A double bedroom and a single bedroom were selected as the investigated rooms.

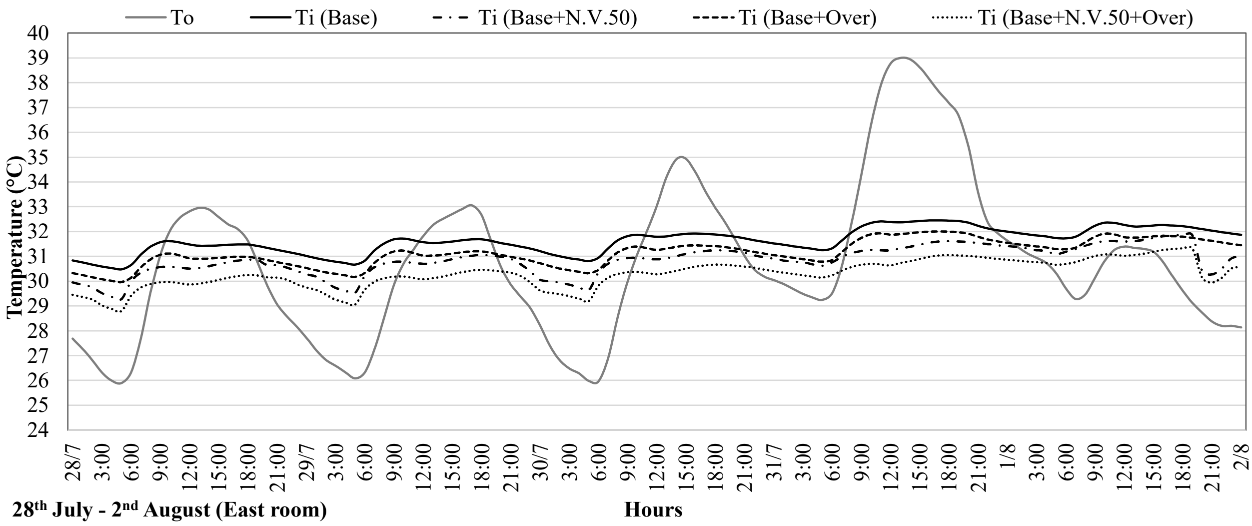


Figure 42 - Hourly profiles of indoor air temperature (Ti) in the investigated cases from 28 July to 2 August

In the base case, the air temperature (T_a) ranges from a minimum of 31.8 °C at 6.00 a.m. to a maximum of 33.5 °C at 12.00 a.m. The effect of night natural ventilation reduces the peak of Ta by approximately 0.80 °C in the Base + N.V. 50 scenario, as shown in Figure 42.

The overhang (Base + Over) scenario shows an average reduction of 0.50 °C with respect to the trend in air temperature of the base case. Consequently, the use of night cross-ventilation is more effective compared to the use of overhangs under indoor air temperature.

With reference to the base case, the reductions in air temperature in the different scenarios are shown in Table 17. The best configuration is the combined strategy (Base + N.V. 50 + Over), which succeeds in lowering the maximum temperatures by 1.40 °C for the east room and 1.51 °C for the west room, while the minimum temperatures are reduced by 1.68 °C in the east room and 1.92 °C in the east room, during the same day.

It should be highlighted that the reductions in the minimum values of air temperature are higher than those in the maximum values of air temperature.

Table 17 - Mean indoor temperature for the investigated cases for east and west rooms.

Scenario	East Room				West Room			
°C	$T_{a,max}$	$T_{a,min}$	$\Delta T_{a,max}$	$\Delta T_{a,min}$	$T_{a,max}$	$T_{a,min}$	$\Delta T_{a,max}$	$\Delta T_{a,min}$
Base	32.46	30.48	-	-	32.66	30.25	-	-
Base + N.V.50	31.61	29.28	0.84	1.20	31.79	28.71	0.99	1.54
Base + Over	32.00	29.97	0.45	0.51	32.35	29.78	0.43	0.47
Base + N.V.50 + Over	31.05	28.80	1.40	1.68	31.27	28.34	1.51	1.92

The indoor thermal comfort of the building was evaluated according to the approach of the adaptive comfort model. The operative temperature (T_{op}), calculated under free-running condition for the entire year and for all investigated cases, was used as the reference parameter for assessing the indoor thermal comfort. The hourly variations in T_{op} during the selected period (28th July to 2nd August) are depicted in Figure 43 as well as the range of the comfort temperatures for categories I, II, and III.

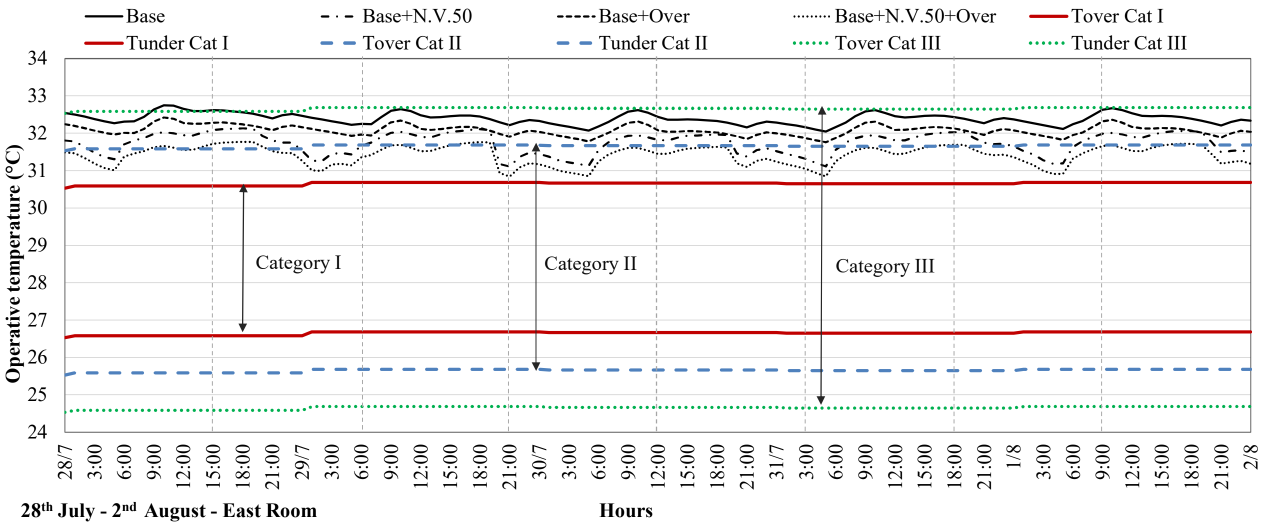


Figure 43 - Hourly profile of operative temperature under all investigated cases and threshold values (T under, T over) for category I, II, and III.

Under the base scenario, the profiles of the operative temperature (T_{op}) range from a minimum value of 32.0 °C to a maximum value of 32.7 °C.
Under the overhang scenario (Base + Over), the path-line of T_{op} is reduced by approximately 0.5 °C with respect to the base case during the entire investigated period.
Both the Base and Base + Over cases show moderate comfort levels because their profiles of T_{op} are predominantly within category III. In the Base + N.V. 50 scenario, the profile of operative temperature lies in category III during the hottest hours, whereas its profile is within category II in early morning.
It is interesting to point out that the use of simple bioclimatic combined strategies (use of night cross-ventilation and overhangs in the case Base + N.V. 50 + Over) allows a further improvement in the trend of operative temperature. The decrease in T_{op} allows for the passage from a moderate level of comfort to a normal expected one, yet not satisfying the limits for the more restrictive category I for the eastern room (double bedroom), while in the western room (single bedroom), they are satisfied in early morning.
Table 18 summarizes the percentages of the analyzed period (28th July to 2nd August) in which the investigated scenarios are within the comfort categories I, II, and III, respectively.

Table 18 - Percentage time during 28 July–2 August in which the investigated cases are in comfort categories I, II, and III for double bedroom (east room) and single bedroom (west room).

Cases (%)	East Room				West Room			
	Base	Base + N.V. 50	Base + Over	Base + N.V. 50 + Over	Base	Base + N.V. 50	Base + Over	Base + N.V. 50 + Over
Cat. I	0	0	0	0	0	5.79	0	12.50
Cat. II	0	35.54	0	80.99	22.31	66.94	52.07	75.21
Cat. III	91.73	64.46	100	19.01	72.72	27.27	47.93	12.30
Out Cat. III	8.26	0	0	0	5.79	0	0	0

As can be observed, for the east and west rooms, the Base case lies for most of the time (respectively, 91.73% and 72.72%) within category III of comfort, with the west room being more comfortable during early morning, when it satisfies category II for 22.31% of the time. The Base + N.V.50 design solution

allows for a consistent passage to higher comfort categories, both for the east (35.54% in category II) and west rooms (66.94% in category II and 5.79% in category I), compared to the use of overhangs, which provides only a moderate improvement in indoor thermal comfort. Finally, combined strategies (Base + N.V.50 + Over) enhance overall comfort in all rooms, with major percentages in category II (80.99% for east room and 75.21% for west room) and minor percentages in category III (east and west rooms) and category I (west room).
The comparison among different proposed investigated cases was also carried out in term of thermal energy needs. The thermal energy needs are calculated considering that the heating system is switched on from December the 1st to March the 31st that is selected period for Catania according to Italian Standard Regulation. The calculated energy needs, as well as the energy savings, for the base configuration and for the other wall configurations, are depicted in Figure 44.

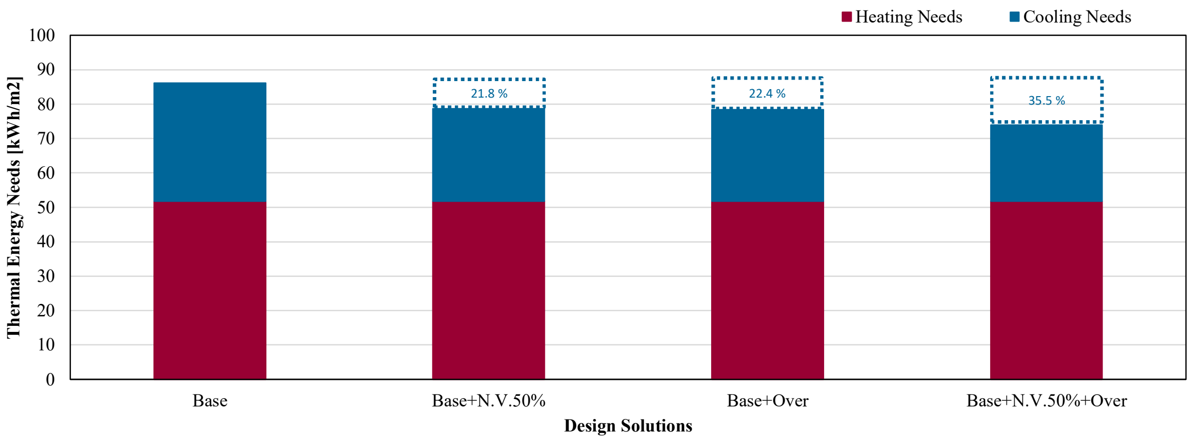


Figure 44 - Annual Thermal Energy needs for all the investigated cases.

The base case is characterized by a specific annual thermal energy equal to 86.1 kWh/m^{2}y. The thermal energy needs for heating and cooling are 51.8 kWh/m^{2}y and 34.3 kWh/m^{2}y respectively.
It worths to be highlighted that the Base + Over and the Base + N.V. 50 scenarios show an energy saving about 9% if compared to the Base case.
The results highlight that the use of combined bioclimatic strategies (for the case Base + N.V. 50 + Over) allow achieving a remarkable improvement in the energy performance of the whole building. The thermal energy needs are reduced from 86.1 kWh/m^2 y to value of 73.9 kWh/m^2 y when the Base + N.V. 50 + Over case is applied. Therefore, a total annual reduction of 14.2% is attained of which 35.5% of energy savings are achieved during summer period.
In the last part of this investigation, on the basis of the best bioclimatic strategy option (Base + N.V. 50 + Over), thirty-one design solutions for the vertical envelope were studied (Opt. + N.V. 50 + Over cases).
The intention of this analysis was to best identify the design approach that must be adopted for massive rammed earth walls to be used in Mediterranean climates. The idea of using thermal insulation was not so obvious for a hot temperate climate as the one in Catania, as it might have caused indoor overheating. Moreover, several considerations had to be made before choosing a compatible type of thermal insulation for a sustainable, affordable, and low embodied-energy building material such as rammed earth.
As mentioned above, the Design Builder Optimization tool was used to plot the design solutions for rammed earth wall constructions, which minimized the heating and cooling loads against three other objectives, aiming at minimizing total building cost, embodied carbon, and discomfort hours. Design Builder offered a wide database concerning embodied carbon and costs for all the materials implemented. Results are depicted in

Figures 45 and 46. For the sake of brevity, it is shown only one of the analyzes aiming at the minimization of discomfort hours, the one fitting category II.

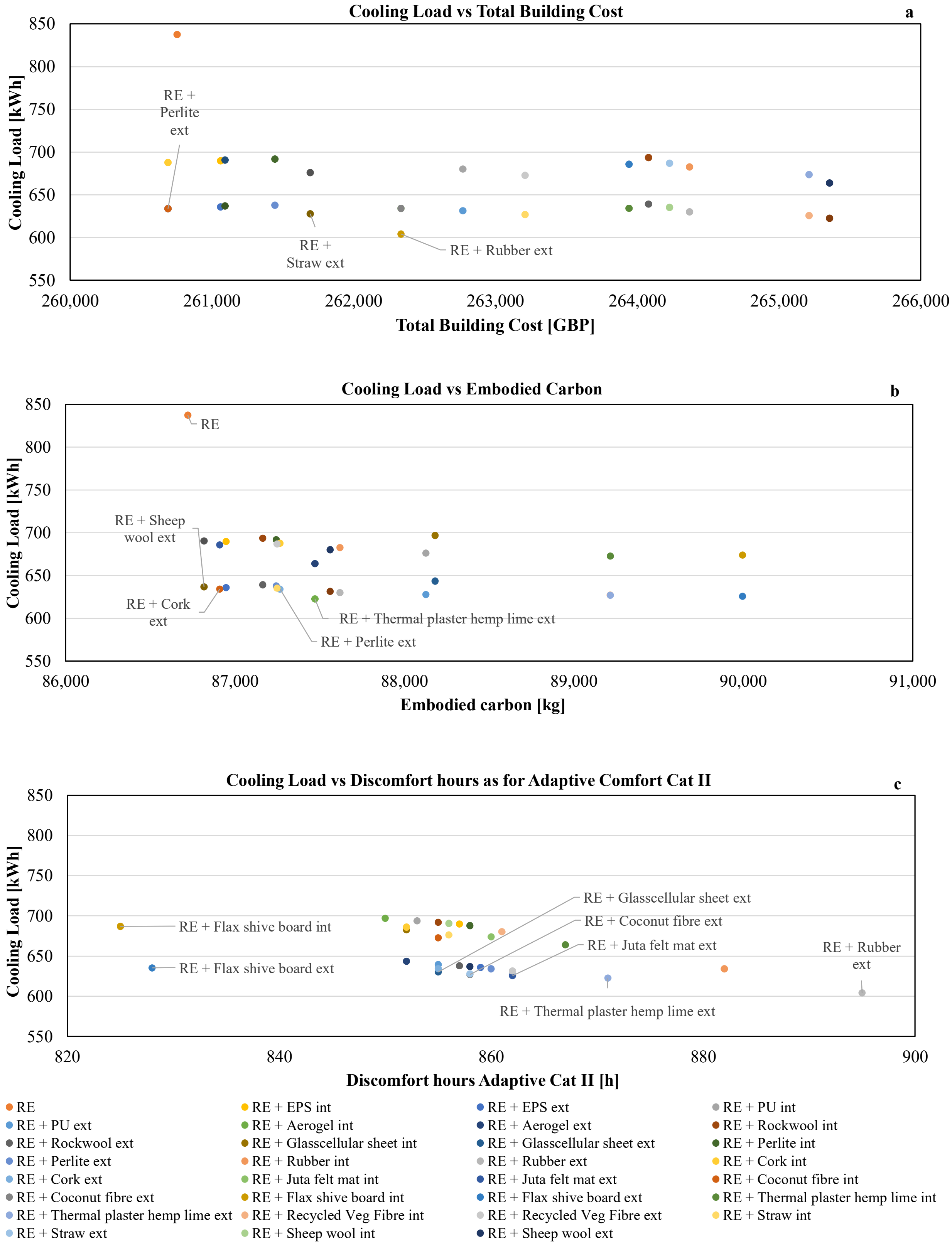


Figure 45 - Cooling loads vs. total building cost (a), embodied carbon (b), and discomfort hours as for category II of adaptive comfort model (c). Optimized rammed earth (RE) insulated wall constructions indicated with labels.

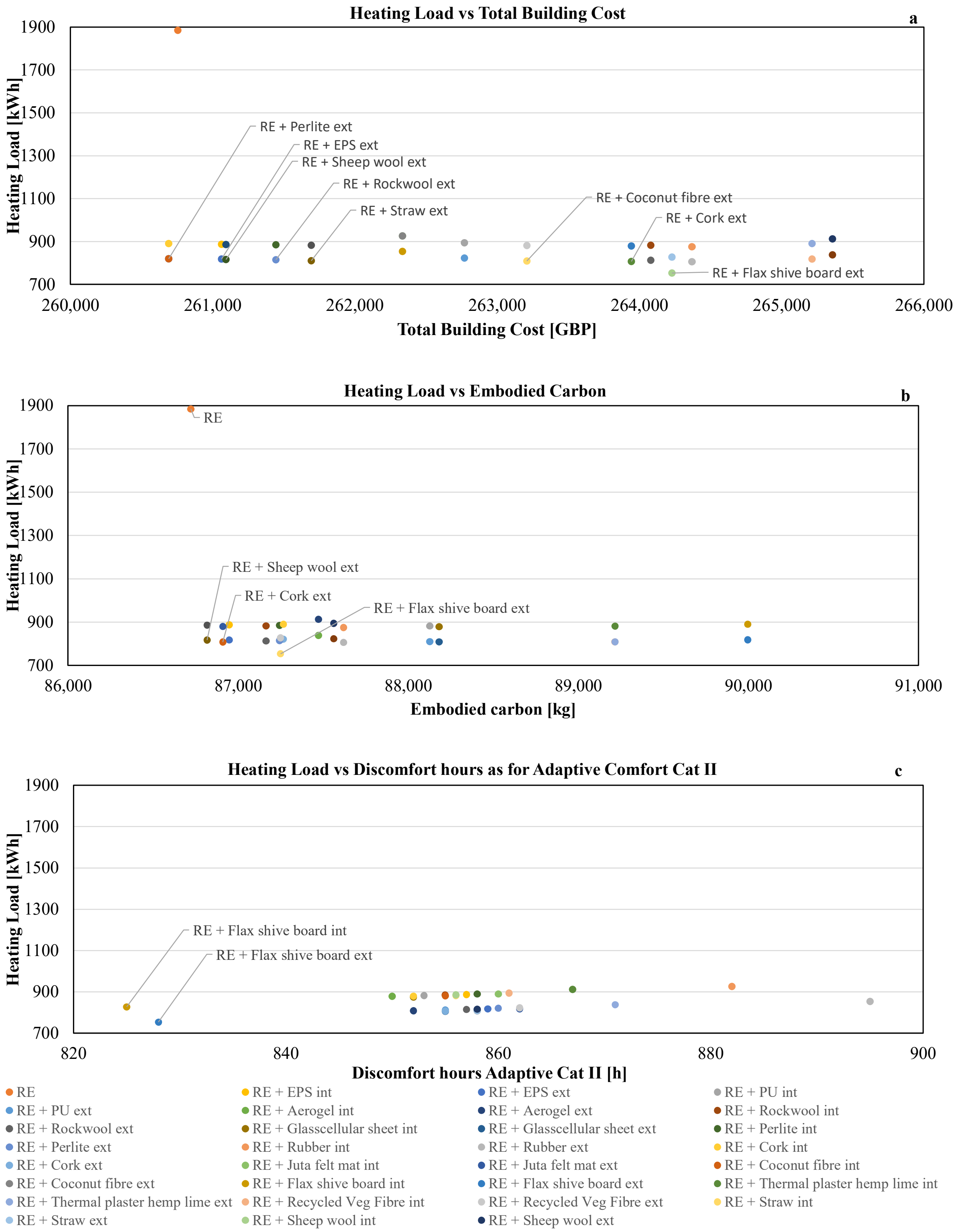


Figure 46 - Heating loads vs. total building cost (a), embodied carbon (b), and discomfort hours as for category II of adaptive comfort model (c). Optimized rammed earth (RE) insulated wall constructions indicated with labels.

Concerning the minimization of cooling load, the minimum cost is found for both conventional insulation types (such as perlite and hard rubber external insulation) and natural-based ones (straw). At the same time, some conventional insulation types (such as perlite and hard rubber) and other natural-based insulation types such as thermocork boards, sheep wool mats, and thermal plaster realized in lime hemp, together with the uninsulated rammed earth (RE) construction, are the best options to achieve the objective of the minimization of embodied carbon. Finally, the objective of the minimization of discomfort hours is satisfied by several insulated construction solutions, most of them using innovative natural-based insulation (10-cm jute felt, 9-cm-thick coconut fiberboard, 2-cm-thick flax shive board, and 12-cm thermal hemp lime plaster), and only two using conventional synthetic insulation (glass cellular and hard rubber). It should be noted that the uninsulated solution lies outside the range presented in Figure 8c, as the annual discomfort hours are 1099. The great presence of optimized solutions using natural-based thermal insulation is remarkable, especially when compared to the low presence of synthetic and composite materials.

A similar result is also visible when minimization of heating load is considered: in this case, some synthetic insulating materials (EPS and rockwool), mineral (perlite), and natural-based ones (thermocork, coconut fiber and flax shive boards, straw, and sheep wool mat) also satisfy the minimization of total building cost. Concerning the minimization of embodied carbon, the uninsulated rammed earth solution, together with flax shive board and sheep wool mat, also meets the minimization of heating loads. Finally, the best design solutions minimizing both heating loads and discomfort hours are the ones encountering the use of flax shive board insulation; the uninsulated solution is not an optimized one concerning comfort, its annual discomfort hours being superior to the shown range. It is interesting to point out that some conventional insulation types used by several Australian and North American rammed earth construction firms, such as polyurethane and expanded polystyrene boards, do not satisfy the economic, environmental, and comfort criteria in the analyzed Mediterranean climate. Indeed, similar results are encouraging for the upcoming generation of natural-based thermal insulation, even when applied to rammed earth construction.

Figures 47 and 48 show two graphs for two representative periods for the summer season (28 July - 1 August) and the winter season (7 - 11 December). In both figures the external dry bulb temperature profiles, the internal and external surface temperatures and the average internal air temperatures are shown, in the basic solution (using bioclimatic improvement strategies such as overhangs and natural ventilation) and in an optimized one (using a cork board on the external side of the rammed earth wall) under free-running conditions (in the absence of an air conditioning system).

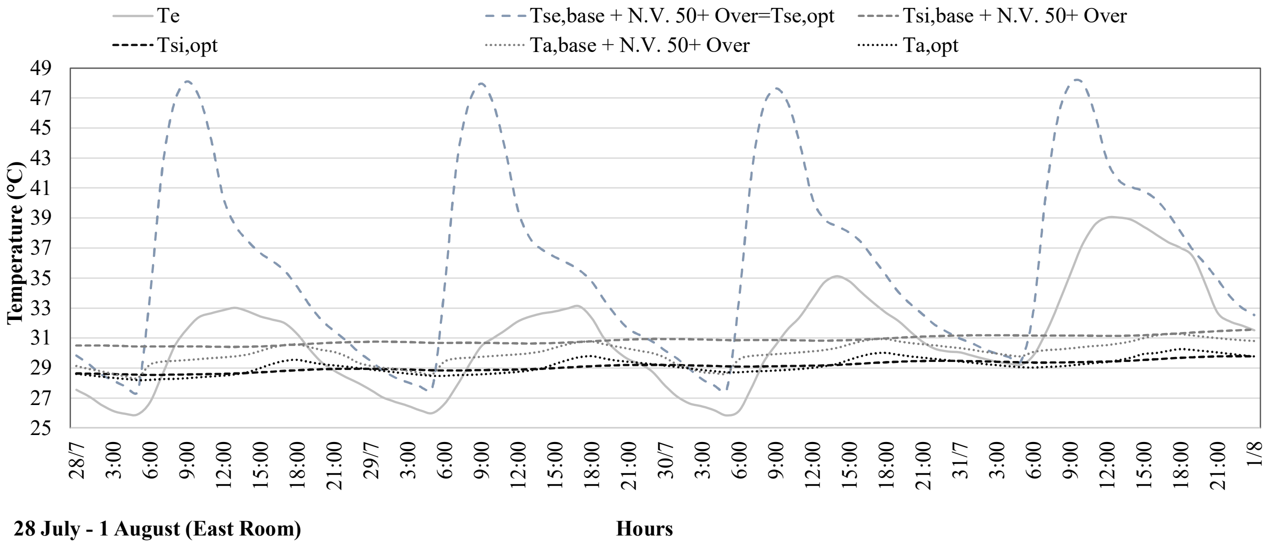


Figure 47 - Temperature profiles in summer period under free running conditions for Base + N.V. 50 + Over case and Optimized case

As can be seen from fig. 47, given a profile of outdoor temperature (T_o) and outdoor surface temperature ($T_{so,base}$=$T_{so,opt}$), the indoor surface temperature profile of the base case ($T_{si,base}$) is on average at least 2 °C higher than in the case with thermal insulation ($T_{si,opt}$), throughout the period considered. The indoor air temperature profile in the base case ($T_{a,base}$) is reduced in the optimized case ($T_{a,opt}$) by at least 1 °C, during the hourly interval from 07:00 to 21:00, while at night this reduction is of the order of 0.5 °C. In the thermally insulated case, a more stable thermal behavior of the indoor air temperature profiles is generally observed.

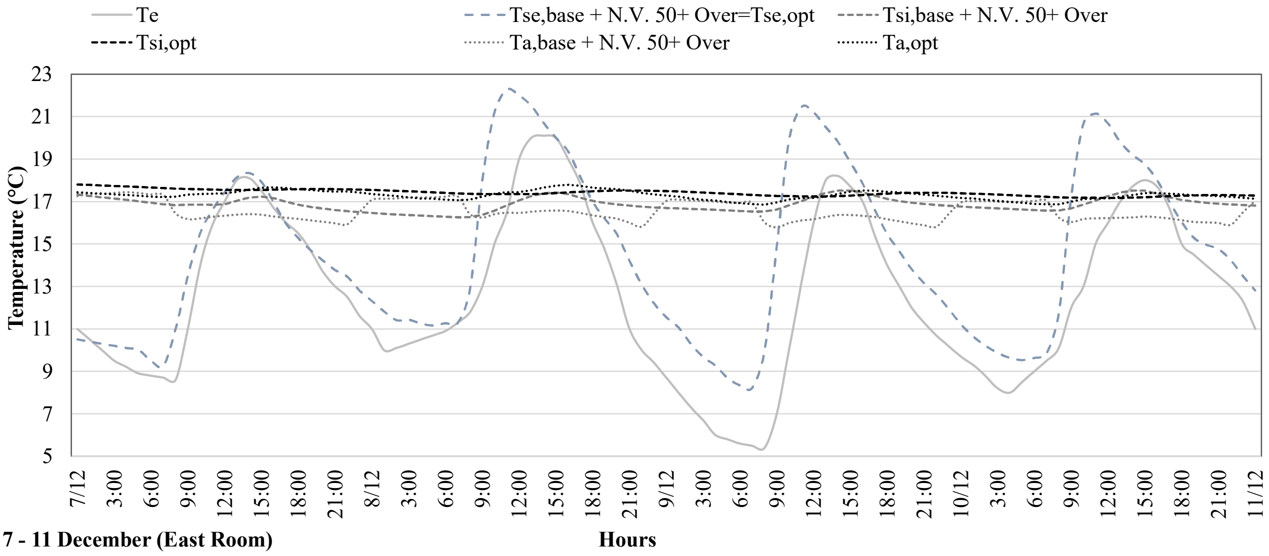


Figure 48 - Temperature profiles in winter period under free running conditions for Base + N.V. 50 + Over case and Optimized case

The observation of the graph in fig. 47 allows us to make interesting considerations. Given the profiles of outdoor temperature (T_o) and outdoor surface temperature ($T_{so,base}$=$T_{so,opt}$), the profile of indoor surface temperatures in the optimized case ($T_{si,opt}$) is almost always above the profile of indoor surface temperatures in the base case ($T_{si,base}$), with an average increase of about 0.35 °C: in particular, the increase of $T_{si,opt}$ is greater in the hours ranging from 18:00 to 22:00 (and of the order of 1°C) and lower in the remaining hours (on average of the order of a few tenths of a degree). Similar considerations can be made for the indoor air temperature profile, which is on average 0.7 °C higher in the optimized case ($T_{a,opt}$) than in the base case ($T_{a,base}$), with greater gaps between the two profiles during the hours from 08:00 to 23:00 (greater than 1°C), while the profiles intersect in the remaining hours.

4.3.2 Hygrothermal behavior of rammed earth walls

As abovementioned, on the base of the thermal and energy analysis, a first exploratory study on the hygrothermal performances of a wall designed with the innovative rammed earth material was run on Delphin software. Results have been elaborated on PostProcessing 2. The analysis aimed to understand which insulating solutions are more compatible with the rammed earth wall, in Mediterranean climate zone.

Delphin is a simulation program, which allows to choose the location where to verify the designed stratigraphy in terms of hygrothermal performance. When a project is created on Delphin, one can choose whether to make a one-dimensional analysis referred to horizontal or vertical elements, two-dimensional and three-dimensional. After creating the reference model, choosing materials, characteristics and thicknesses of the various layers, it is possible to set the outputs and the internal and external boundary conditions; the program conventionally assumes the right side of the model as the internal side and the left side as the external side. When entering the boundary conditions, it is possible to refer to different standards and set the internal and external temperature, the values of internal and external relative humidity, the heat transfer coefficient, the vapor diffusion coefficient, the thermal conduction, the short-wave solar radiation, the long wave radiation exchange etc. Once established these conditions, the initial temperature and humidity can be set up, as well as the orientation of the model and the temporal arc that is wished to analyze.

On the base of the optimization analysis, it was decided to carry out the one-dimensional hygrothermal analysis of three stratigraphies for the vertical closure that differ in the type of external insulation applied to the rammed earth wall. In the study [62] we referred to three different climatic locations (classified by Köppen - Geiger as Csa, Catania, BWh - Helwan and Dfb - Quebec), analyzing for each of them the hottest and coldest week of the year. For the sake of brevity, here we will report only the results related to the Mediterranean climate, for the city of Catania.

In this final validation, we wanted to verify the influence of synthetic material-based insulations or natural-based ones in combination with the rammed earth wall. The analyzed stratigraphies are:

- an uninsulated rammed earth wall, with interior earth render and exterior lime plaster (U=0.98 W/m^2K);
- an externally insulated rammed earth wall, using EPS panel, with interior earth render and exterior lime plaster (U=0.43 W/m^2K);
- an externally insulated rammed earth wall, using a thermocork panel, with interior earth render and exterior lime plaster (U=0.43 W/m^2K).

These stratigraphies were chosen between the best performing ones in the optimization analysis.

Table 19 – Materials used in the hygrothermal analysis of the stratigraphies

MATERIAL	Delphin ID	Density $\rho\ \left[\frac{kg}{m^3}\right]$	Specific Heat Capacity cp $\left[\frac{J}{kg\ K}\right]$	Thermal Conductivity $\lambda\ \left[\frac{W}{m\ K}\right]$	Water vapor resistance factor μ [−]	W_{80} $\left[\frac{kg}{m^3}\right]$	W_{sat} $\left[\frac{kg}{m^3}\right]$	Water absorption coefficient $A_w\left[\frac{kg}{m^2 s^{0.5}}\right]$	Porosity $\left[\frac{m^3}{m^3}\right]$
Earth Render	128	1567	488.4	0.582	11.4	38.6	405	0.176	0.41
Lime Plaster	150	1520	850	0.8	51	57.9	380	0.071	0.43
EPS	188	40.0	1500.0	0.030	150	1.1	950.0	0	0.95
Cork	515	114	2253.2	0.047	28.9	9.8	93.3	0.009	0.95
Rammed Earth wall	-	1930	1000	0.508	13	20	150	1.10	0.15

Rammed earth moisture-dependent thermal conductivity values were taken from the material investigation (subsection 4.1.4). Missing values as water vapor resistance factor, water absorption coefficient and porosity were taken both from similar raw earth-based material in Delphin database and from literature values [63, 64].
Then, it was created a new material in Delphin database, characterized as soil, and for this material it was allowed the thermal transfer and vapor transport (based on values in table 20), which are necessary to define the variation law for some of the desired analysis (thermal transfer, heat storage, moisture retention and vapor transport).
The dependence between relative humidity, equilibrium moisture content, volumetric humidity and thermal conductivity was found on the base of results obtained on the experimental campaign. As abovementioned, data were measured for RH% equal to 15%, 30% 50% and 70%; other values below RH 80% were then calculated on the base of the tendency of experimental results. Values above RH 80% were taken from [64]. Data are summarized in table 20. The dependencies between these properties are expressed in the figures 49 – 51.

Table 20 – Hygrothermal properties of the rammed earth material

Relative humidity φ [%]	Relative humidity φ [-]	Volumetric humidity θ_l	Moisture dependent thermal Conductivity [W/m K]	Vapor Permeability [s]
0	0	0.0029	0.5075	1.6 e-11
10	0.1	0.00369	0.5075	-
20	0.2	0.00470	0.5225	-
30	0.3	0.00615	0.5402	-
40	0.4	0.00760	0.5525	-
50	0.5	0.00880	0.582	-
60	0.6	0.01231	0.5825	-
70	0.7	0.01611	0.588	-
80	0.8	0.01994	0.6125	-
90	0.9	0.085	0.6275	-
100	1	0.15	0.6425	0.15

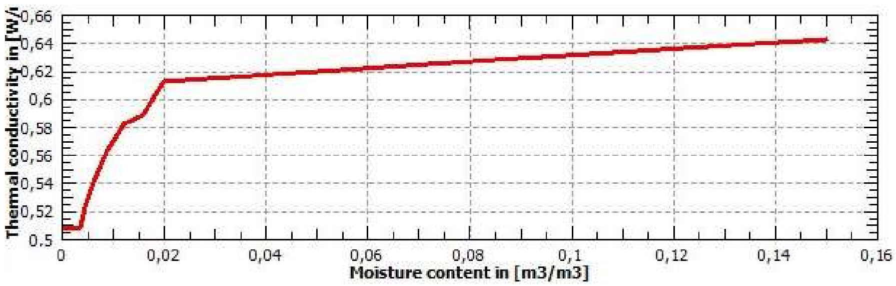


Figure 49 – Moisture dependant thermal transfer

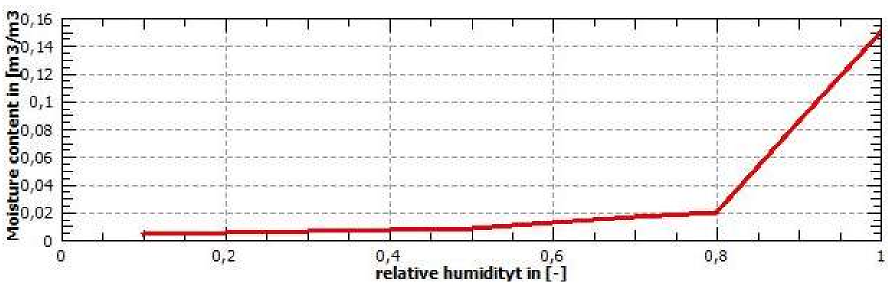


Figure 50– Moisture storage with absorption isotherm

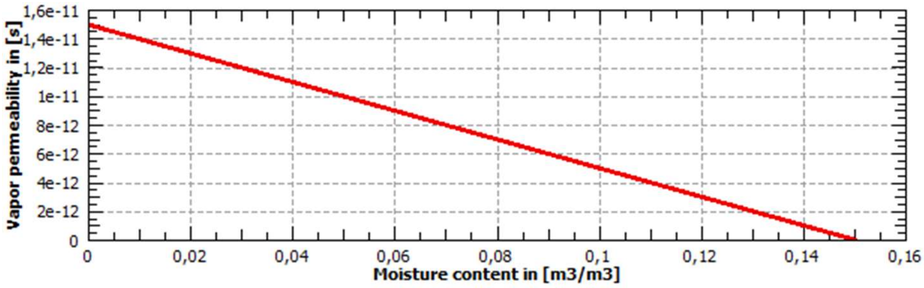


Figure 51– Vapor transport

The software provides basic outputs for the simulation, which are applied to the whole section, except for those with distinction between left (external) and right (internal) side, as in the case of surface temperature, relative humidity and heat flux; in these cases it is necessary to assign the output to the leftmost stratigraphy, for the external side, and the rightmost one, for the internal side.

The following outputs are thus defined: Temperature profile, Relative Humidity Profile, Humidity content profile, Surface temperature - left side (external), Surface temperature - right side (internal), Surface relative humidity - left side (external), Surface relative humidity - right side (inside), Total Flux Heat in W/m^2, Flux Vapor diffusion in kg/m^2s, Total Flux Moisture in kg/m^2s and Moisture Load in kg/m^3s.

In the software it is possible to set the boundary conditions for both inside and outside. For Indoor boundary conditions, we refer to DIN EN 15026 [65], setting the minimum and maximum temperature, minimum and maximum relative humidity, heat transfer coefficient and surface vapor diffusion coefficient, as follows:

Table 21 – Indoor boundary conditions

Name	Value
Max Temperature [°C]	26
Min Temperature [°C]	20
Max relative humidity [%]	65
Min relative humidity [%]	35
Surface heat transfer coefficient (convective+ radiative) $\left[\frac{W}{m^2K}\right]$	8
Surface vapor diffusion coefficient [s/m]	2,5e-08

For Outdoor boundary conditions, the values of thermal conduction, vapor diffusion, short-wave and long-wave solar radiation were set as follows, imposing the exposure orientation of the wall to the east (i.e., 90°, as per program convention):

Table 22 – Outdoor boundary conditions

Thermal conduction	Convective heat transfer coefficient $\left[\frac{W}{m^2K}\right]$	12
	Effective heat transfer coefficient $\left[\frac{W}{m^2K}\right]$	12
Vapor diffusion	Mass exchange coefficient by vapor diffusion [s/m]	7,5e-08
	Sd-value for painting / coating surface [m]	0
Short wave solar radiation	Absorption coefficient for short wave radiation [-]	0,7
Long wave radiation exchange	Long wave emissivity [-]	0,9

Before running the simulation, we set the balance equation dependent on material humidity and water content, with an initial temperature of 20 °C and relative humidity at 50%. Then it is imposed the period of simulation, that is given from the warmest and coldest week relative in Catania 2019 weather data, and particularly going from 10/08/2019 - 17/08/2019 for the warmest week and 02/01/2019 - 09/01/2019 for the coldest week.

Two initial graphs, representing the relative temperature and humidity of the coldest and warmest week will be reported. In addition, the following profiles will be analyzed, referring to the different building packages:

- Temperature distribution cross section of the wall;
- Comparison of the internal and external surface temperature;
- Comparison of the internal and external surface heat;
- Comparison of the water vapor diffusion mass flux and thermal conductivity;
- Relative Humidity distribution cross section of the wall;
- Comparison of the internal and external surface relative humidity;
- Total mass density of liquid water, water vapor and ice and thermal conductivity;
- Comparison of the total mass density of liquid water, water vapor and ice and thermal conductivity.

Below are the graphs related to the study of the different building packages referred to the hot week (10/08/19 - 17/08/19) and cold week (02/01/19 - 09/01/19). We examine first the uninsulated earth wall, then the one externally insulated with EPS and finally the one externally insulated with cork.

4.3.2.1 Hygrothermal behavior during summer period

During the hot week examined for the city of Catania, we attest a maximum outdoor temperature of 33 ° C and a minimum temperature of 20 ° C, the average temperature being 27.94 ° C. From the graph 52 we can see that the temperature range between day and night is quite regular throughout the week.
During the hot week the value of the minimum relative humidity is 25% while that of the maximum relative humidity is 79%, the average relative humidity is 54.14%. We have a minimum of relative humidity in day 16th, with 25%, while on days 10th and 14th, during the night hours (between 01.00 and 02.00) we attest to a greater amount of relative humidity, in order 79% and 77%.

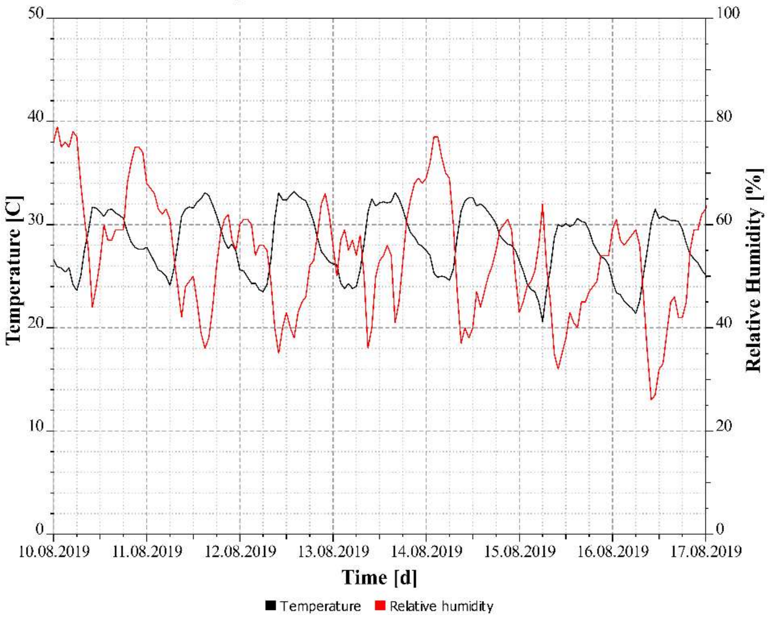


Figure 52 – Catania, comparison of outdoor temperature and relative humidity in the hot week (10/08/19 - 17/08/19)

In the following figures 53 – 60 are shown the graphs referred to the uninsulated rammed earth wall.

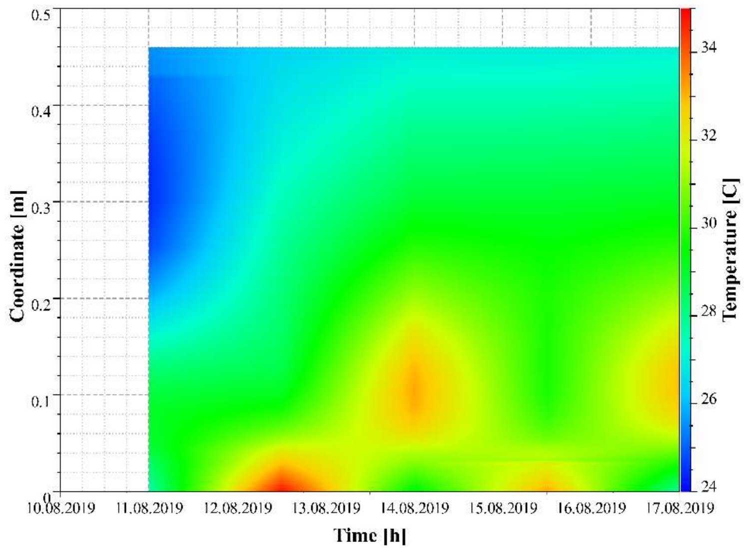


Figure 53 – Temperature distribution across the uninsulated RE wall, hot week (11/08/19 - 17/08/19)

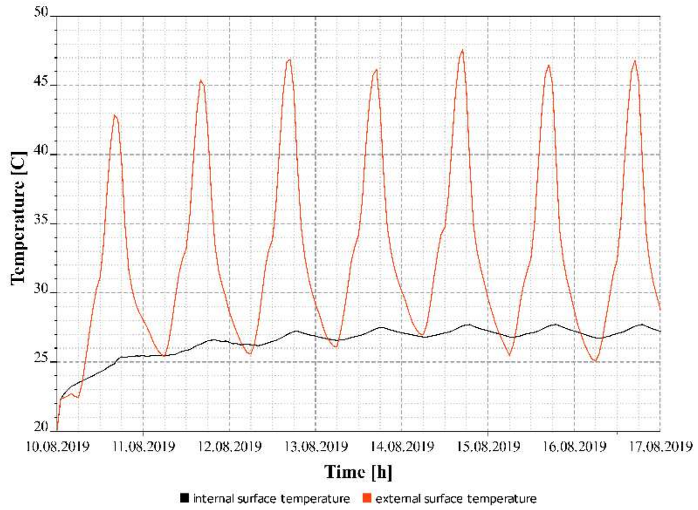


Figure 54 – Internal and external surface temperature in the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

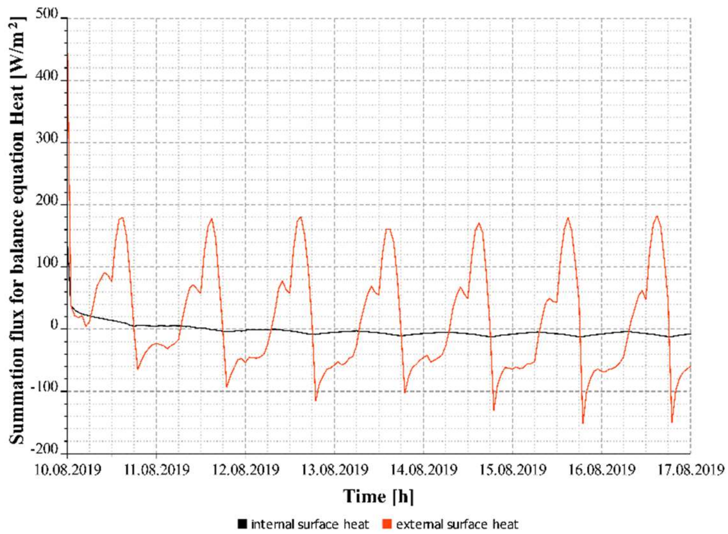


Figure 55 – Internal and external surface heat in the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

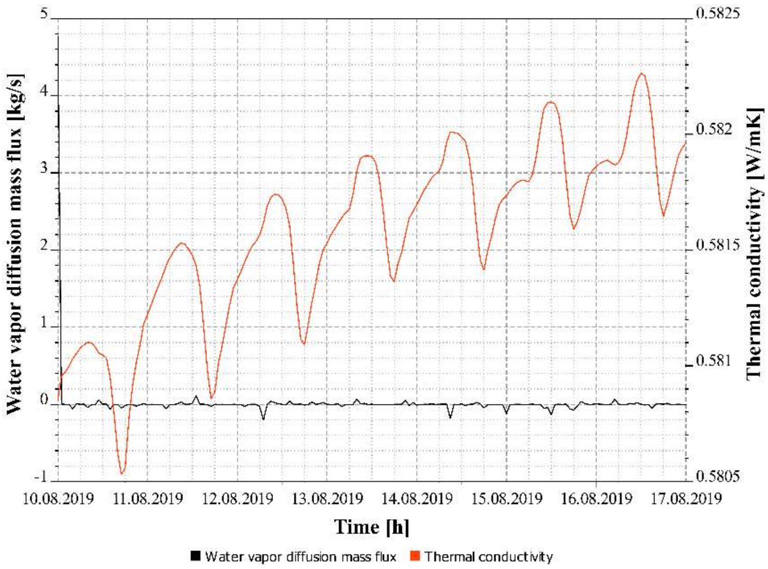


Figure 56 – Water vapor diffusion mass flux and thermal conductivity in the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

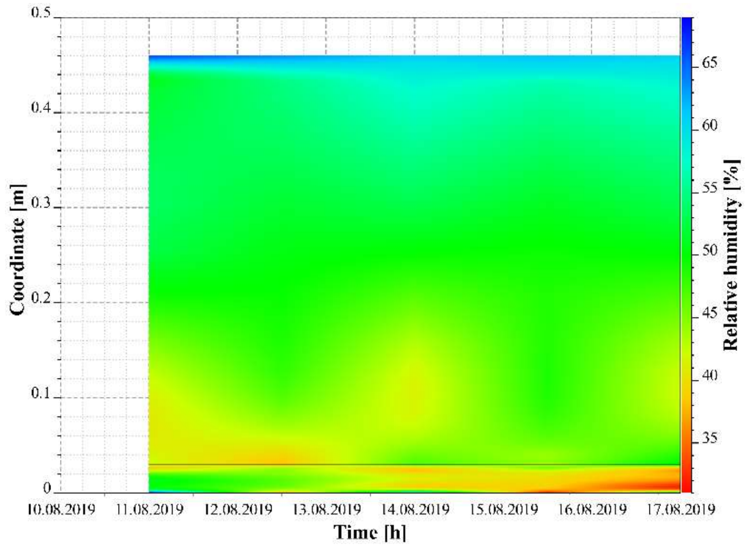


Figure 57 – Humidity distribution across the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

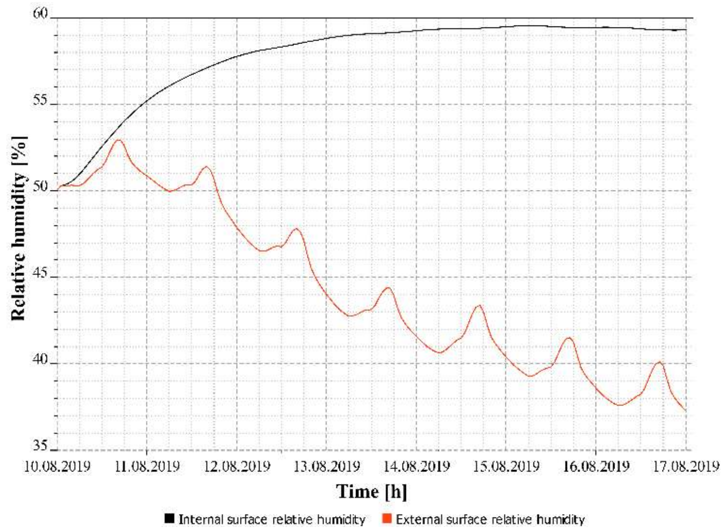


Figure 58 - Internal and external surface relative humidity in the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

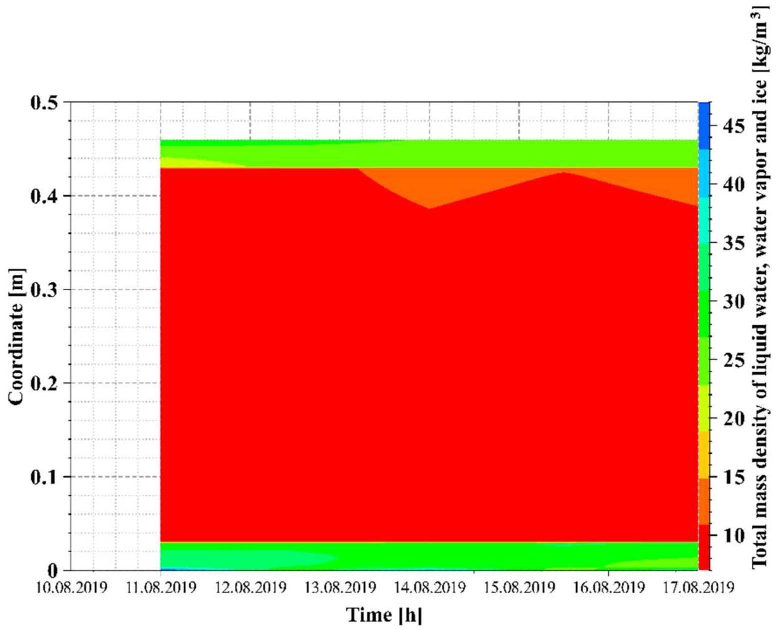


Figure 59 - Total mass density of liquid water, water vapor and ice in the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

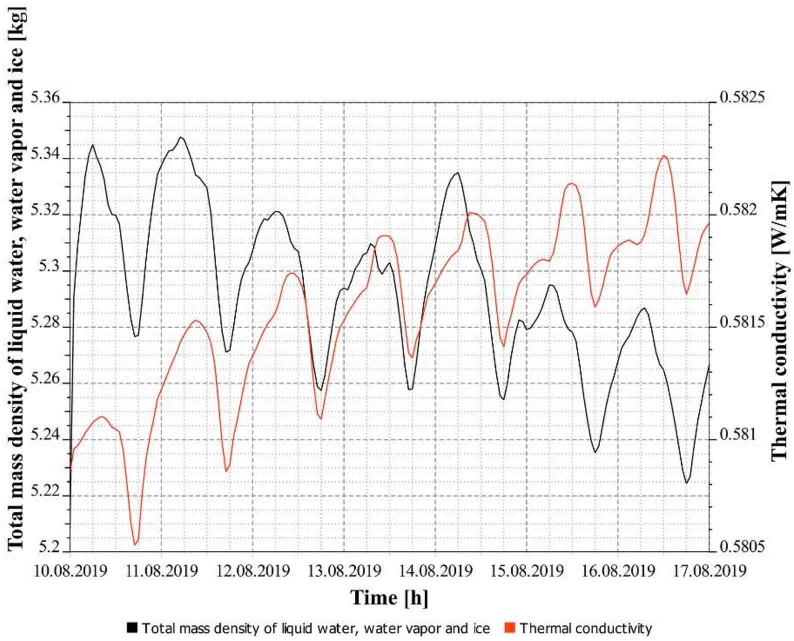


Figure 60 - Total mass density of liquid water, water vapor and ice vs thermal conductivity in the uninsulated RE wall, hot week (10/08/19 - 17/08/19)

From the analysis of the graphs related to the behavior of the uninsulated rammed earth wall in the hottest week, 10/08/2019 - 17/08/2019, we can make the following considerations.

Figure 53 shows the temperature distribution through the wall section. It is analyzed the behavior of the different stratigraphies, arranged horizontally, from the bottom to the top, in the order: lime render, earth wall and earth plaster, in relation to the reference week. While the internal plaster manages to maintain a constant temperature, between 26 °C and 28 °C, the external plaster is more subject to temperature variations, presenting peaks with higher temperatures on days 12^{th} and 15^{th}; the earthen wall presents a temperature variation from the inside, 28 °C, to the outside 32 °C, demonstrating its thermoregulating capabilities.

From fig. 54 where it is shown the comparison graph between the internal and external surface temperature, it can be pointed out a range of 25.62 – 27.72 °C for the former, while the latter moves in the range of 25.5 –

45 °C. The internal surface temperature has a range of variation of 2.09 °C; while the external surface temperature varies from 45 °C, around 15:00 h, to 25.5 °C around 06:00 h, with a range of variation of 19.5 °C. From the 3d graph of the relative humidity content through the section (fig. 57), we observe that the internal plaster maintains a relative humidity around 60%, while the rammed earth wall shows a slight variation from the inside, where it maintains values around 55%, towards the outside, reaching a 43%; finally, the external render has a lower average relative humidity around 36%.

From the comparison graph between the internal and external surface relative humidity (fig. 58), we can see that the former varies from 56 % to 59.54 %, with an average value of 57.77 %, while the latter has an average value of 45% and varies from 37 % to 53 %, with a range of variation of 16 %.

From the 3d graph of the distribution of liquid water, vapor and ice inside the wall (fig. 59), we observe that the external lime render presents a water content between 25 and 30 kg/m^3, the internal plaster between 22 and 26 kg/m^3, therefore it results to be slightly drier; finally, the earthen wall undergoes a variation of the average water content from the inside, 14 kg/m^3, towards the outside 10 kg/m^3.

From the graph that relates the content of liquid water, vapor and ice with the thermal conductivity (fig. 60), we can say that the average value is 5.278 kg, while the average value of thermal conductivity is 0.581 W /m K, higher than the design values (0.508 W/m K). The value, during the week, varies from 5.348 to 5.208 kg, with a variation of 0.139 kg; while the thermal conductivity values vary from 0.58225 to 0.5805 W/m K, with a variation of 0.00175 W/m K.

In the following figures 61 – 68 are shown the graphs referred to the EPS - insulated rammed earth wall.

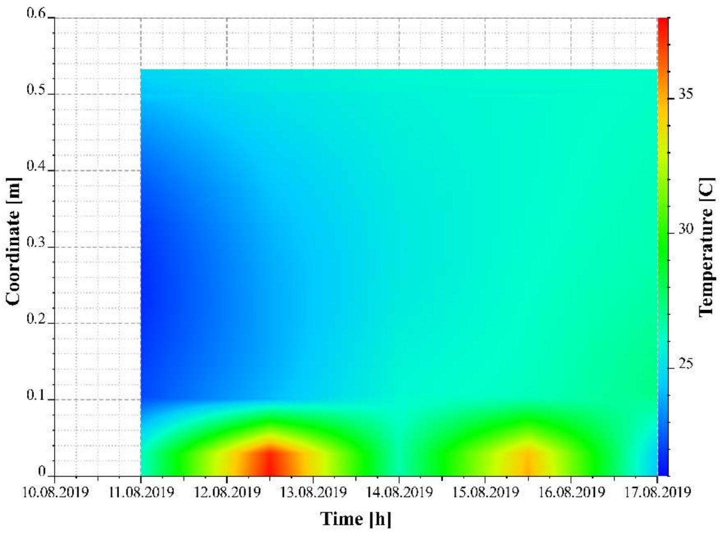


Figure 61 – Temperature distribution across the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

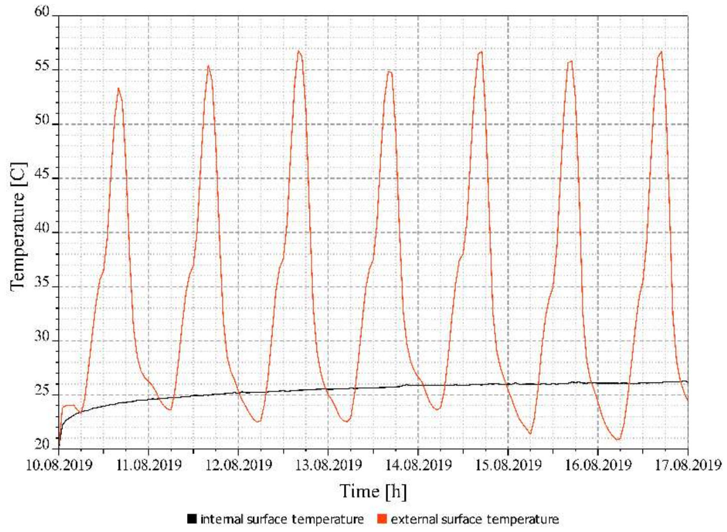


Figure 62 – Internal and external surface temperature in the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

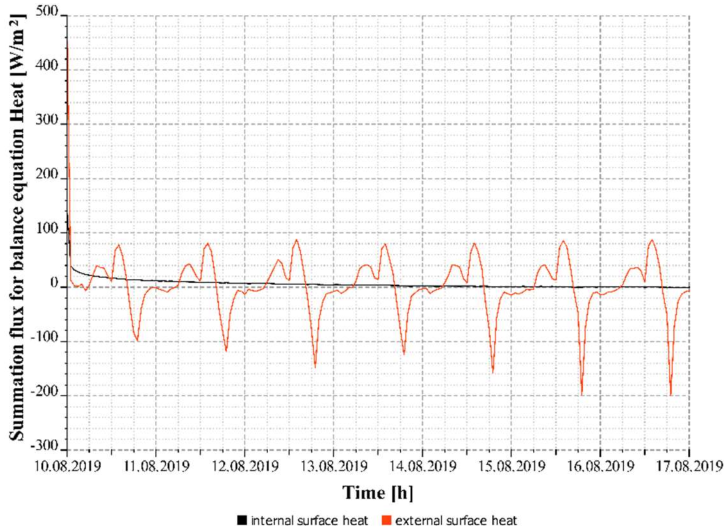


Figure 63 – Internal and external surface heat in the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

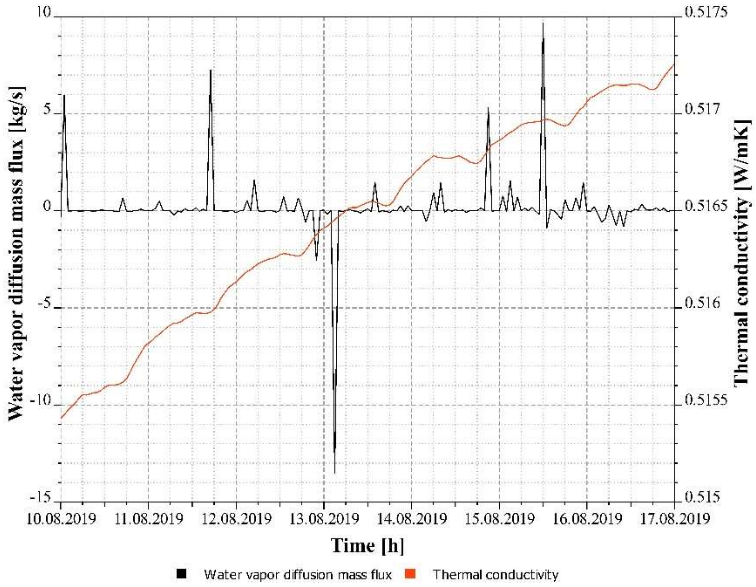


Figure 64 – Water vapor diffusion mass flux and thermal conductivity in the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

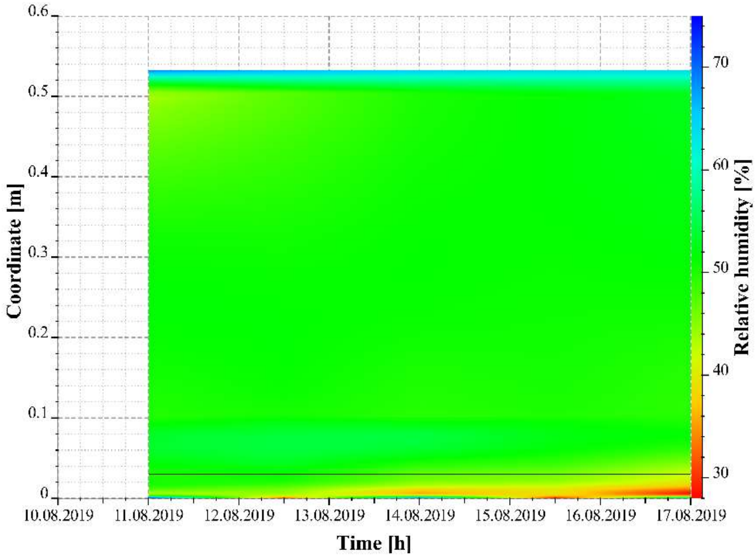


Figure 65 – Humidity distribution across the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

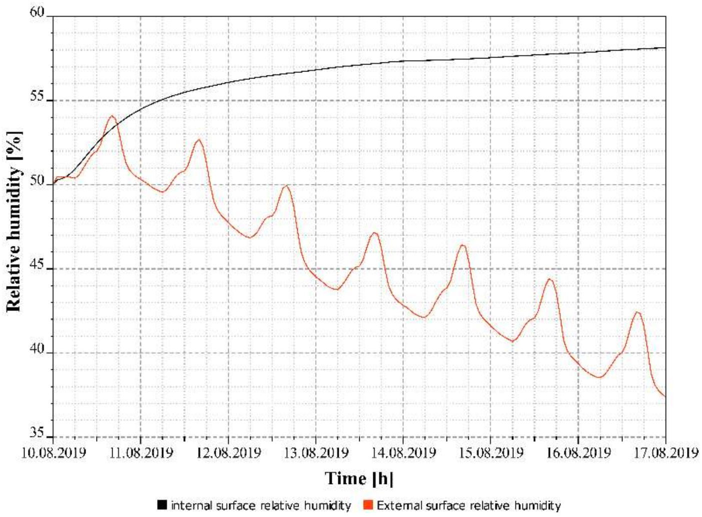


Figure 66 - Internal and external surface relative humidity in the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

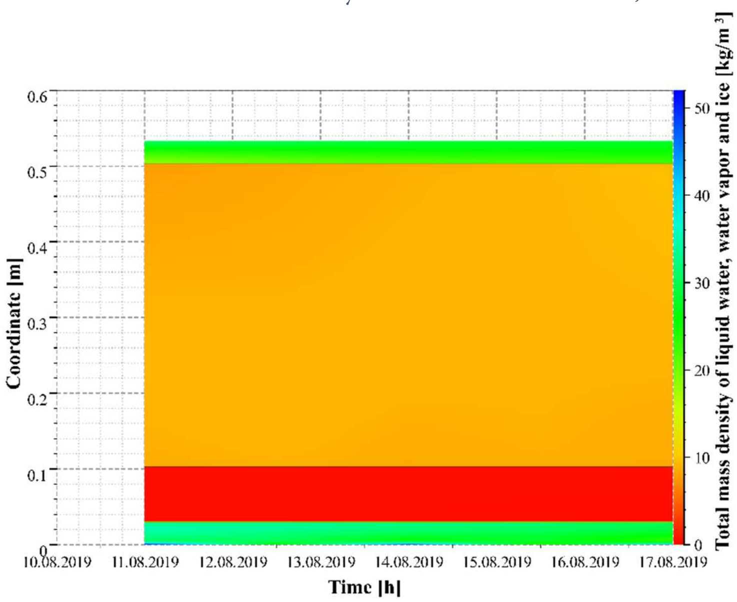


Figure 67 - Total mass density of liquid water, water vapor and ice in the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

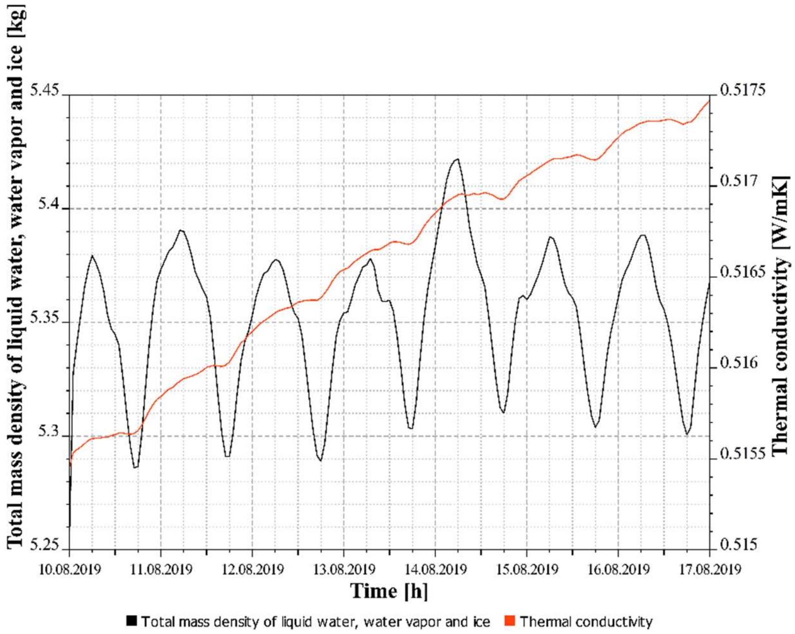


Figure 68 - Total mass density of liquid water, water vapor, ice vs thermal conductivity in the EPS insulated RE wall, hot week (10/08/19 - 17/08/19)

From the analysis of the graphs related to the behavior of the EPS insulated earth in the hottest week, 10/08/2019 - 17/08/2019, we can make the following considerations.

From the 3d graph of the temperature distribution through the section of the wall (fig. 61), we can analyze the behavior of the different stratigraphies, arranged horizontally, from the bottom to the top, in order: lime render, EPS insulation, earth wall and earth plaster, in relation to the reference week. While the interior plaster manages to maintain a constant temperature, between 25 ° C and 26 ° C, the exterior render is more subject to temperature variations, presenting peaks with higher temperatures, on days 12th and 15th, which also affect the layer of insulation, with temperatures ranging from 27 to 38 °C. The earth wall presents an almost constant temperature, between 24 and 27 °C, for all the week.

From the comparison graph between the internal and external surface temperature (fig. 62), we can say that the former has an average value of 25.66 °C, while the latter has an average value of 38 °C. The internal surface temperature varies from 25 °C to 26.32 °C, with a range of variation of 1.32 °C; while the external surface temperature varies from 56 °C to 20 °C, with a range of variation of 36 °C.

From the 3d graph of the relative humidity content through the section (fig. 63), we can analyze the behavior of the various stratigraphies. We can say that internal stratigraphies, which are the earth wall and plaster, maintain a relative humidity value between 50 and 62 %, while the external plaster layer is in the range of 31 – 45 %; finally, the layer with the insulation is at 42 – 52 RH%.

From the comparison graph between the internal and external surface relative humidity (fig. 64), we can see that the former has an almost constant trend, with an average value of 56.57 %, while the latter, with a less constant trend, has an average value of 31 %. The internal surface relative humidity varies from 55 % to 58.14 %, with a range of variation of 1.2 %; while the external surface relative humidity varies from 37.5 % to 54 %, with a range of variation of 16.5 %.

From the 3d graph of the distribution of liquid water, vapor and ice inside the wall (fig. 67), we can analyze the behavior of the different stratigraphies. In particular, it is worth nothing that the external lime render presents a value between 26 and 36 kg/m^3, the internal plaster instead of 24 - 28 kg/m^3; the earthen wall presents an average distribution of liquid water, vapor and ice value of 8 kg/m^3, while the stratigraphy corresponding to the insulation layer is dry.

From the graph that relates the content of liquid water, vapor and ice with the thermal conductivity (fig. 68), we can say that the first has an average value of 5.338 kg, while the average value of thermal conductivity is 0.516 W/m K. The liquid water content, during the week, varies from 5.255 to 5.422 kg, with a variation of 0.167 kg; while the value of the thermal conductivity varies minimally from 0.515 to 0.518 W/m K, with a range of variation of 0.003 W/m K.

In the following figures 69 – 76 are shown the graphs referred to the cork insulated rammed earth wall.

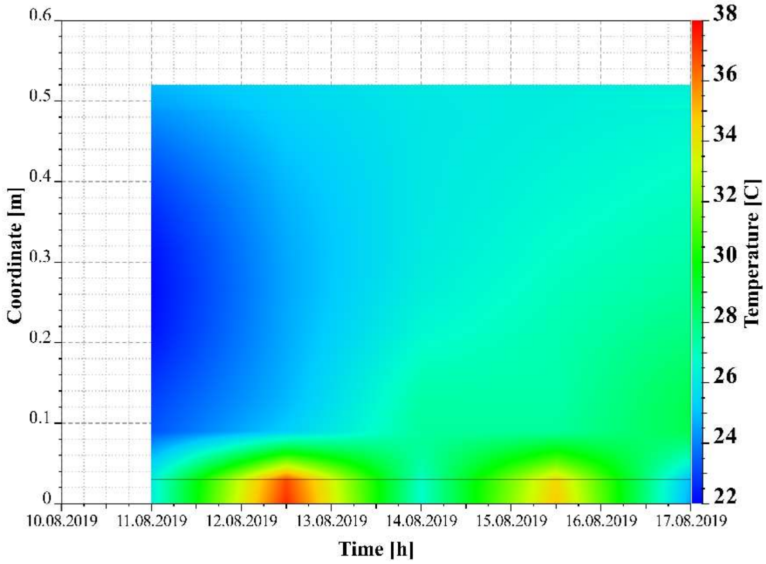


Figure 69 – Temperature distribution across the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

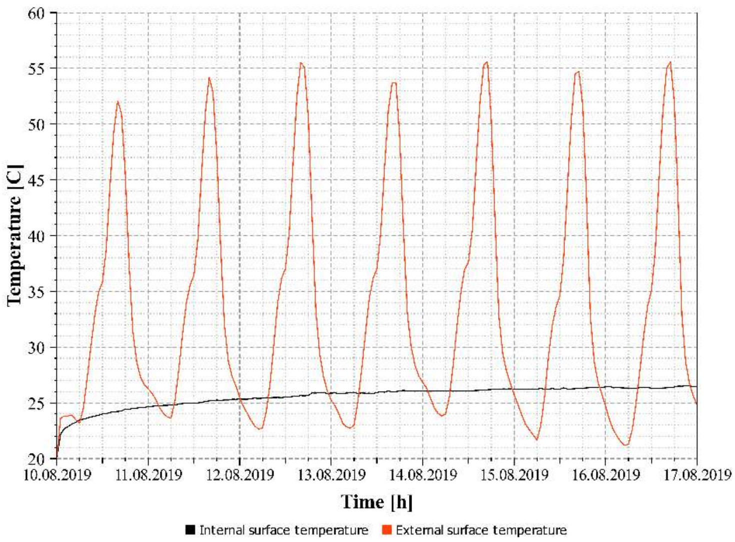


Figure 70 –Internal and external surface temperature in the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

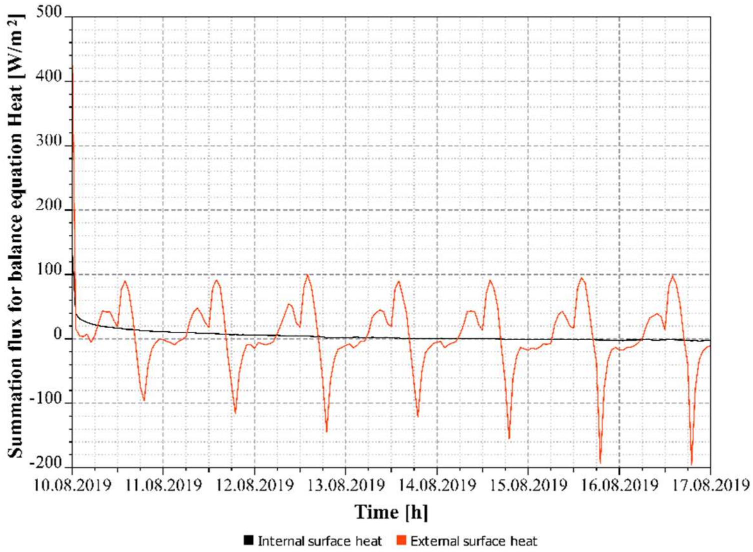


Figure 71 – Internal and external surface heat in the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

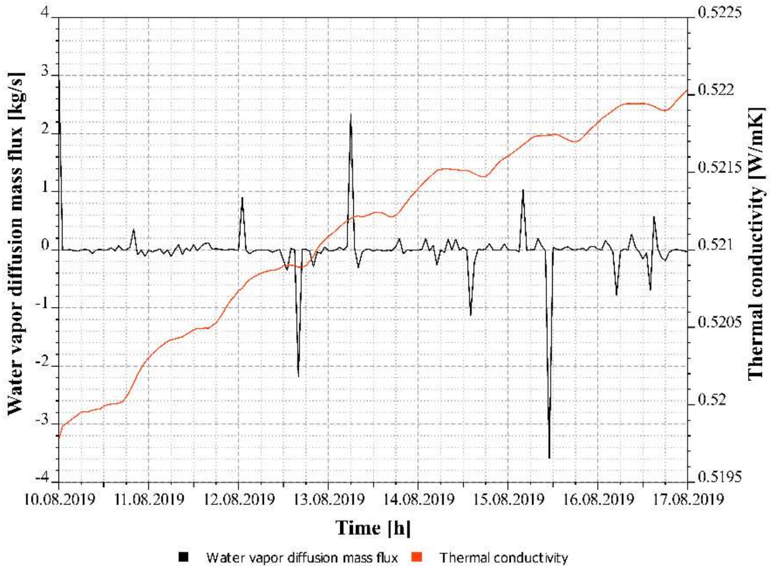


Figure 72 – Water vapor diffusion mass flux and thermal conductivity in the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

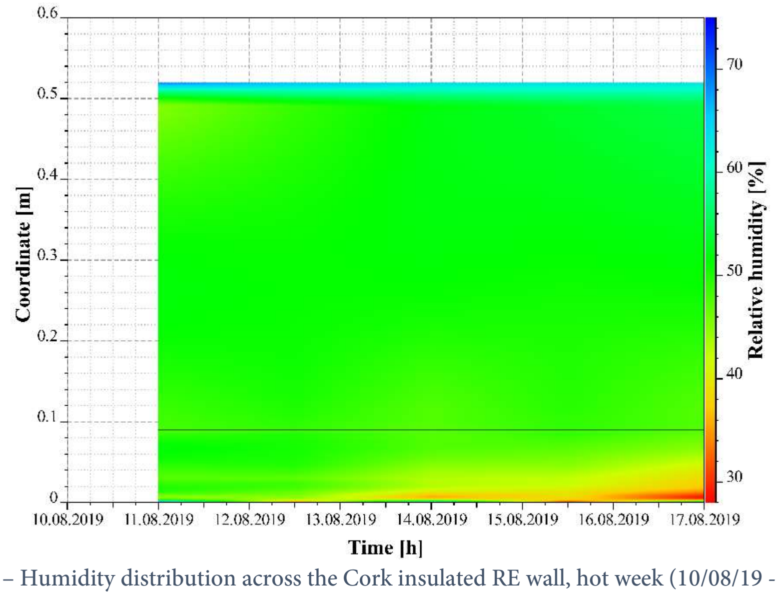


Figure 73 – Humidity distribution across the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

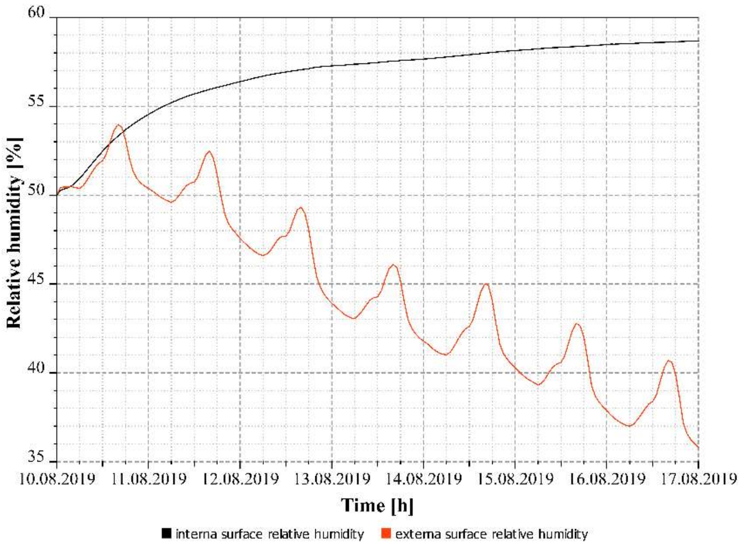


Figure 74 - Internal and external surface relative humidity in the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

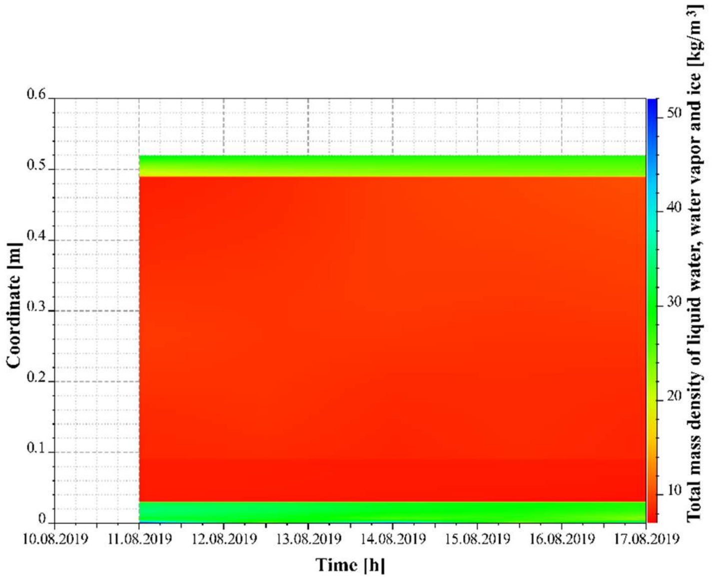


Figure 75 - Total mass density of liquid water, water vapor and ice in the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

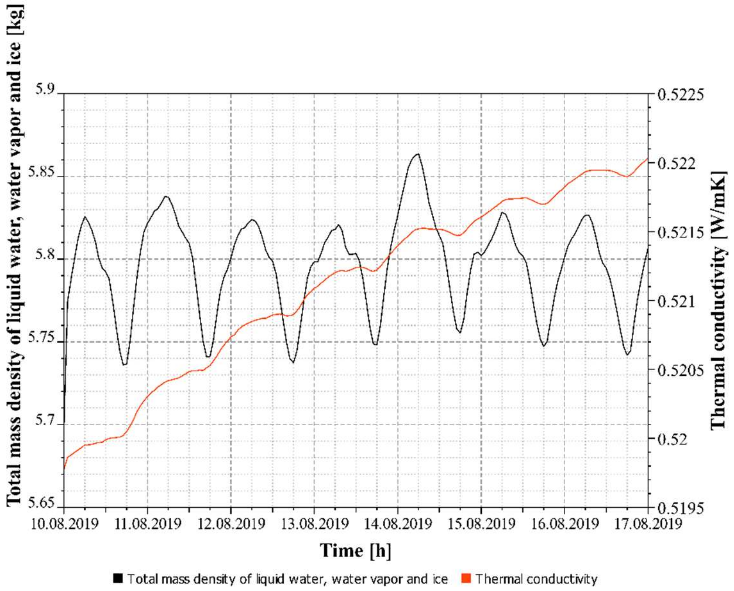


Figure 76 - Total mass density of liquid water, water vapor and ice vs. thermal conductivity in the Cork insulated RE wall, hot week (10/08/19 - 17/08/19)

From the analysis of the graphs related to the behavior of the cork insulated rammed earth wall in the hottest week, 10/08/2019 - 17/08/2019, we can make the following considerations.
From the 3d graph of the temperature distribution through the wall section (fig. 69), we can analyze the behavior of the different stratigraphies, arranged horizontally, from the bottom to the top, in order: lime render, cork insulation, earth wall and earth plaster, in relation to the week of reference. While the internal plaster manages to maintain a constant temperature, between 25,57 °C and 26,70 °C, the external plaster is more subject to temperature variations, presenting peaks with higher temperatures, in the days 12th and 15th, which also affect the insulation layer, with temperatures ranging from 28 to 37 °C. The earth wall presents a temperature range between 24 and 28 °C.
From the comparison graph between the internal and external surface temperature (fig. 70), we can say that the former has a constant trend and an average value of 25.84 ° C, while the latter has an average value of 38.25 ° C, being the external surface temperature variations comprised in the range from 21.2 °C to 55.5 °C, with a range of variation of 34.3 °C.
From the 3d graph of relative humidity content through the section (fig. 73) we can affirm that the internal plaster has a relative humidity ranging from 50 to 63%, while the earth wall has an almost constant value around 50%; the insulation experiences a variation from the inside towards the outside, respectively from 50 % to 36 %. The external render has a relative humidity range from 32 to 50 %.
From the comparison graph between the internal and external surface relative humidity (fig. 74), we can see that the former has an almost constant trend, with an average value of 57 %, while the latter, with a less constant trend, has an average value of 44.75 % and relative humidity varying from 35.5 % to 54 %, with a range of variation of 18.5 %.
From the 3d graph of the distribution of liquid water, vapor and ice inside the wall (fig. 75), we can affirm that the external lime render values are around 30 kg/m^3, the internal plaster ones are between 22 and 30 kg/m^3; the earthen wall presents an average liquid water, vapor and ice value of about 8 kg/m^3, homogeneous to the adjacent insulation which is dry.
From the graph that relates the content of liquid water, vapor and ice with the thermal conductivity (fig. 76), we can say that the first is on average equal to 5.782 kg, while the average value of thermal conductivity is 0.521 W /m K. The liquid water, vapor and ice content, during the week, varies from 5.700 to 5.864 kg, with a range of variation of 0.125 kg; while the value of the thermal conductivity varies minimally from 0.5197 to 0.522 W/m K, is almost constant, with a range of variation of 0.0023 W/m K.

4.3.2.2 Hygrothermal behavior during winter period

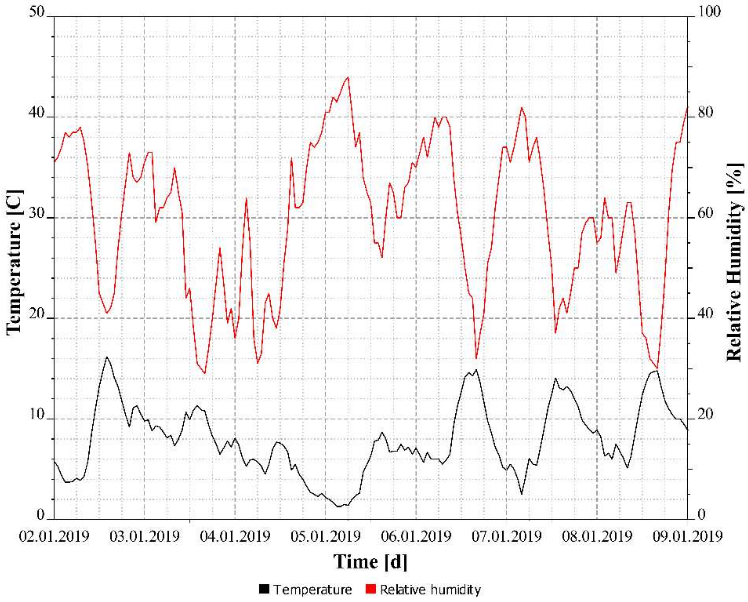


Figure 77 – Catania, comparison of outdoor temperature and relative humidity in the cold week (02/01/19 - 09/01/19)

During the cold week examined for the city of Catania, we attest a maximum outdoor temperature of 16 ° C and a minimum one of 1 ° C, the average temperature is 8.38 ° C. From the analysis of the graph, day 5 and 7 result to be those with lower temperatures. In the cold week the minimum relative humidity is 28% and the maximum relative humidity is 88%, the average relative humidity is 61.07%. There are minimum values of relative humidity on days 3rd, 6th and 8th (between 15.00 and 17.00), in order 28%, 31% and 29%, while there is a maximum value on day 5, with a relative humidity of 88%. From the comparison of the two graphs referring to the city of Catania, for the hot and cold week, we can say that the relative humidity is higher in winter, but we still have a humid summer.

In the following figures 78 – 85 are shown the graphs referred to the uninsulated rammed earth wall.

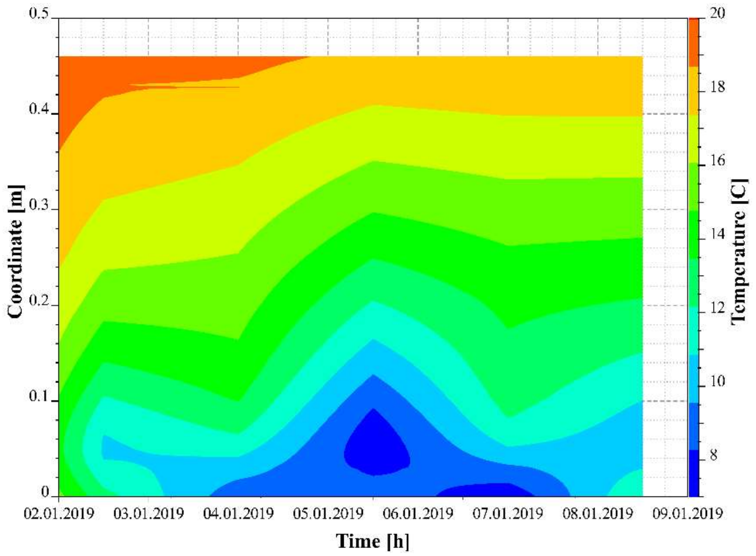


Figure 78 – Temperature distribution across the uninsulated RE wall, cold week (02/01/19 - 09/01/19)

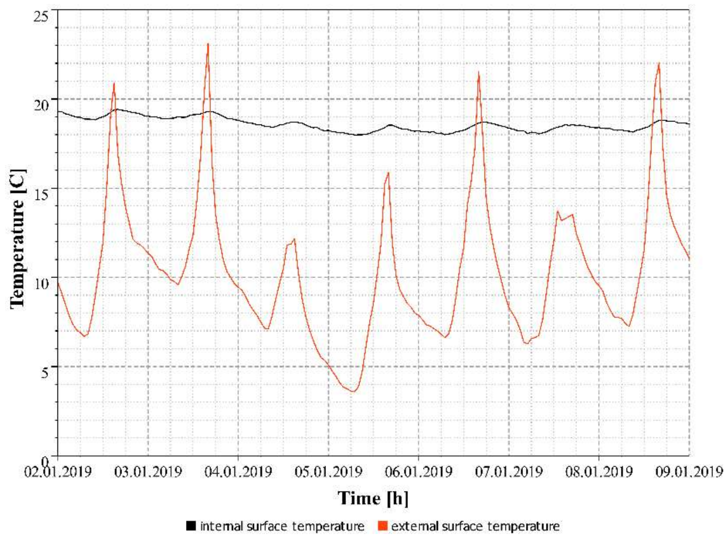


Figure 79 - Internal and external surface temperature in the uninsulated RE wall, cold week (02/01/19 - 09/01/19)

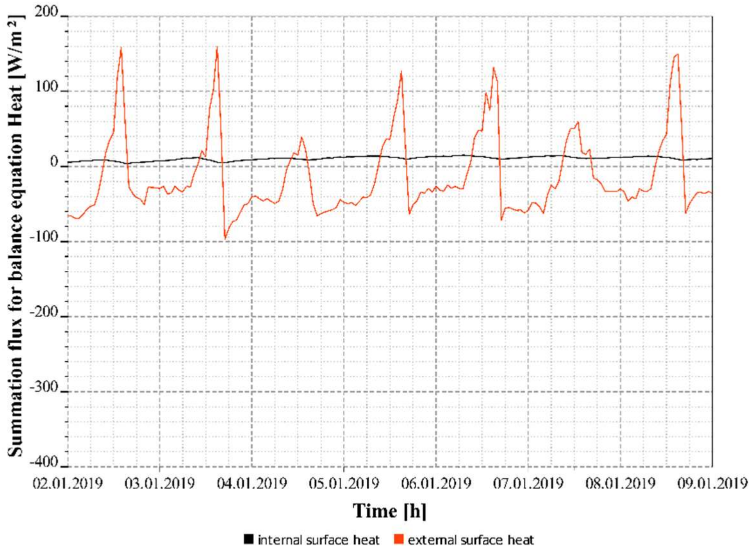


Figure 80– Internal and external surface heat in the uninsulated RE wall, cold week (02/01/19 – 09/01/19)

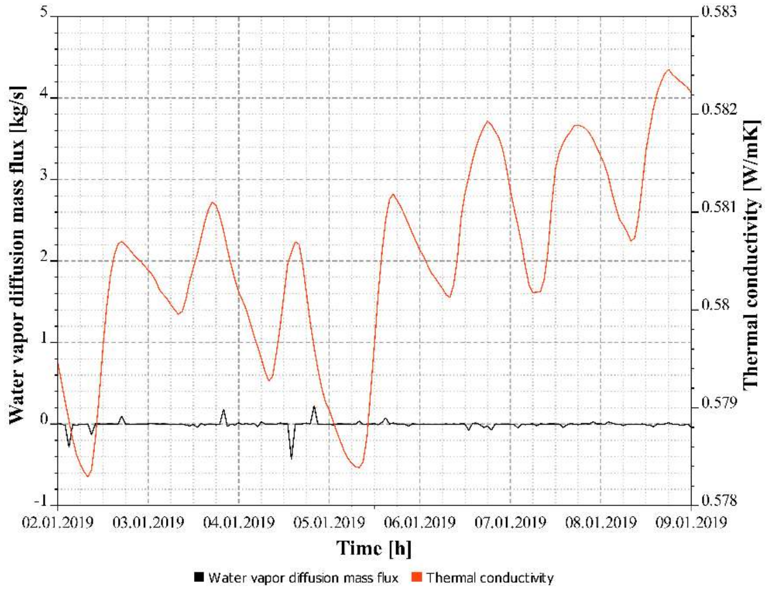


Figure 81 – Water vapor diffusion mass flux and thermal conductivity in the uninsulated RE wall, cold week (02/01/19 – 09/01/19)

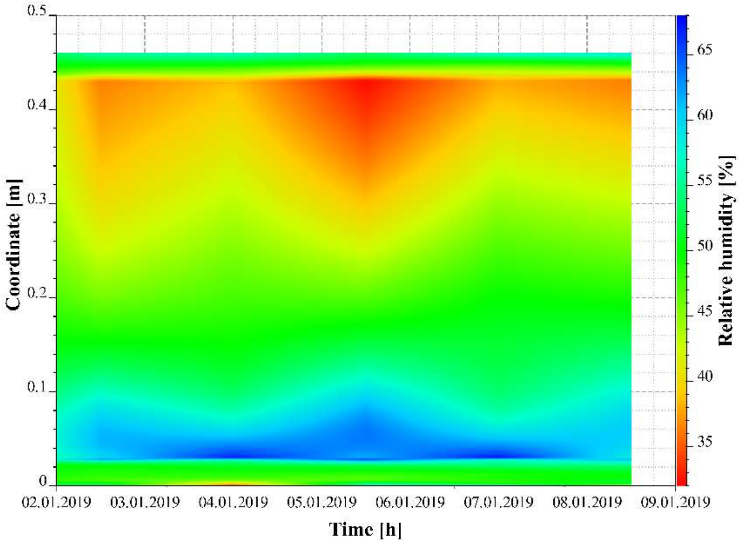


Figure 82 – Humidity distribution across the uninsulated RE wall, cold week (02/01/19 – 09/01/19)

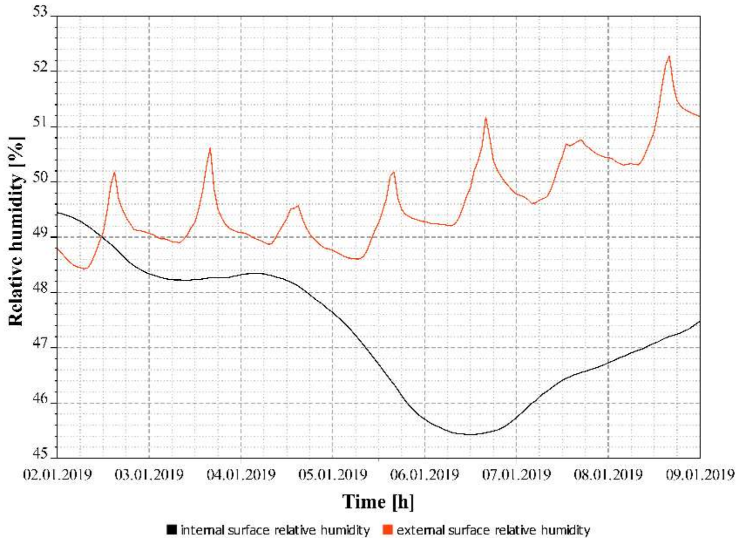


Figure 83 – Internal and external surface relative humidity in the uninsulated RE wall, cold week (02/01/19 – 09/01/19)

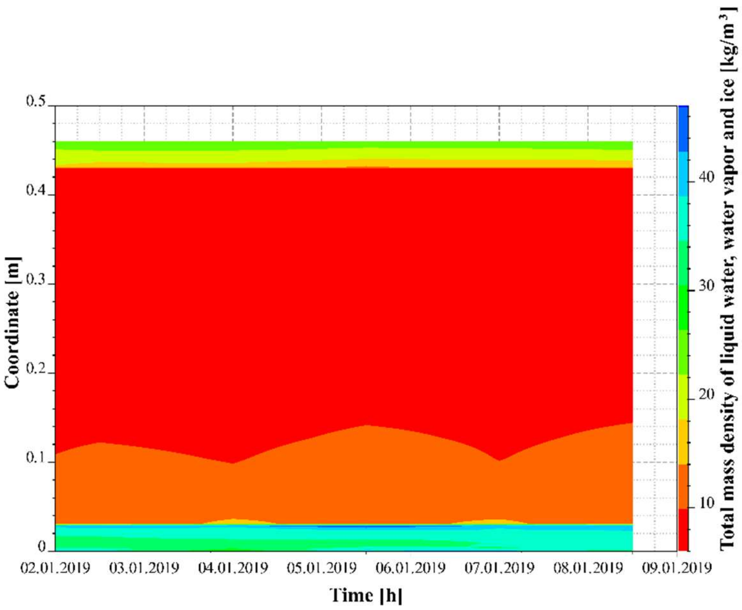


Figure 84- Total mass density of liquid water, water vapor and ice in the uninsulated RE wall, cold week (02/01/19 – 09/01/19)

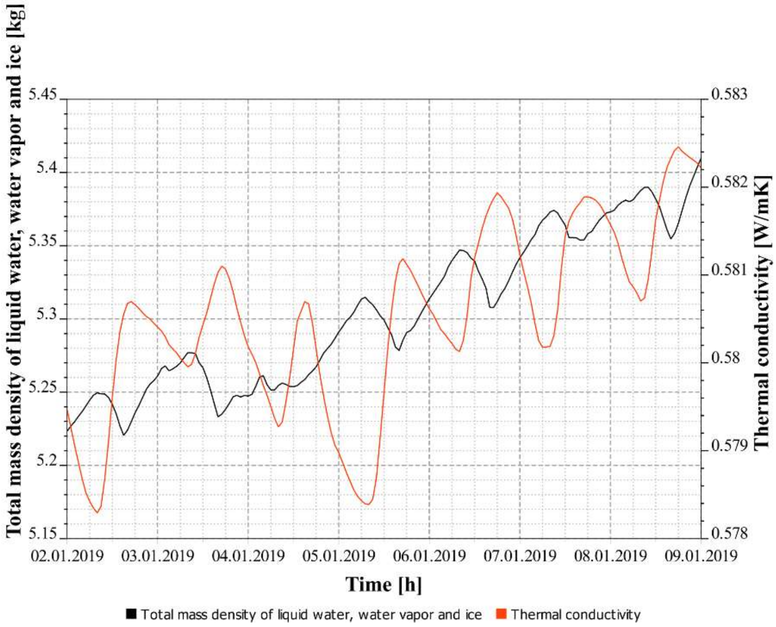


Figure 85 – Total mass density of liquid water, water vapor and ice vs thermal conductivity in the uninsulated RE wall, cold week (02/01/19 – 09/01/19)

From the analysis of the graphs related to the behavior of the uninsulated earth in the coldest week (02/01/2019 - 09/01/2019) we can make the following considerations.

From the 3d graph of the distribution of temperature through the section of the wall (fig. 78), we can analyze the behavior of the different stratigraphies, arranged horizontally, from the bottom to the top, in the order: lime render, earthen wall and earthen plaster, in relation to the week of reference. While the internal plaster maintains a temperature, between 18 °C and 20 °C, the external render temperature variations, presenting lower peaks temperatures, from day 4th to day 7th, with temperatures ranging from 7 to 12 °C, while in the other days the temperature reaches 15 °C. The earth wall presents a temperature variation from the inside, 17 °C, to the outside 9 °C, which is more pronounced from day 4th to day 7th.

From the comparison graph between the internal and external surface temperature (fig. 79), we can state that the former has an average value of 18.70 °C, while the latter has an average value of 13.25 °C, the coldest days being days 5th and 6th. The internal surface temperature varies from 17.98 °C to 19.42 °C, with a range of variation of 1.44 °C; while the external surface temperature varies from 3.5 °C to 23 °C, with a variation of 19.5 °C.

From the 3d graph of relative humidity percentage through the section (fig. 82), we can say that the internal plaster and the external render maintain a relative humidity value between 45 and 55%, with a slight increase on the outermost layer on day 4th, until 35 %. The earthen wall has average relative humidity between 34 % (in the interior part) and 65 % (on the exterior part).

From the comparison graph between the internal and external surface relative humidity (fig. 83), we can see that the former has an average value of 47.44 %, while the latter has an average value of 50.35 %. The internal surface relative humidity varies from 45.43 % to 49.44 %, with a range of variation of 4.02 %; while the external surface relative humidity varies from 48.4 % to 52.3 %, with a range of variation of 3.9 %.

From the 3d graph of the distribution of liquid water, vapor and ice inside the wall (fig. 84), we can affirm that the external lime render presents values between 30 and 40 kg/m^3, the internal plaster values are between 16 and 22 kg/m^3, therefore it results to be drier; finally the earthen wall maintains values inside the range of 8 kg/m^3 (in the interior part of the wall) and 16 kg/m^3 (in the exterior part of the wall).

From the graph that relates the content of liquid water, vapor and ice with the thermal conductivity (fig. 85), we can say that the average value for the first is 5.315 kg, while the average value of thermal conductivity is 0.58 W / m K. The liquid water, vapor and ice content, during the week, is between 5.221 and 5.410 kg, with a range of variation of 0.189 kg; while the value of the thermal conductivity has an increasing trend, from 0.5782 to 0.5821 with a variation of 0.0039 W/mK.

In the following figures 86 – 93 are shown the graphs referred to the EPS insulated rammed earth wall.

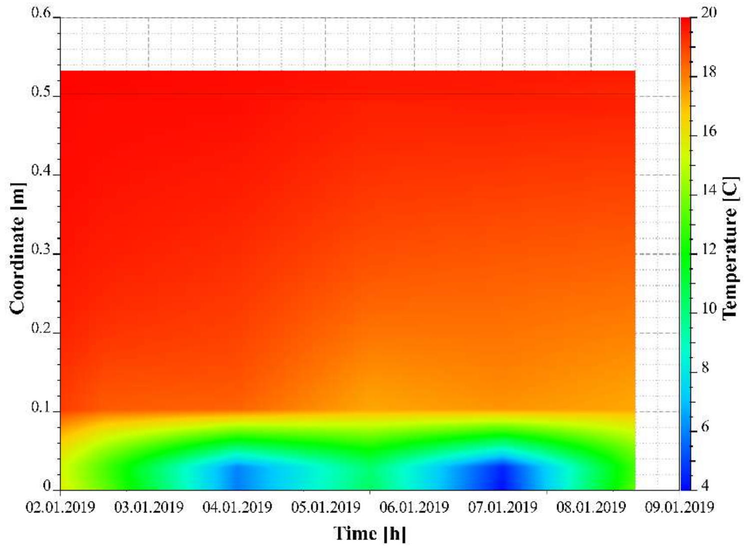


Figure 86 – Temperature distribution across the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

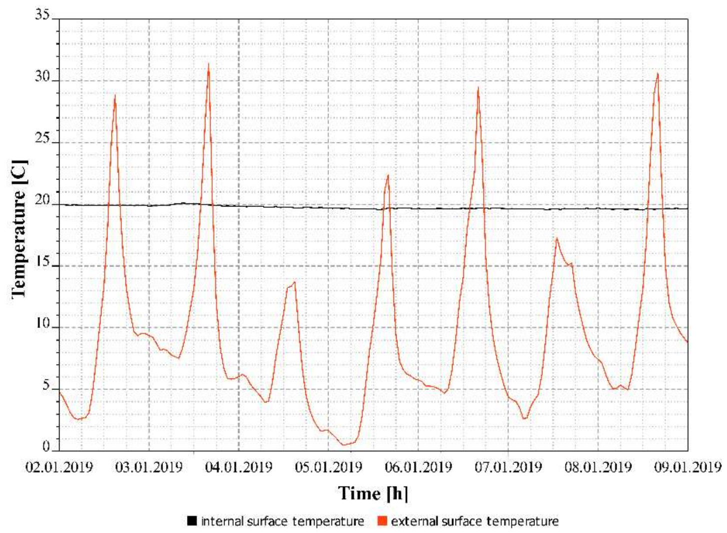


Figure 87 - Internal and external surface temperature in the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

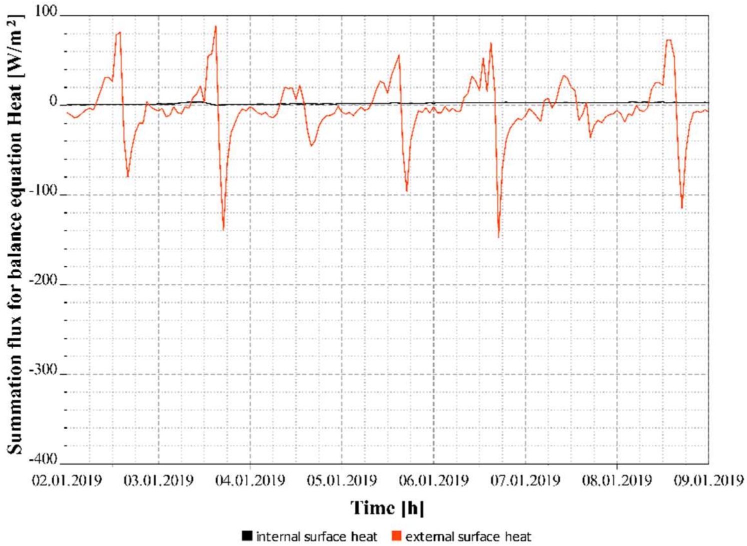


Figure 88 – Internal and external surface heat in the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

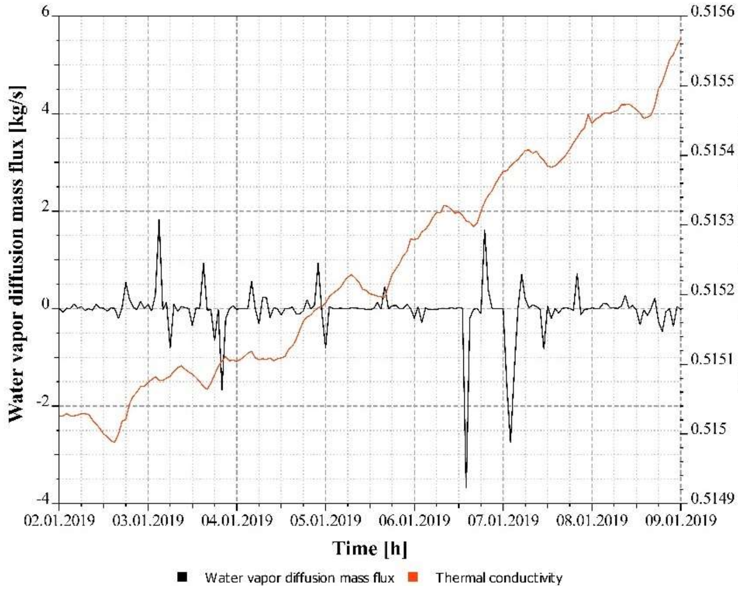


Figure 89 – Water vapor diffusion mass flux and thermal conductivity in the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

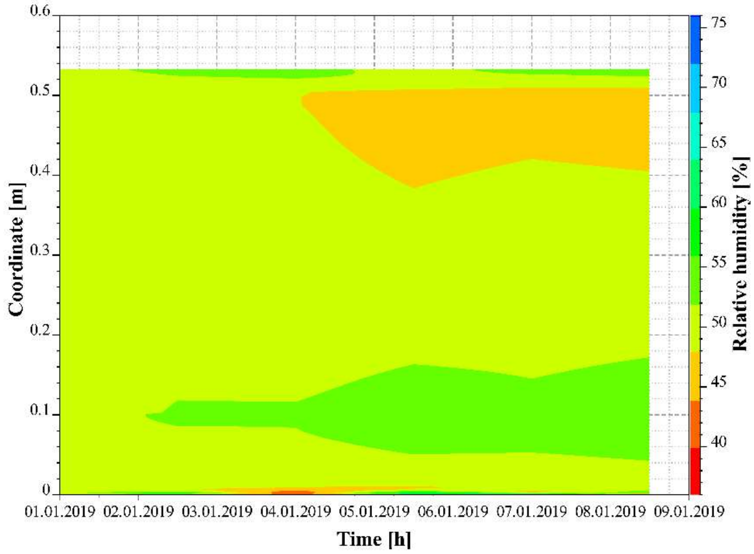


Figure 90 – Humidity distribution across the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

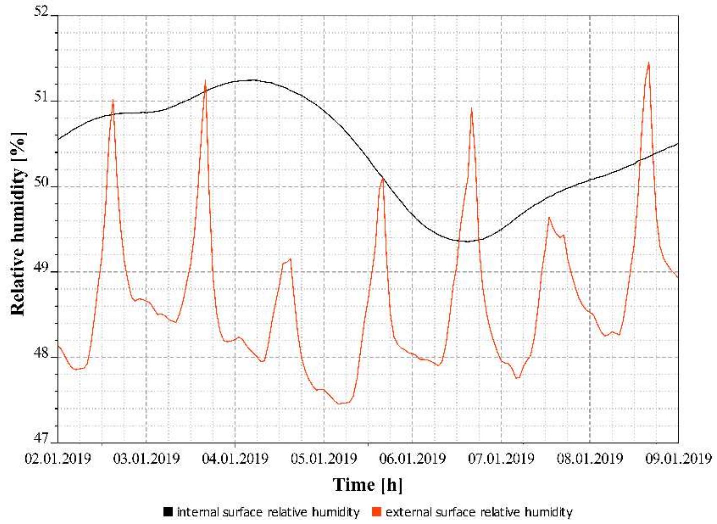


Figure 91 - Internal and external surface relative humidity in the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

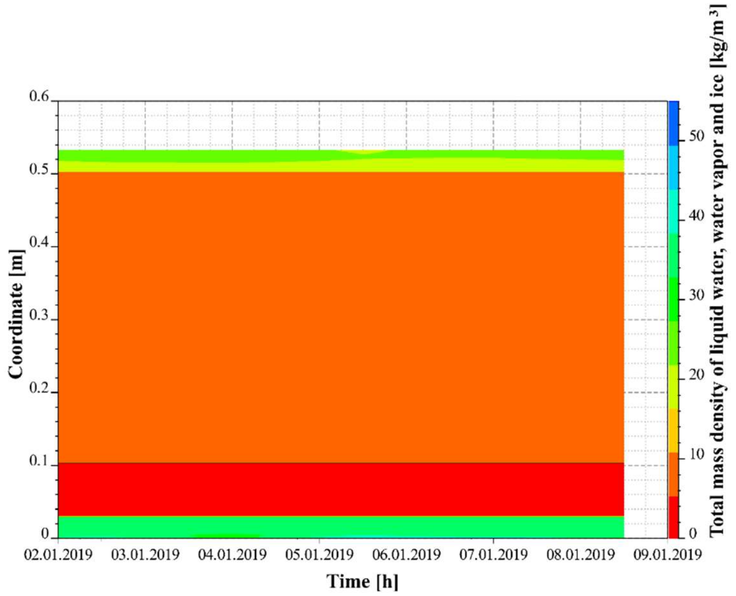


Figure 92 - Total mass density of liquid water, water vapor and ice in the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

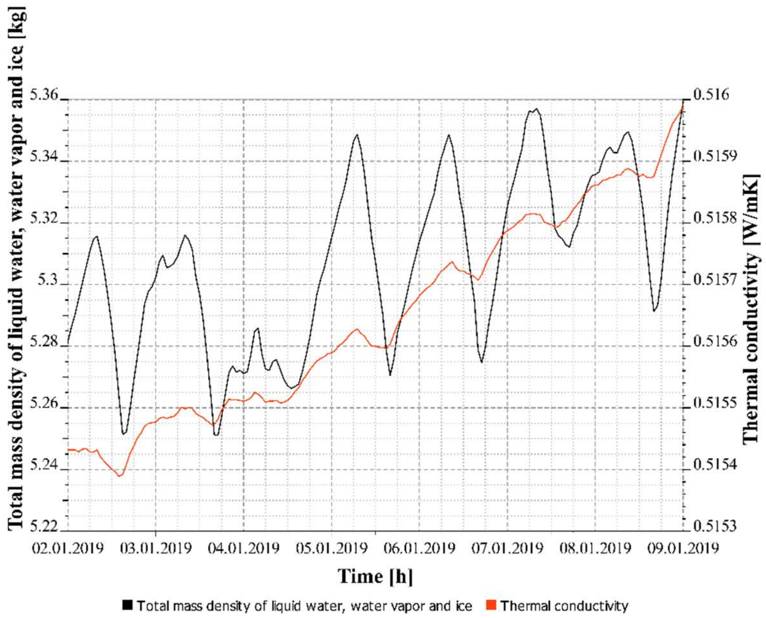


Figure 93 - Total mass density of liquid water, water vapor and ice vs thermal conductivity in the EPS insulated RE wall, cold week (02/01/19 - 09/01/19)

Concerning the behavior of the EPS externally insulated rammed earth wall in the coldest week (02/01/2019 - 09/01/2019), we can make the following considerations.
From the 3d graph of the temperature distribution through the wall section (fig. 86), we can analyze the behavior of the different stratigraphies, arranged horizontally, from the bottom to the top, in order: lime render, EPS insulation, earth wall and earth plaster, in relation to the week of reference. While the inner plaster manages to maintain a constant temperature around 20 °C, the outer render is more subject to temperature variations, presenting lower temperatures peaks, from day 4^{th} to day 7^{th}, which are also found in the EPS layer, with temperatures ranging from 4 to 15 ° C. The earthen wall shows a temperature variation from the inside, 19°C, to the outside 17 °C.
From the comparison graph between the internal and external surface temperature (fig. 87), we can say that the former has an average value is 19.81 °C, while the latter has an average value of 16.75 °C, the coldest days is the 5th. The internal surface temperature varies from 19.52°C to 20.10 °C, with a range of variation of 0.58 °C; while the external surface temperature varies from 1 °C to 32.5 °C, with a range of variation of 31.5 °C.
From the 3d graph of the relative humidity content through the section (fig. 90), we see that the exterior render has relative humidity values between 40 - 50%, the EPS layer between 50 and 55 % RH, the earth wall between 45 – 50 % and the interior earth plaster has relative humidity values ranging from 50 % to 55 %.
From the comparison graph between the internal and external surface relative humidity (fig. 91), we can see that the former has an average value of 50.30 %, while the latter has an average value of 49.45 %. The internal surface relative humidity varies from 49.35 % to 51.25 %, with a variation of 1.89 %; while the external surface relative humidity varies from 47.45 % to 51.45 %, with a variation of 4 %.
From the analysis of the 3d graph of the distribution of liquid water, vapor and ice inside the wall (fig. 92) we can affirm that the external lime plaster has values between 35 and 38 kg/m^3, the EPS layer is totally dry, the earth wall is almost dry (10 kg/m^3) and the interior earth plaster has values ranging from 20 to 25 kg/m^3.
From the graph that relates the content of liquid water, vapor and ice with the thermal conductivity (fig. 93), we notice that the first has an average value of 5.305 kg, while the average value of thermal conductivity is 0.516 W/m K. The first value, during the week, is oscillating between 5.251 and 5.359 kg, with a variation of 0.108 kg; while the thermal conductivity value varies from 0.5153 to 0.516 with a range of variation of 0.0007 W/m K.
In the following figures 94 – 101 are shown the graphs referred to the cork insulated rammed earth wall.

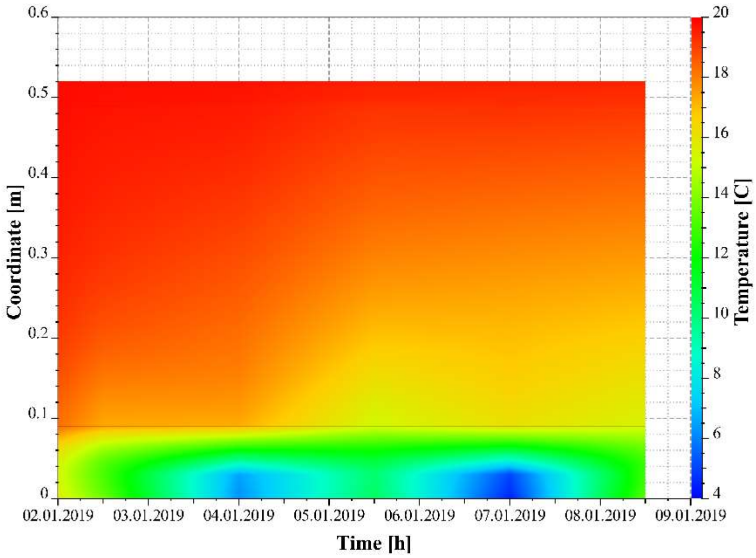


Figure 94 – Temperature distribution across the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

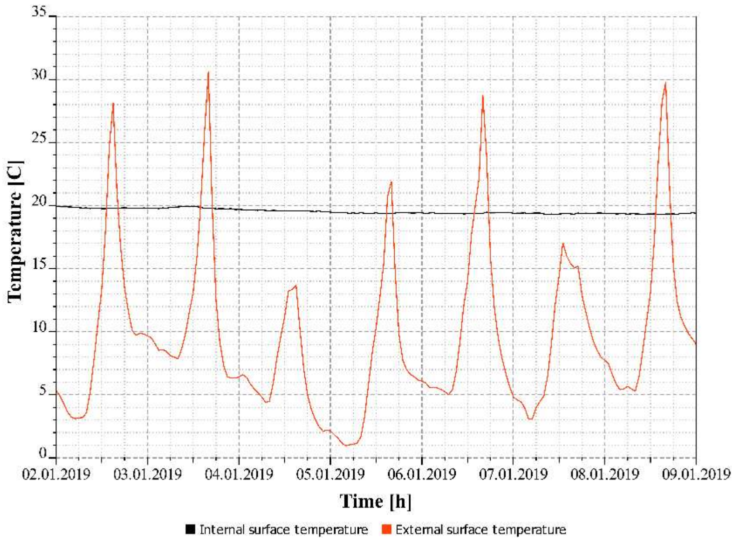


Figure 95 - Internal and external surface temperature in the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

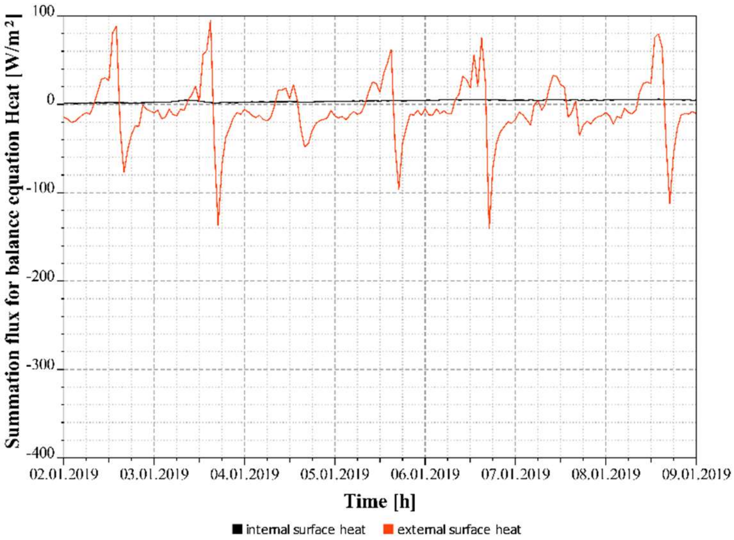


Figure 96– Internal and external surface heat in the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

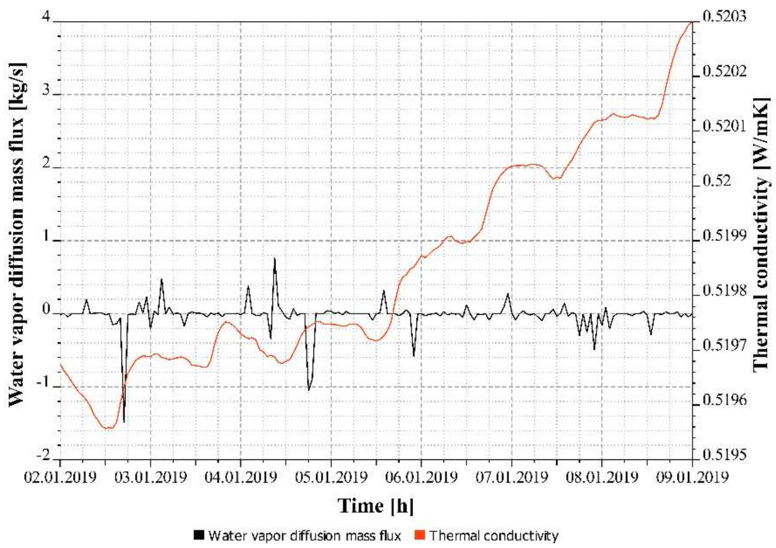


Figure 97 – Water vapor diffusion mass flux and thermal conductivity in the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

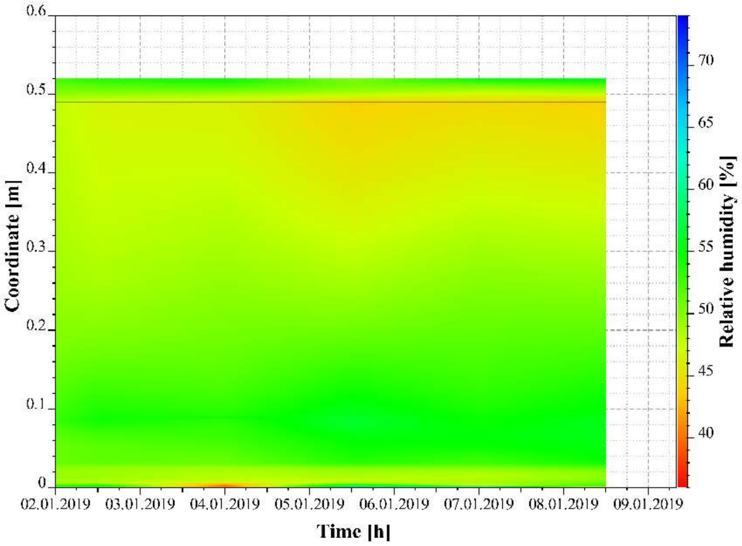


Figure 98 – Humidity distribution across the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

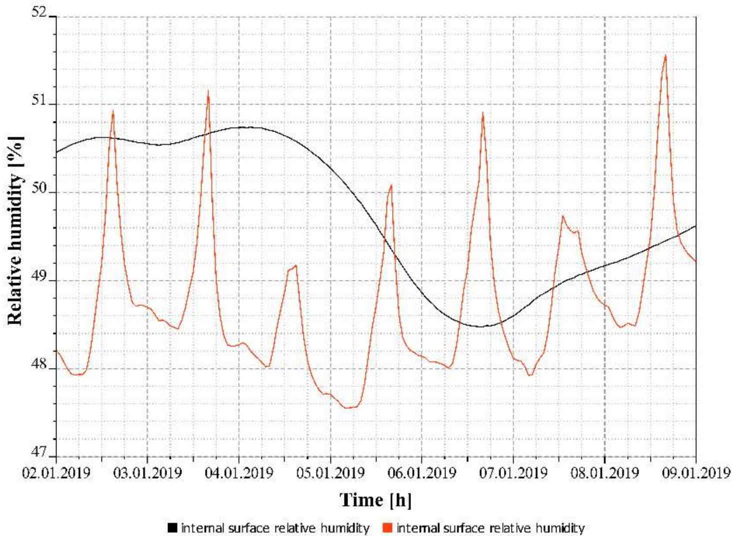


Figure 99 - Internal and external surface relative humidity in the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

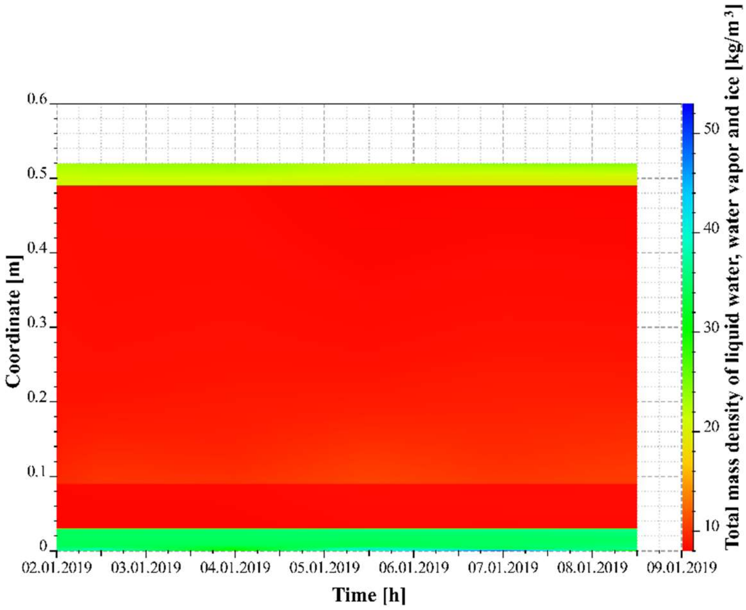


Figure 100- Total mass density of liquid water, water vapor and ice in the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

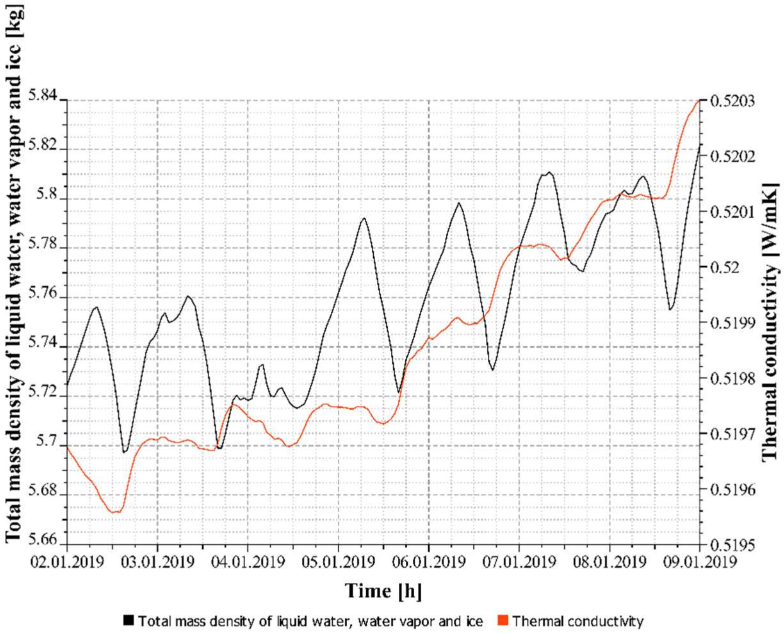


Figure 101 - Total mass density of liquid water, water vapor and ice vs thermal conductivity in the cork insulated RE wall, cold week (02/01/19 - 09/01/19)

From the analysis of the behavior of the rammed earth wall externally insulated with cork, in the coldest week (02/01/2019 - 09/01/2019) we can make the following considerations.

From the 3d graph of the temperature distribution through the section of the wall (fig. 94), we can analyze the behavior of the different stratigraphies, arranged horizontally, from the bottom to the top, in order: lime render, cork insulation, earth wall and earth plaster, in relation to the week of reference. While the internal plaster manages to maintain a constant temperature of 19 °C, the external plaster is more subject to temperature variations, presenting peaks with lower temperatures, from day 4th to day 7th, which are also found in the cork layer, with temperatures ranging from 4 to 12 °C. The earthen wall shows a temperature variation from the inside, 19 °C, to the outside 16.5 °C.

From the comparison graph between the internal and external surface temperature (fig. 95), we can say that the former has an average value of 19.62°C, while the latter has an average value of 16.5 °C, being the 5th the coldest day. The internal surface temperature varies from 19.29 °C to 19.95 °C, with a range of variation of 0.66 °C; while the external surface temperature varies from 2 °C to 31 °C, with a range of variation of 29 °C.

The 3d graph of relative humidity percentage through the section (fig. 98), shows that all the stratigraphies maintain relative humidity values between 42 and 54 %.

From the comparison graph between the internal and external surface relative humidity (fig. 99), we can see that the former has an average value of 49.61 %, while the latter has an average value of 49.5 %. The internal surface relative humidity varies from 48.47 % to 50.74 %, with a variation of 2.27 % while the external surface relative humidity varies from 47.5 % to 51.5 %, with a variation of 4 %.

From the 3d graph of the distribution of liquid water, vapor and ice inside the wall (fig. 100), we notice that the external lime render values are between 35 and 38 kg/m^3, the internal plaster between 18 and 22 kg/m^3; the earth wall maintains a constant liquid water, vapor and ice value of 12 kg/m^3, while the cork insulation results to be dry.

From the graph that relates the content of liquid water, vapor and ice with the thermal conductivity (fig. 101), we can say that the first property has an average value of 5.760 kg, while the average value of thermal conductivity is 0.52 W/m K. The liquid water content, during the week, varies between 5.697 and 5.822 kg, with a variation of 0.125 kg; while the value of the thermal conductivity has an increasing trend, from 0.5196 to 0.5203 W/m K with a variation of 0.0007 W/mK.

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5. Discussion

This section encounters with the discussion of the results presented in Section 4.

In the first paragraph (5.1) we will compare the results obtained in this study with data examined in the literature review (Section 2.2.3) concerning physical, mechanical and thermal performances of rammed earth materials. We will discuss the advantageous effects of the alternative stabilization methods used in the present study.

In the second paragraph (5.2), the innovative technology will be compared to existing ones (both for the design and the constructive process examined in Section 2.2.4) and the advantages of the prototyping phases will be commented.

Finally, in the third paragraph (5.3) results of the hygrothermal and energy performance for a representative rammed earth building using the abovementioned technology will be commented and compared with the results of previous works (introduced in Section 2.2.6).

At the end of each paragraph some comments on the approach and methodology adopted will be also made.

5.1 Effects of alternative stabilization for rammed earth material

As we already introduced in the background chapter, the stabilization of raw earth materials in general, and rammed earth materials, is a paramount necessity for raw earth construction to enhance material properties inside the constructive system. While in seismic prone areas, the material is required to have an improved compressive and flexural strength, accompanied by a ductile behavior in rupture case, a good resistance to water absorption is always necessary as it has direct consequences on the durability of the base materials.
Conventional stabilization techniques for rammed earth materials were applied to our experimental campaign in 2018, using cement and lime binders. The compressive behavior of these samples did not satisfy the ductility requirement and it was chosen to change the stabilization method, also to improve the sustainability and recyclability of the rammed earth material.
In 2019 an innovative stabilization technique was tried, basing on the assumption that two combined techniques were to be implemented: one for the improvement of compressive, flexural and ductility properties of the material (i.e. the use of fibers, in this case, natural sisal fibers), and one for the reduction of water absorption (i.e. the use of a material which could fill the void of the earth matrix, in this case the marble cutting waste). Moreover, this stabilization technique proved to be convenient also regarding thermal properties.
Figures from 1 to 7 compare results on raw earth material performances in previous works analyzed in Sec. 2, and the ones obtained in the present study. Moreover, the discussion focuses also on the compliance with raw earth construction standard when data are available. The analyzed performances are compressive strength, Young's modulus, thermal conductivity, specific heat capacity and water absorption.
Regarding compressive strength, figure 1 plots average dry density values and average unconfined compressive strength for different study. As it can be seen, our studies (both the 2018 and 2019 experimental campaign) are in the central part of the graph, beyond the inferior limits of 1.30 MPa and 1.00 MPa indicated by the [1] and [2] respectively.

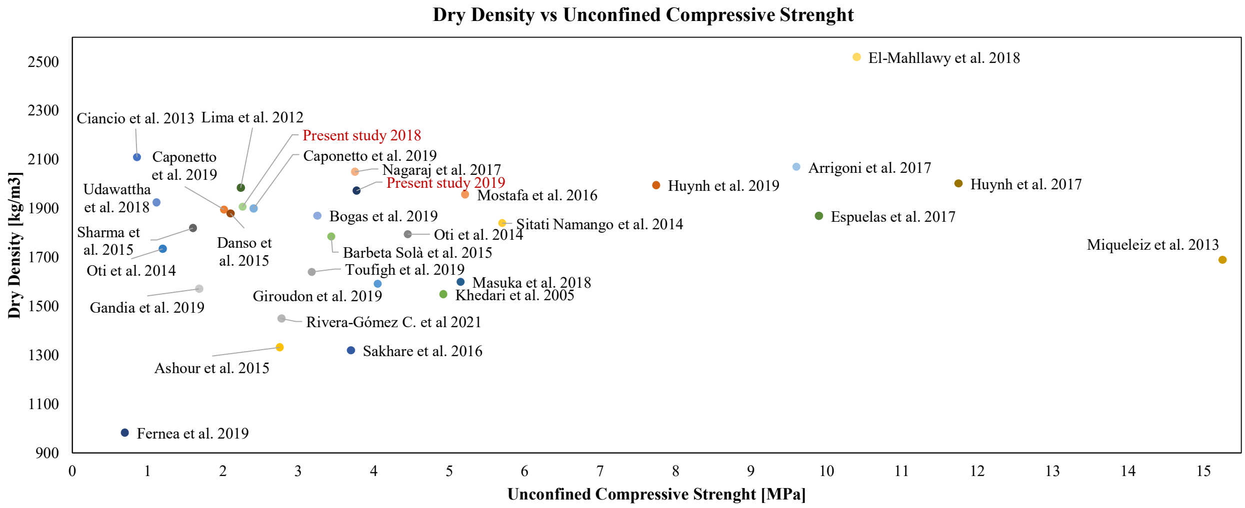

Figure 1 - Average dry density vs Unconfined compressive strength for the analyzed studies in Sec. 2 compared to present studies (2018-2019).

Indeed, figure 2 show that several studies used cement or lime to improve material properties (area in grey), and compressive strengths superior to 5.00 MPa are difficult to obtain without those kinds of stabilization. If we consider this limitation, our study is then located in the higher performances area of this graph.

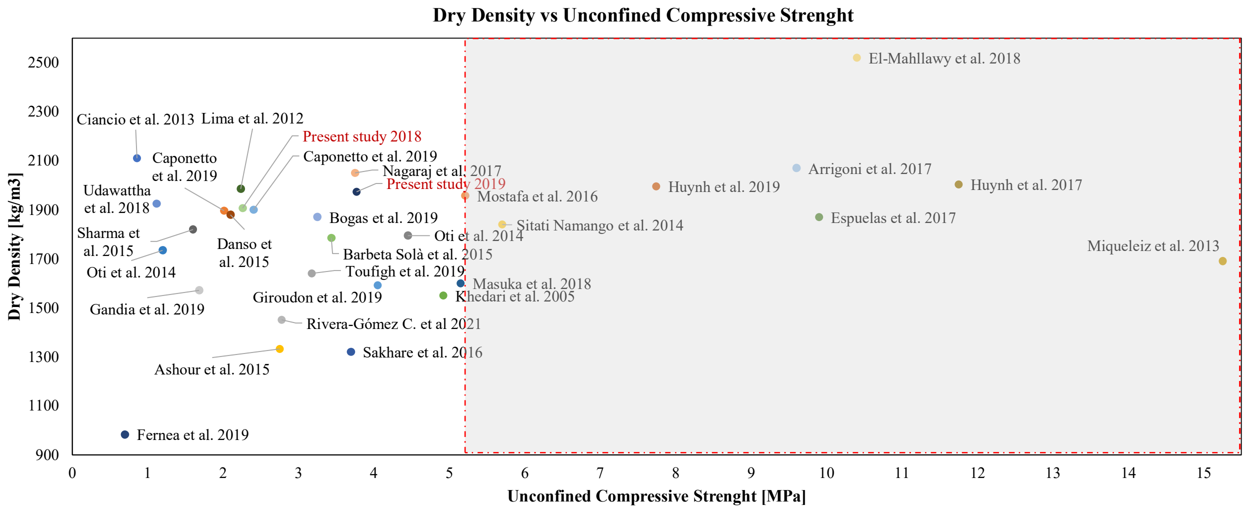

Figure 2 - Limitation for studies using non-recyclable materials for the stabilization methods.

If we now consider studies which only use alternative stabilization methods as natural fibers, geopolymers and recycled aggregates or by-products without using binders which interfere with the recyclability properties of the raw earth material (and so, with its environmental sustainability) [16 – 19, 26, 27, 29 - 31, 36, 37, 42, 43, 55], our 2019 study uses similar materials and achieves comparable average results. Similar fiber length (maximum 2-3 cm) and fiber percentages (maximum 1%) have been used in all the best mixes. Hemp, flax, coir, sisal, kenaf fibers and several types of straw have been used. Compared to the average compressive strength of the analyzed cases (the red dotted line in figure 3), our study presents an improvement of 41.3 %, being better than it only the studies by [16, 17, 31] all using natural fibers to improve compressive strength, and it exceeds the inferior limits of [1, 2] by the 190 % and the 277 % respectively.

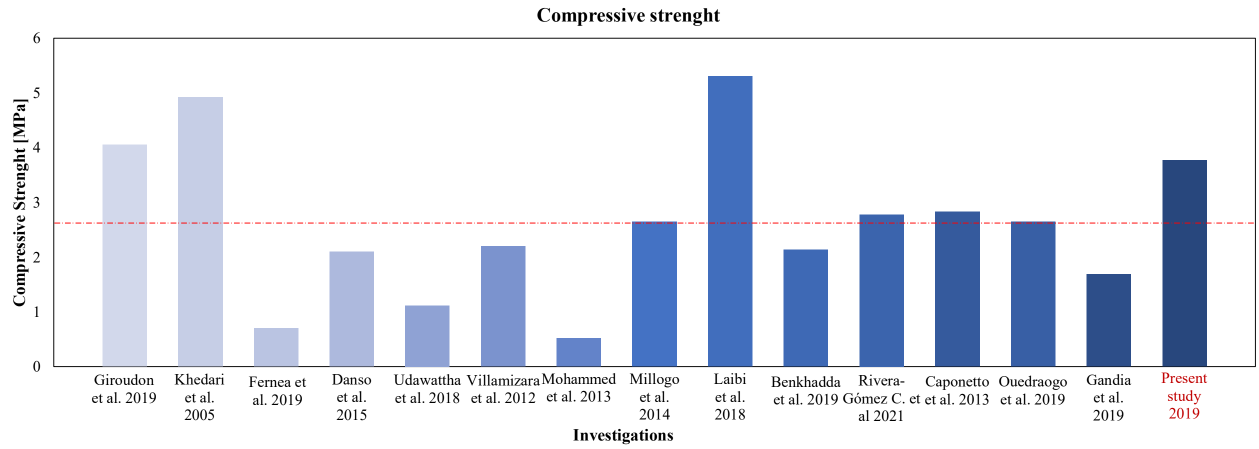

Figure 3 - Comparison between compressive strength values of studies using sustainable stabilization methods and our 2019 study.

Young's modulus is a material property rarely investigated in previous study. Between the fifty-seven studies analyzed in the background, only seven investigated it [3, 9, 16, 31, 34, 35, 49]. If we compared the average Young's modulus value (which is equal to 252 MPa and represented in figure 4 by the dotted red line), our 2019 study is just below it, with a reduction of 5 %.

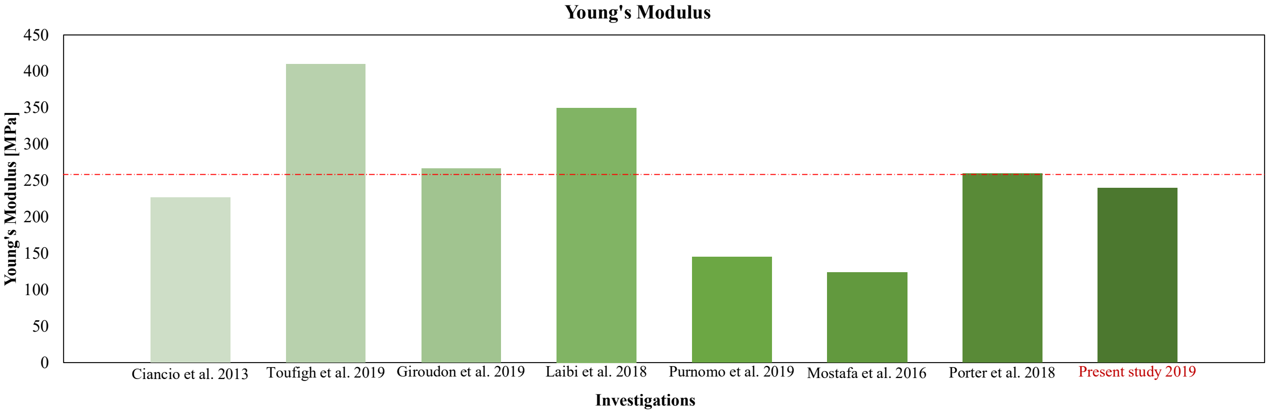

Figure 4 - Comparison between Young's modulus values of previous studies and our 2019 study.

In the following figure 5 it is shown a comparison between average dry thermal conductivity values plotted against average dry density. Also in this case, results of our study are located in the middle of the graph, in an interesting position between typical values of conventional stabilized raw and rammed earth material (with thermal conductivity around 0.80 – 1.00 W/ m K) and lower ones (0.15 – 0.40 W/ m K) which are more typical of lightweight raw earth materials.

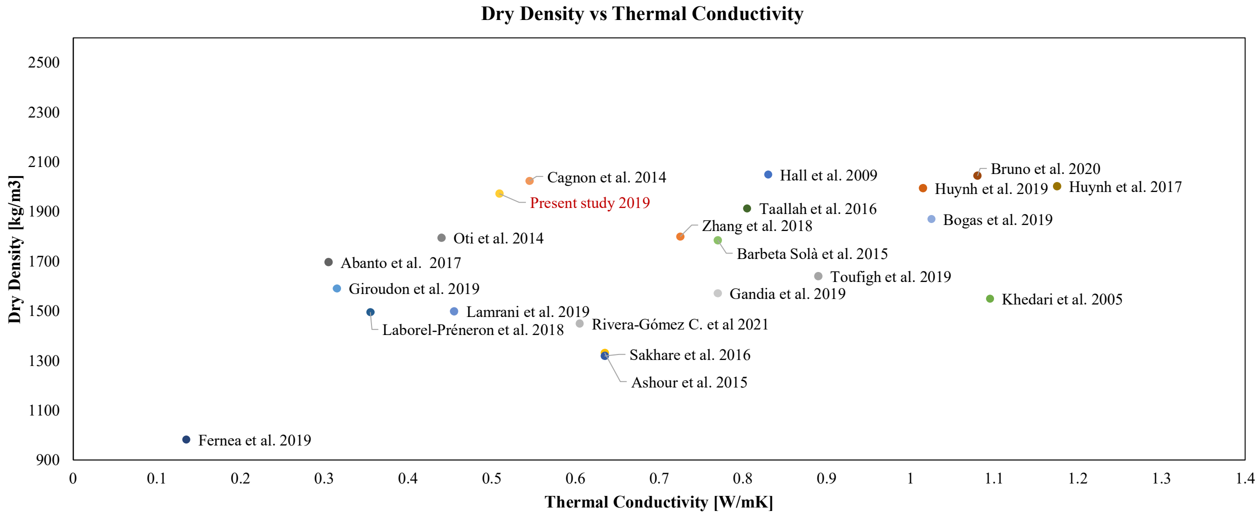

Figure 5 - Average dry density vs dry thermal conductivity for the analyzed studies in Sec. 2 compared to our 2019 study.

Again, the average thermal conductivity value for the investigated studies is 0.73 W/ m K, represented by the dotted red line in figure 6, which is the 30% higher than the average results for our 2019 study.

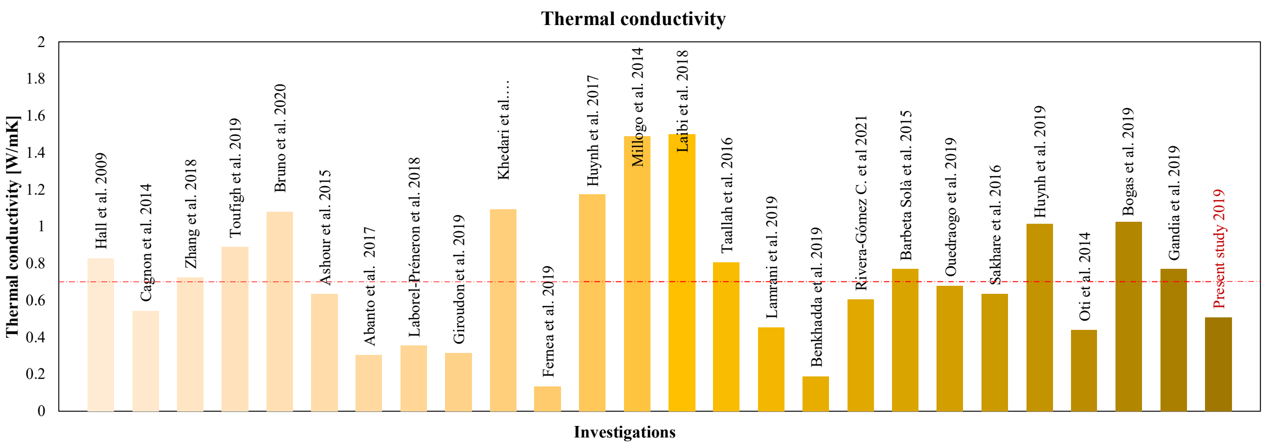

Figure 6 - Comparison between dry thermal conductivity values of previous studies and our 2019 study.

The specific heat capacity is rarely determined between the studies analyzed in Sec. 2, but the comparison of our 2019 study with the few references [6, 14, 15, 23, 49, 51] assessing this important material property (shown in figure 7) show really encouraging results, considering that our results exceed the average specific heat capacity of 992 J/ kg K by the 11 % (being equal to 1098 J/ kg K).

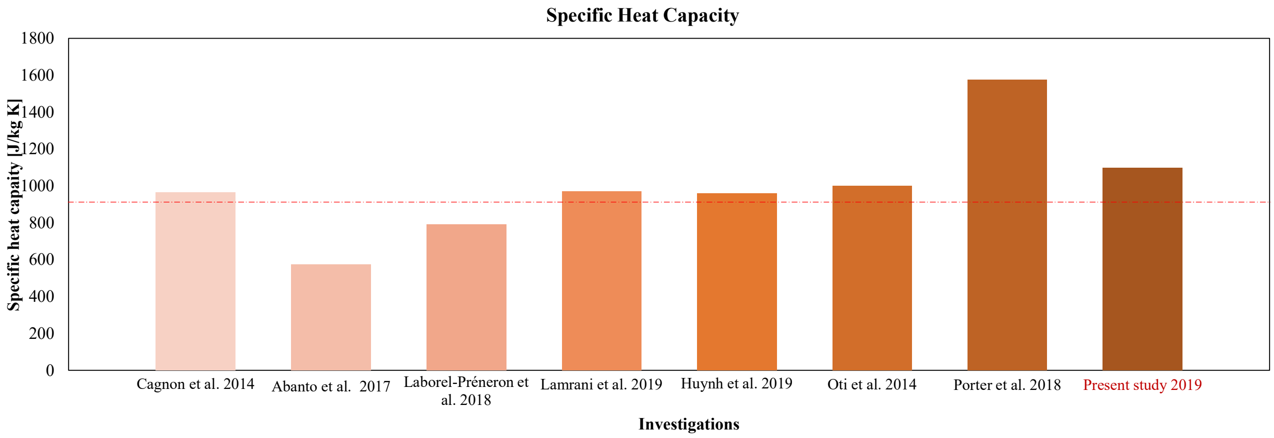

Figure 7 - Comparison between specific heat capacity values of previous studies and our 2019 study.

Finally, concerning the percentage of water absorbed during the capillary absorption test, we calculated an average value of 13.8 % of absorbed water in previous studies. Compared to this average value, our 2018 study showed a reduction of absorbed water by almost the 50%, while our 2019 study showed a reduction of 32 % (figure 8). In this case is evident the positive effect of using stabilizers like cement and lime to reduce raw earth affinity to water absorption, but it is interesting to point out that the use of the marble cutting waste filler helped in keeping this absorption relatively low compared to average absorption values.

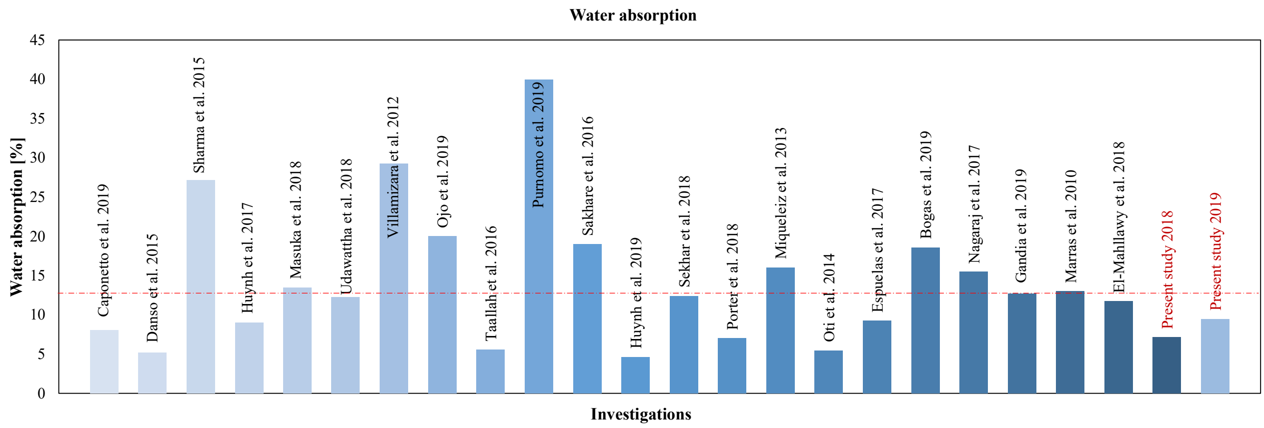

Figure 8 - Comparison between water absorption percentages of previous studies and our 2018 and 2019 studies.

Altogether these results, condensed in table 1, show the good effect of using combined stabilization strategies for rammed earth materials.

Table 1 - Resume of the improvements/worsening of material properties observed in the 2019 study compared to average ones.

	Mechanical properties		Thermal Properties		Physical Properties
	Compressive Strength [MPa]	Young's Modulus [MPa]	Thermal Conductivity [W/mK]	Specific Heat Capacity [J/kgK]	Water absorption [%]
Average values from previous studies	2.67	253	0.73	1098	13.83
Improvement/Worsening	+ 41.32 %	- 5.07 %	- 30.22 %	+ 10.69 %	- 31.65 %

These results are really encouraging because they show that alternative stabilization methods, using natural fibers and recycled fillers instead of conventional binders as cement and lime, are possible and competitive when it comes for the improvement of rammed earth material properties. The use of this alternative stabilization method returns promising material performances (both mechanical, physical and thermal) thus not compromising the recyclability and overall sustainability of raw earth-based materials.
Some observations must be made on some aspects of the 2019 experimental campaign, regarding both production, material design and economic issues:

- Our mixtures could be still improved, for instance by optimizing the integration process of the tenacious sisal fibers in the earth matrix; nevertheless, in this research it was preferred to assume as best mixture the MFRE one, which comprises use of marble cutting waste and sisal fiber, and to focus on the complete development of the innovative constructive system which will be commented in the next paragraph.
- fibers are assumed to improve mechanical properties, which may not necessarily also improve thermal properties; so, a trade-off analysis is always to be implemented for material optimization;
- the hydrophilicity of rammed earth material can be reduced with the use of a filler instead of using cement. The resulting material is less cohesive but is 100% recyclable;
- this innovatively stabilized rammed earth material, using materials from other production chains, is competitive compared to more conventionally stabilized materials;
- the challenge lies in the fact that in order to use by-products from other production chains, manufacturers have to be sure that these substances are not harmful for human health, which entails having to carry out fairly costly analysis;
- it misses to be solved the eventual collection procedure of these by-products from other production chains which could be supported by eventual policies rewarding policies for producers who incorporate these products into their production chains;
- it is also necessary to find economically viable ways of processing these basic materials promoting the use of passive energy production processes (in this sense, the Guglielmino Soc. Coop. suggested the realization of a photovoltaic system for the drying process of marble cutting waste);
- finally, is always preferrable to use local materials: concerning the natural fibers, cultivations compatible with the territory characteristics (like sisal fibers, which is endemic in Sicily but not currently extracted locally) should always be encouraged; if not, building products using natural materials will always be more expensive than conventional building materials.

5.2 Constructive issues and opportunities

The comparison of previously developed reinforced raw earth constructive systems (shown in Sec. 2.2.4) and, specific construction processes (Sec. 2.2.4.1), have been compared with the technology proposed in this thesis for future rammed earth construction. In table 2 is presented a brief comparison between various constructive systems based on:

- the material optimization proposed (both if in the sources typical mix are described or if material is chemically stabilized and/or prefabricated);
- the structural reinforcement adopted to prevent from out of plane and in plane mechanisms;
- thermal improvement of vertical raw earth envelopes;
- attention paid to the use of sustainable materials for the material design, structural reinforcements and thermal refurbishment of the walls.

Moreover, the last two sections of the table refer to the eventual enhancement of formwork system for the fastening of production procedures and integration of the reinforcements during construction phases.

From table 2, some constructive systems which were studied in the background have been omitted because their features and constructive processes were too different from rammed earth ones; among these, the tabique-adobillo [61] and the canes-reinforced and geogrid-reinforced adobe walls [2] have been excluded because, even if they uses reinforcement systems which could be applied to rammed earth with minor adjustments, the construction processes are not comparable as they do not imply use of formworks.

Table 2 - Comparison of previously developed rammed earth constructive system and the one designed in this thesis.

		Constructive system					Constructive process	
Ref	Name	Material Optimization	Structural Reinforcement: Out of plane mechanisms	Structural Reinforcement: In plane mechanisms	Thermal Improvement	Use of Sustainable Materials	Enhanced Formwork System	Integration of reinforcement during construction
2	Nylon rope - reinforced RE wall	Typical mix described	YES	YES	YES	YES	NO	NO
62, 63	RE wall with timber posts	Typical mix described	YES	YES	NO	YES	NO	NO
64	RE Panel with bamboo	NO	YES	NO	NO	YES	YES	YES
65	S_LOW	NO	YES	NO	NO	YES	YES	YES
66	E-logic wall	Typical mix described	YES	YES	NO	YES	NO	YES
67	Reinforced RE wall NZS	PC stabilization	YES	NO	YES in building practice	NO	NO	YES
68	Reinforced RE wall	PC stabilization	YES	NO	YES in building practice	NO	NO	YES
69	Reinforced COB wall	PC stabilization	YES	NO	NO	NO	NO	YES
70, 71	SIREwall	PC stabilization	YES	NO	YES	NO	YES	YES
72, 73	Prefabricated RE	Prefabrication	YES	NO	YES	YES for the mix, NO for the structure	NO	NO
	Present study	Prefabrication	YES	YES	YES	YES	YES	YES

Note: RE= Rammed earth, PC= Portland Cement

Concerning the **material optimization** , the Peruvian Code [2] gives indications about typical mix to be adopted, and so, the reinforced system described (rammed earth reinforced with nylon ropes) is supposed to use a fiber reinforced rammed earth material. In this case we cannot talk about a real standardization made on the material. In other systems as rammed panel reinforced with wood members [62, 63] or bamboo [64], S_Low [65] and E-logic wall [66] systems, material is not detailed and usually is formulated from what is available on site. All the New Zealand [67], American [68], Canadian [70, 71] rammed earth systems use Portland cement stabilized rammed earth material with no reinforcing components (i.e., fibers). Also, the prefabricated rammed earth panels by [72, 73] do not use fibers reinforcements in the earth matrix but the material is prefabricated with recyclable aggregates. We already discussed in the previous paragraph 5.1 that our material is conceived to be prefabricated, by using a combined stabilization strategy to improve mechanical and thermal performance (by the addition of natural fibers) and physical ones (by the use of a filler deriving from other production chain).
Concerning the **structural reinforcement** , all the analyzed systems use a primary reinforcing structure whose aim is to enhance the flexural resistance of the wall by the addition of external or internal reinforcement. Quite often, external reinforcements used wood posts [62, 63, 65, 66] as in the system presented in this thesis. The use of wood posts placed at regular distance is interesting for integration purposes with exterior/interior cladding walls or insulation layers. Internal reinforcements used are bamboo columns [64], wood members or canes [2, 62, 63], steel rebar [67 - 73], which often cause issues in the construction process as explained in the Sec. 2.2.4.1 of the background. Sometimes, an auxiliar reinforcement is added to prevent from collapse of fractured elements out of the wall: these are geogrids (as those used for adobe walls in [2]), nylon rope meshes [2] and nylon rope bindings as in the system presented in this study.
The **construction system** proposed in this thesis uses a reinforcing mesh made up of vertical timber elements (posts) and horizontal rope elements (nylon/polyester ties). These two reinforcement systems respond to two complementary needs. The main wooden reinforcement system provides extra strength to the fiber-reinforced rammed-earth masonry: in this way, the wall assumes greater inertia and resistance to shear and bending and is effectively bound to the foot and head of the wall by connection to two wooden ring beams. The auxiliary rope reinforcement system allows for the control of displacements of portions of the wall that may have cracked because of in-plane stress: in this way, the possibility of the formation of cracks in the wall is assumed without compromising the safety of the construction system and the inhabitants.
In the proposed system, the rammed earth wall performs essentially under vertical loads. The characteristics of the wooden reinforcement system (spacing and section of the wooden posts) can be calculated in such a way that they provide the wall with greater resistance against horizontal forces caused by earthquakes, which induce shear and bending stresses in the masonry. At the same time, the auxiliary surface reinforcement of nylon/polyester ropes, attached to the wooden skeleton and tensioned to confine the rammed earth wall, makes it possible to protect against out-of-plane collapse mechanisms, which would cause the projection of portions of cracked masonry during the seismic phenomenon. The innovation proposed by the system is the use of the anti-seismic reinforcement system as part of the system of support and anchorage of the formworks that allow the compaction of the earth-based material for the realization of the rammed earth wall.
Regarding the **construction process** , our system demonstrates to be very competitive compared to existing technologies because it conjugates the use of sustainable and low-cost reinforcements (as timber posts and nylon ropes) with the simplification of the constructive process. The constructive system herein presented allows a saving in construction time compared to other reinforced raw earth building systems, since the installation of the structural reinforcement elements (timber posts and type 1 ropes ties) takes place before the casting and ramming of the material, and not after. Moreover, this choice is advantageous for the integrity

of the structure, since the drilling of the solid wall executed *a posteriori* for the passage of transversal reinforcing elements, as provided by other investigations, could lead to a damage of the masonry. Moreover, unlike other investigations using reinforcing elements placed inside the masonry section, our system consisting of flexible elements does not hinder the compaction of the earth material.

The greater effort made in this thesis is to connect the issue of seismic reinforcement to the simplification of constructive process: wood vertical posts, which help in the installation of the formwork for the wall construction, where connected by rope ties which are part of the auxiliar rope reinforcement realized with horizontal ropes bindings. This means that the horizontal reinforcement does not interfere with the construction of the wall, which is realized by the progressive compaction of horizontal layers. In this way, the structural reinforcement is actively integrated during the construction of the walls and ropes are totally embedded in the rammed earth material, creating a good cohesion between the earth matrix and the reinforcement.

Only few other systems present a similar integration between the construction process and particular formwork systems which allow for the installation of eventual reinforcements [64, 65, 70, 71].

Being rammed earth a technique where thick walls are always used, few systems optimize the final **thermal performance** of the walls by the addition of thermal insulations, and usually these are rigid synthetic insulations as in [67 - 71]. Sometimes other insulations can be used as granulated cellular glass [72, 73] or *totora* mats [74], which could be easily applied to rammed earth construction. In the present study, the presence of wood posts helps the installation of natural based insulations boards (cork, coconut, flax shiv), thermal plaster (lime hemp), mats (jute felt, sheep wool) as presented in Sec. 4.3 and discussed in the following paragraph 5.3.

Finally, regarding the **use of sustainable materials** , both in insulation layers and in material composition, some reinforced rammed earth constructive system pay attention to the sustainability value and the importance of using almost 100% recyclable material in end-of-life phases of buildings [2, 62 - 66, 74]. Still, most of the current production of rammed earth buildings is less concerned about the environmental issue and continue to use chemical binders which preclude from the recyclability of the rammed earth material [67 - 71] or, even more commonly, it uses reinforcing structural elements deriving from the highly pollutant steel and cement production chains [67 - 73] or synthetic insulations [67 - 71]. Our study had the primary objective to design a system which could reach high mechanical and thermal performances without neglecting the attention to environmental sustainability of the base materials adopted for rammed earth formulation, reinforcing structures and thermal improvement. Obviously, the choice to prefabricate the rammed earth material in the factory increase its carbon footprint, but this issue is partially counterbalanced by the use of the marble cutting waste by-products which would otherwise be disposed as waste. This carbon compensation should be investigated in the future.

All previous considerations were confirmed during the production of the full-scale prototype. The opportunity of building and testing the constructive system allowed us to confirm certain hypothesis and to discard others.

For instance, the initial hypothesis about the possibility to hang the formworks for the construction of the rammed earth wall by the use of the type 1-ties, has been discarded as soon as we realized that this connection was not enough stiff to withstand the compaction of the rammer. For this reason, we decided to add removable steel tie bar which helped to block the formworks.

Nonetheless, the idea to block the tie-type 1 on the other side of the formwork was confirmed to be good because it allows the ropes to stay tensioned during the compaction procedure, so the confinement provided by the horizontal rope bindings is more effective.

Moreover, during the prototype construction it was observed that a similar block system has to be implemented also for ties-type 2 (which do not cross the wooden posts) which are used to reinforce the corner. In addition, it has been observed the necessity to implement a prefabricated and precise production process for the timber members composing the reinforcing structure, especially the timber posts where it is fundamental to have reliable positions of the holes for the passage of type 1- ties and grooves where type 2 ties cross the rammed earth walls: these holes, grooves and visual signs on the posts are important because they simplify the construction process and clearly indicate the position where the rope reinforcement (type 1 and type 2 ties and horizontal bindings) must be installed.

The construction system proposed above inherits technical knowledge developed in highly seismic areas of our planet and integrates it with a logic strongly linked to the industrial production of bio-based materials and the optimization of the construction process. The estimated costs for this technology presented in Sec. 4 are consistent with costs provided by common rammed earth construction enterprises but with the advantage of installing, at the same time, the wall and its reinforcing structure. The comparison with other previously patented systems highlights how the proposed technology, by skillfully combining natural base materials or recycled and low-cost ones, simplifies the construction process of rammed earth walls and their integration with anti-seismic reinforcement systems.

5.3 Hygrothermal and Energy optimization

The last part of the research focused on the study of the thermal comfort and energy needs in a rammed earth building using the technology defined in this thesis. A representative rammed earth residential building located in Catania (Italy) has been designed on the basis of the Peruvian Standard [2], which regulates the design of reinforced and seismic-resistant raw earth buildings. Being Catania classified as a Csa Mediterranean climate by Köppen, the design of the representative rammed earth building was done considering the use of passive design strategies (night-cross ventilation, overhangs) traditionally used in Mediterranean climates to improve indoor thermal comfort. The thermal behavior in free-running conditions and energy performances of the building have been simulated with Design Builder software. The model was calibrated using weather data implemented by the research group in 2019. Thermophysical performance of the innovative fiber-reinforced rammed earth material which were previously assessed (Sec. 4.1) have been implemented in the Design Builder model.

The investigation shows the effects of different design solutions inherited by traditional Mediterranean bioclimatic strategies, as the use of massive walls with high thermal inertia (as rammed earth ones), use of night cross-ventilation, overhangs, and a combination of the strategies. The effectiveness of the use of this technology, in combination with bioclimatic design approaches was proven by the assessment of inner surface temperature, indoor mean air temperature, comfort expectations, and energy needs for heating and cooling. Furthermore, in the last part of the research, we explored the potentiality of using multicriteria analysis to design the optimal thermal insulation for rammed earth walls in hot temperate climates. The key findings of this study can be summarized as follows:

- The development of an innovative rammed earth material with combined stabilization strategies (fibers and filler) resulted in a material with lower thermal conductivity and satisfactory specific heat capacity, compared to conventional rammed earth material values;
- during summer season, the use of a massive material as rammed earth for the envelope keeps the curve of inner surface temperature almost constant on values ranging between 30.3 and 32 °C with respect to the curve of outer surface temperature, with low values of decrement factor (DF < 0.005 for East wall and West wall of the reference building) and satisfactory values of time lag (TL > 17 h for East and West wall of the reference building);
- during winter season, the use of uninsulated rammed earth envelopes allows to maintain an indoor surface temperature between 16.4 °C and 17.4 °C;
- during summer season, indoor mean air temperature profile for the best bioclimatic design option (named "Base + Over + N.V.50" scenario in Sec. 4.3) lies between 28.3 and 31.27 °C in the analyzed period, with a reduction of 1.40 – 1.92 °C compared to the base model;
- during winter season, the indoor mean air temperature profile ranges from 15.9 °C to 17.5 °C;
- the innovative fiber-reinforced rammed earth walls behave as a thermal flywheel and remarkably dampen the incoming heat wave during summer period;
- combined bioclimatic strategies (namely "Base + Over + N.V.50" scenario in Sec. 4.3) succeed in satisfying normal comfort expectations for uninsulated rammed earth walls without use of HVAC systems in summer conditions, for more than 75% of the analyzed time;
- concerning energy needs for space cooling, the use of combined bioclimatic strategies (namely "Base + Over + N.V.50" scenario in Sec. 4.3) reduces energy demand for heating and cooling by 14.2 % with respect to the base case, being 35.5% the reduction in cooling demand.

Even if results on thermal performances of rammed earth walls were encouraging, the need to further minimize energy consumption led us to consider the use of a thermal insulation layer to be applied on the rammed earth walls. The last part of the thesis focuses on the potentiality of using multicriteria analysis to design the optimal thermal insulation for rammed earth walls in hot temperate climates. The Optimization Design Builder tool was used to find the design options for wall constructions (with a choice between 30 rammed earth stratigraphies using internal or external layers of insulation) which could, at the same time, minimize energy consumption, costs, environmental impact, and discomfort. Interesting outputs of this analysis are:

- The identification of several optimized solutions using an external layer of natural-based thermal insulation (as jute felt mats, coconut fiber and flax shive boards, and thermal hemp lime plaster);
- an improvement on indoor surface temperature both in summer (with Tsi values between 28.5 and 29.8 °C) and winter conditions (with Tsi values between 17.2 and 17.9 °C), compared to the "Base + Over + N.V.50" scenario;
- an improvement in indoor mean air temperature both in summer (with Ta values between 28.5 and 29.5 °C) and winter conditions (with Ta values between 16.8 and 17.7 °C), compared to the "Base + Over + N.V.50" scenario;
- an additional reduction in discomfort hours in summer conditions of around 20% for the abovementioned optimized insulated constructions (comfort conditions were maintained for more than the 95 % of time);
- an average reduction in total energy demand for cooling and heating of 45% (22% for cooling and 68% for heating respectively) for the optimized insulated options;
- the exclusion of several synthetic insulation types (EPS, PU boards) conventionally used in Australian and American rammed earth construction, for the optimized solutions in Mediterranean climates.

In the last part of the analysis three well-performing stratigrafies were chosen to simulate the hygrothermal behavior of the rammed earth wall on Delphin software. As explained in subsection 4.3.2, three constructions were chosen, an uninsulated rammed earth one, an EPS externally insulated rammed earth one (representing the synthetic insulations) and a cork externally insulated rammed earth wall (to test the natural based insulations). These constructions were tested for the city of Catania, both in summer and winter conditions.
For each of these stratigraphies were extrapolated different graphs aiming at characterizing the behavior of the rammed earth wall and particularly: the temperature and relative humidity distribution across the section of the wall, the comparison of the internal and external surface heat, the comparison of the water vapor diffusion mass flux and thermal conductivity and finally, the total mass density of liquid water, water vapor and ice and its comparison of the thermal conductivity.
Results of this extensive analysis have been condensed in the table 3, where are reported the indoor surface temperature and relative humidity variations, the total mass density of liquid water, water vapor and ice across the wall section and the range of variation of thermal conductivity values. Similarly, are reported the average values of these properties. These values are shown both for the warmer and the coldest week and for the three constructions alternatives.

Table 3 - Hygrothermal comparison of uninsulated and insulated constructions for the rammed earth wall.

Catania								
Uninsulated rammed earth wall								
	Indoor Surface Temperature [°C]		Indoor surface relative humidity [%]		Total mass density of liquid water, water vapor and ice in the wall [kg/m³]		Thermal conductivity [W/mK]	
	ΔTsi_{max}	Tsi_{media}	$\Delta\varphi_{max}$	φ_{media}	ΔW	w_{media}	$\Delta\lambda$	λ_{media}
Warm week	27.7-25.62= 2.09	26.67	59.54-56.00= 3.54	57.77	5.348-5.208= 0.139	5.278	0.582-0.581= 0.002	0.581
Cold week	19.42-17.98= 1.44	18.70	49.44-45.43= 4.02	47.44	5.410-5.221= 0.189	5.315	0.582-0.578= 0.004	0.580
EPS insulated rammed earth wall								
	Indoor Surface Temperature [°C]		Indoor surface relative humidity [%]		Total mass density of liquid water, water vapor and ice in the wall [kg/m³]		Thermal conductivity [W/mK]	
	ΔTsi_{max}	Tsi_{media}	$\Delta\varphi_{max}$	φ_{media}	ΔW	w_{media}	$\Delta\lambda$	λ_{media}
Warm week	26.32-35.00= 1.32	25.66	58.14-55.00= 3.14	56.57	5.422-5.255= 0.167	5.338	0.517-0.515= 0.002	0.516
Cold week	20.10-19.52= 0.58	19.81	51.25-49.35= 1.89	50.30	5.359-5.251= 0.108	5.305	0.516-0.515= 0.001	0.5155
Cork insulated rammed earth wall								
	Indoor Surface Temperature [°C]		Indoor surface relative humidity [%]		Total mass density of liquid water, water vapor and ice in the wall [kg/m³]		Thermal conductivity [W/mK]	
	ΔTsi_{max}	Tsi_{media}	$\Delta\varphi_{max}$	φ_{media}	ΔW	w_{media}	$\Delta\lambda$	λ_{media}
Warm week	26.56-25.13= 1.43	25.84	58.80-55.20= 3.6	57.00	5.864-5.700= 0.164	5.782	0.522-0.520= 0.002	0.521
Cold week	19.95-19.29= 0.66	19.62	50.74-48.47= 2.27	49.61	5.822-5.697= 0.125	5.760	0.520-0.519= 0.001	0.520

The uninsulated rammed earth wall manages to maintain, in summer conditions, an average indoor surface temperature of 26.67 °C for the city of Catania, close to the design temperature of 26°C. While the indoor surface temperature, in winter conditions, results to be 18.70 °C, slightly below the reference value of 20°C. From the comparison of these values with the ones detected in the analysis run on DesignBuilder with use of bioclimatic strategies, we deduce that the effect of moisture in rammed earth wall causes lower Tsi values in summer conditions (about 3.12 °C lower than the average between the values 28.3 and 31.27 °C of the Design Builder analysis). In winter conditions, the Tsi contemplating the moisture effect results to be higher than the one not considering it (the value obtained from Delphin simulation is 18.70 °C, which is 2.00 °C higher than the average between the previously reported values 15.9 °C to 17.5 °C from DesignBuilder simulation).

The average relative humidity assumed by the uninsulated rammed earth wall is between 57.77 % and 47.44 %, for the hot and cold week, similar to the design ones (65% - 35%). The water content stored by the wall results to be on average 5.278 kg/m³ in summer and 5.315 kg/m³ in winter conditions. The thermal conductivity is always around 0.58 W/mK.

The rammed earth wall externally insulated with EPS manages to maintain, in summer conditions, an average indoor surface temperature of 25.66 °C for the city of Catania, close to the design temperature of 26°C. While

the indoor surface temperature, in the representative winter week, turns out to be 19.81°C, slightly below the reference temperature of 20°C. This can be due to moisture effect.
The average relative humidity assumed by the rammed earth wall externally insulated with EPS, is between 56.57 % and 50.30 %, for the hot and cold week, with the cold week value farer to the higher comfort limits compared to the uninsulated case.
The liquid water and water vapor mass content stored by the wall results to be between 5.338 kg/m^3 during summer week and 5.305 kg/m^3 during winter week; during summer, the EPS insulated wall contains more mass density of liquid water and water vapor (5.338 kg/m^3) than the in the uninsulated case (5.278 kg/m^3), while during winter week the water contents are lower (5.305 kg/m^3) and closer to those of the uninsulated wall (5.315 kg/m^3). The thermal conductivity, both in the summer and winter week, is on average 0.516 W/mK, close to the design conductivity value (0.508 W/mK).
The rammed earth wall externally insulated with cork manages to maintain, in summer conditions, an average indoor surface temperature of 25.84 °C for the city of Catania, close to comfort temperature of 26°C. While indoor surface temperature in winter conditions, turns out to be 19.62 °C, slightly below the reference temperature of 20°C.
The average relative humidity assumed by the rammed earth wall externally insulated with cork, is between 57.00 % and 49.61 %, for the hot and cold week, with values near to those of the uninsulated case.
The mass content stored by the cork-insulated wall is between 5.782 and 5.760 kg/m^3, with slightly higher values than the other proposed stratigraphies for the city of Catania, both for the summer and the winter week. The thermal conductivity navigates around 0.522 – 0.520 W/mK, both in the summer and winter week, closer to the design conductivity value (0.508 W/mK) compared to the uninsulated earth.

We can therefore say that the uninsulated earth wall offers good performance in Mediterranean environments, with values slightly worse than those of the earth wall insulated with EPS and cork, in terms of internal surface temperatures. In terms of indoor surface relative humidity, the uninsulated and the cork insulated rammed earth wall perform better than the EPS insulated rammed earth wall. The equivalent thermal conductivities for the uninsulated rammed earth wall are respectively 0.065 W/mK and 0.06 W/mK higher than the EPS-insulated and Cork-insulated cases. Yet it is worth nothing that the use of such insulations involves an increase in the liquid water and water vapor content inside the insulated earth walls compared to the uninsulated solution, unexpectedly also during summer week, which could lead to other complications concerning the durability of the rammed earth solid wall.
This last paragraph discussed the results obtained from numerical simulations based on real data concerning both the material composing the vertical envelope (the innovative fiber-reinforced rammed earth mix) and the local weather. Use of realistic data is fundamental to obtain reliable simulation which can help in the design process of future building stocks.
In the context of new construction, solid rammed earth building systems (also in combination with framed support structures) have undoubted environmental benefits and high thermal performance in mild climates characterized by a large temperature swing between day and night. The high thermal mass, and therefore the inertia of these building envelopes, stabilize and balance the internal temperatures and humidity of buildings, ensuring conditions of internal comfort.
It is understood that design optimization strategies of future rammed earth buildings must be based on a good bioclimatic design, which is made specific to the dwelling site by collecting data via secular research regarding the adaptation to local climatic and geographic conditions, and then moving to the optimization of all the building components and the materials used.

Choices concerning thermal insulation should be made considering the real economic and environmental prices of these products, which strongly depend on the geographical context where the building will be located, and carefully selecting the products which can positively affect indoor comfort and energy consumption.
Finally, as some of the optimized construction solutions depicted in this study require the use of natural-based thermal insulation, the last part of the analysis focused on the influence of moisture contribution to energy, thermal and physical behavior of rammed earth walls, from a hygrothermal point of view. It is confirmed that the application of an external insulation layer to rammed earth wall helps in terms of approaching comfort temperatures both in summer and winter weeks. Indoor relative humidity values seem to be closer to comfort ones only in the uninsulated and cork-insulated rammed earth stratigraphies. It is confirmed that use of insulations involves an increase in the liquid water and water vapor content inside the earth walls compared to the uninsulated solution, in all seasons. This analysis is of paramount importance because it gives a glance on the performances and the durability properties of wall constructions using both synthetic and natural-based insulations in combination with rammed earth walls. Further investigations should focus on hygrothermal, and durability tests made on real walls realized with the investigated constructions.

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6. Conclusions

The research herein presented moves in the field of sustainability applied to new constructions. This sustainable approach implies the need to rethink our way to produce and construct in such a way as to reduce the environmental impact of building products manufacturing processes, the energy demand for heating and cooling of buildings during their use phase and the disposal of building materials in their end-life phase. The will to apply this development paradigm to future building stock brought us to search an alternative to conventional materials and processes used nowadays, recovering the constructive knowledges applied to natural based buildings. Particularly, this research focused on the use of inorganic soils for construction purposes (e.g., raw earth construction).

Raw earth historic and contemporary architectures are renowned for their good environmental properties, for the wide availability, improved recyclability and low embodied energy along the production process. Earth massive walls, as rammed earth ones (a particular raw earth technique in which damp soil is compacted inside formworks to build the walls) are universally known to be able to regulate indoor thermal and hygroscopic conditions, to contain energy consumptions and create comfortable interior spaces with a low carbon footprint. Therefore, earth buildings are *de facto* green buildings. As a result of this, earthen technologies as rammed earth one have been rediscovered and implemented to be adapted to the contemporary building production sector.

Nevertheless, nowadays the diffusion of contemporary rammed earth buildings is decelerated by the lack of proper specific building standards, which causes lack of reliability in earth-based materials and technologies. Often this lack of knowledge in rammed earth construction is solved by the application of manufacturing procedures and construction methods inherited by conventional constructive technique. These latter ones are based on the generalized use of chemical binders like Portland Cement and artificial materials (steel reinforcement, synthetic insulations) which have proved to have a strong negative impact on the environment (for the energy consumed during production, for the contaminants released in the atmosphere, for the impossibility of entirely recycling these materials with consequent increase of landfilling).

For this reason, this thesis has focused on the pursue of a holistic design approach for a seismic resistant and energy efficient innovative rammed earth construction technology, which aims to be reliable, recyclable, and competitive in the current Italian and International construction sector. This aim has been pursued by the adoption of semi-industrialized production processes (both for the material and constructive system) which can help in creating a confident image of innovative rammed earth technology, thus not neglecting the cost-effectiveness, sustainability, and recyclability of this type of construction. This programmatic aim has been translated in three practical objectives which are:

(1) the design of a reliable rammed earth product with superior physical, mechanical and thermal performances;

(2) the adoption of correct design principles for a rammed earth technology which could be less prone to seismic hazard; this meant to find seismic resistant devices for the constructive system which could be easily integrated in the constructive process;

(3) the validation of the correctness of wall stratigraphy design by the control of the building system's hygrothermal and energetic performances.

In Section 2 we presented a wide literature review aiming at constructing knowledge on the previous points, by a brief analysis on the context of the research (subsection 2.1), on historic earthen architectures (subsection 2.2.1), contemporary raw earth building standard with focus on seismic resistant ones (subsection 2.2.2), on the cutting-edge research on raw earth material optimization (subsection 2.2.3), a state of the art on raw and rammed earth reinforced and seismic resistant construction system and processes (subsection 2.2.4), their

structural behavior (2.2.5) and finally, a review on the expected thermal and energy performance of rammed earth buildings (subsection 2.2.6).
Section 3 provides an overview on the research goals and on the methodological approach. In 3.1 it is explained the research gap and the process which brought to the definition of the research goals. In 3.2, the research questions and the hypothesis on which this thesis works are clarified. Finally, in 3.3, an overview on the Research by design methodological approach and the mixed methods used in this research is provided.
Results of the research are exposed in Section 4, which is divided in three subsections. Subsection 4.1 focuses on the experimental results on the material optimization investigation, pursued by the use of innovative and combined stabilization methods aiming at using only recyclable and/or by products from other production chain to confer high physical, mechanical and thermal performance to the rammed earth material. Subsection 4.2 focuses on the research-by-design approach used to define an innovative reinforced rammed earth constructive system in which the seismic reinforcements are actively integrated during the constructive process. A preliminary investigation on the structural validation of this system subjected to an earthquake of medium intensity has given positive results in terms of maximum stress and strain displayed. Moreover, the preliminary investigation highlighted the positive effect of the reinforcement system in the increase of final bending stress and in the limitation of cracks in a damage model. This part of the research will be further developed in the future. Finally, subsection 4.3 shows the validation phase which confirmed the good thermal and energy performance of a reference building whose walls were modelled on the base of the innovative rammed earth material's performances (contained in 4.1) and whose planimetry and constructions features reflected those defined in subsection 4.2.
The discussion of these results is presented in Section 5. In subsection 5.1 the effects of alternative stabilization methods for rammed earth material presented in this study, are compared with the data found in the literature (subsection 2.2.3), confirming that the innovative rammed earth material meets the standards requirements and is competitive compared to more conventionally stabilized materials. Subsection 5.2 shows a comparison between the innovative constructive system features defined in the present thesis and previous ones presented in subsection 2.2.4, highlighting the progresses made in the integration of environmentally sustainable reinforcements during the construction process of rammed earth walls in seismic areas, with consequent simplification of the process and possibility of integration with external or internal thermal insulation layers. Finally, subsection 5.3, through a point-by-point analysis of the thermal and energy simulation results, shows the possible energy and environmental benefits of the presented technology, applied to the case of Mediterranean climates.
The relevance of this research is therefore found in the strong ecological connotation, in the seismic resistant design applied to the constructive system, in the low energy consumption resulting from the characteristics of the designed rammed earth envelope and in the reduced construction times and costs due to the optimization of the construction process.
This thesis has strong innovative features compared to the current state of the art on rammed earth construction and that make it particularly competitive:

- first of all, concerning the base material: the rammed earth mix design and the manufacturing process implemented with the *Guglielmino Società Cooperativa* is fundamental to achieve high physical, mechanical and thermal performances;
- secondly, in terms of the effectiveness of the construction system: the timber structural elements and the nylon/polyester rope reinforcement system are effective anti-seismic devices that increase the resistance of the rammed earth wall to in plane and out of plane seismic actions;

- in relation to the optimization of the construction process: the integration of the anti-seismic timber reinforcement with the formwork (modular and reusable) allows the reduction and rationalization of execution times as well as savings in economic terms.
- finally, in relation to the accuracy in modelling and predicting the thermal, energy and environmental performance of a building made from the innovative prefabricated mix for rammed earth walls and sized on the basis of the studies carried out on the construction system (dimensions of the rooms, of the openings, of the construction elements).

Although the investigated construction system does not represent a technology applicable to multi-story buildings, it could be particularly well suited to single or double story buildings in suburban contexts (where it is possible to use the soil available in situ and/or give preference to certain exposures at the design stage, to maximize free energy from solar radiation, store it inside the wall and thus have a beneficial effect on indoor environmental conditions), but also in urban contexts. There is no lack of examples, especially outside Italy (Spain, Germany, France, Latin America, New Zealand and, of course, third countries) of rammed earth buildings constructed within the existing building fabric to replace obsolete buildings. These are residential buildings (*Casa de Tapial* in Ayerbe, *Haus Rauch* and *Haus M* in Voralberg, *Lehmhaus für Umweltbildung* in Basel, *Tucson Mountain House* and *Catalina House* in Arizona, etc.) or buildings for other uses (*L'Orangery* in Lyon, *Ricola Herb Centre* in Basel, *Oaxaca School* in Mexico, *Amangiri Resort and Spa* in Utah, *Schlins Workshop* in Voralberg, *Swiss Ornithological Institute* in Sempach).
The proposed solution combines environmental concerns (satisfied using rammed earth material with recycled aggregates) with the resistance to dynamic actions (guaranteed by the designed reinforcement system), to propose a construction system for seismic areas, as is now the case throughout Italy. The system is designed to ensure low costs, time efficiency, high durability and guaranteed thermal, acoustic, and mechanical performances. It should be noted that the possibility of prefabricating the mix for rammed earth (as well as the timber members for the stiffening structure), together with the definition of a protocol for structuring the production and construction process, make it possible to obtain a system characterized by quantitatively defined performances, in line with a design based on performance parameters attributable to the individual components, according to the BIM logic that has long been widespread abroad and is now mandatory - partially from 2019, totally from 2025 - for public works in Italy.
As part of the thermal and energy improvement of existing buildings, the mixtures proposed in this invention can also be used for internal counterwalls to improve the thermal capacity of the envelope, acoustic insulation, air humidity control and, in general, internal comfort of existing buildings.
The very fact of designing a technology and a production process with a local manufacturer, the Guglielmino Società Cooperativa, it is an important output of this research.
On a theoretical level, the research relates to emerging developments trajectories based on the concepts of circular economy and three Rs approach (reuse-reduce-recycle), which must be taken into account by today's construction industry and transferring this debate to Sicilian territory. The research is therefore based on the use of resources that are currently present in the area, or on productions that could potentially be allocated there, reconnecting the Sicilian university and small/medium-sized enterprises in the area, which can thus benefit from this collaboration to become more competitive and respond to the renewed demands for sustainability that affect the entire production sector.
On a methodological level, by conducting research outside the university rooms, the engineering knowledge is hybridized with that of related disciplines working in different socio-economic contexts (also by means of comparison with foreign research groups) and with various professionals who populate the local production

realities, leading to the creation of an intense activity of mutual transfer of expertise and consequent creation of shared knowledge.
Finally, on a practical level, we laid the foundations for future production lines based on the use of natural materials and local production waste which, being scarcely processed and totally recyclable, allow the activation of sustainable innovation processes within commercial realities historically existing on the Sicilian territory, with beneficial effects in environmental, economic and social terms.
Further developments of this thesis should focus on other aspects which are connected to the main issues investigated in this work.
First of all, an analysis of the effective seismic response of the designed constructive system should be performed by the realization of full-scale tests on reinforced rammed earth walls or representative buildings. This analysis could be realized by the use of shake table tests which investigate, at the same time, the goodness of the transverse connections between masonry and reinforcing elements, and the strength and ductility characteristics of the designed building elements in different earthquake directions.
Secondly, the durability of the rammed earth wall's assemblies using thermal insulations should be verified by full scale tests aiming at assessing the effect of intrinsic moisture of rammed earth walls on the particular insulation used, and evaluating any performance degradation due to the accumulation of pathological moisture content. In this sense, projects as the CobBauge one, are currently betting on the use of composite earth walls realized with an internal loadbearing cob wall and an external lightweight earth insulation in order not to alter the natural hygroscopicity and breathability of the raw earth materials.
Finally, a life cycle assessment concerning environmental impact of the studied earth material and rammed earth technology should be realized and compared to other contemporary construction technology. In particular, the LCA of the prefabricated earth material should be performed taking into account the carbon compensation resulting from repurposing the marble cutting waste by-products which would otherwise be disposed as waste. On the other hand, the LCA of the designed rammed earth constructive system should be realized and compared to the LCA of current reinforced concrete framed constructive systems (with bricks or blocks infill and external thermal insulations) which are still the most widely used building systems in the Mediterranean area. Moreover, the LCA of the investigated system could be compared to other natural-based technologies which are currently adopted, as cross laminated timber, platform frame and hempcrete constructions.
In conclusion, it is necessary to dedicate a few words on the applicability of new constructive technologies based on the use of natural materials, which cannot ignore the context in which they operate.
The environmental, cultural, productive, and economic context in which we are called to work in, determines preferential design trajectories, often forcing choices in relation to the available options regarding human, materials, and production resources available in the territory and on the technologies to be improved.
Among the most important aspects to be taken into consideration:

- The existence of a workforce specialized in a specific constructive technique;
- The possibility of accessing basic materials of controlled and/or certified origins: if not, this issue could have devastating effects on the territories from which the resources derive (e.g., the use of wood from non-certified sources could generate deforestation, the extraction of land from noncertified quarries could bring contaminated base materials to our houses);
- The adaptability of the constructive system to the changing environmental conditions in which it can be adopted.

This means that the technology must always respects the ideas from which it originates. Projects can be adapted to various contexts using different layers of information and degrees of detail that make them adjustable to different boundary conditions, being removable and/or editable. But its programmatic characteristics must be maintained.
The constructive system defined in this work seeks to improve static schemes already in use in some parts of the world (like Latin America, and particularly Peru) characterized by a high seismic risk and limited access to construction resources, making them applicable to the productive/constructive context of more developed countries, which are characterized by the need to reply to performances-based design criteria that would prevent the direct application of these technologies at our latitudes.
The proposed system has good improvements compared to the historical rammed earth constructive technique: rationalization and standardization of the production process and construction plan, rapidity of execution, optimization of formwork systems, feasibility by non-expert personnel (for the prefabricated rammed earth mix and timber stiffening members), guaranteed seismic-resistant design and energy efficiency of the system.
Yet all these requirements, which must be considered when moving in a normative context such as that of Europe, Oceania and North America, lose their meaning in less industrialized and poor countries as Asian, African or Latin American countries.
Countries like Peru, for instance, are still provided by a workforce specialized in raw earth construction (and working with a broad variety of constructive systems such as adobe, rammed earth and wattle and daub), while the possibilities of prefabrication (even the lighter ones) of raw earth mixes or building components with guaranteed performance are still difficult to be implemented at an industrial scale. Peru, a largely rural country, is nowadays seeing a rebirth of earth construction because of the modifications and enhancements proposed by the widely quoted Peruvian earth construction standard, with the aim of making them safer against seismic and flooding events; even so, in these areas it is more complex to trigger the idea of bringing typical concepts of industrial tradition to the construction field, specializing and standardizing the production process (through the prefabrication of components) and using machineries which could ease the construction.
Local and traditional constructive knowledges must be always considered when it comes to test innovative constructive technologies, because they can have consequences in the use of materials, in the selection of the manufacturing procedures and in the chosen design strategies.
In this way, innovation is enriched by traditional knowledge developed over time, and it acquires beauty and dignity for the ethical, cultural, and social values it brings with it.