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# An overview on contemporary rammed earth buildings: technological advances in production, construction and material characterization

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**Abstract.** Raw earth is a traditional material used worldwide in vernacular architectures. For its wide availability, recyclability and low embodied energy in its life cycle, earth is acknowledged as one of the most environmentally sustainable material. Earth construction diffusion has been slowed by the lack of broadly accepted standards. Due to it, earth has been used as an artisanal material or adapted to existing technologies in combination with high embodied energy materials as steel, concrete and EPS or PU insulations (as in rammed earth technique, from now on RE). Aim of the research is to propose an innovative RE constructive technology, more coherent with the sustainable features of the base material, which can reach the high performances and the quality target required by the constructions sector using a low-tech prefabrication process. Prefabrication of RE elements can also reduce the construction times and the risks of technological faults, enhancing the quality of the entire building. The basic idea is to create manageable and transportable rammed earth panels with superior mechanical and thermal performances. The prefabrication under controlled conditions ensures a high-quality product which can be combined, on site, with a reinforcing timber structure with anti-seismic function. A characterization campaign on different local soils has been performed in order to implement the desired RE elements. The soils have been analysed with a set of geotechnical tests and qualitative assessments in order to detect their suitability for constructions. Once a suitable soil has been identified, a physical and / or chemical stabilization is needed to improve the physical features, mechanical characteristics and thermal properties of the natural soil. In the last section of the paper, the first results on natural local soil and *engineered* soil (an optimized mix of soil, sand and gravel) are presented and compared to identify a suitable material for the RE panel.

## 1. A brief introduction to raw earth architecture

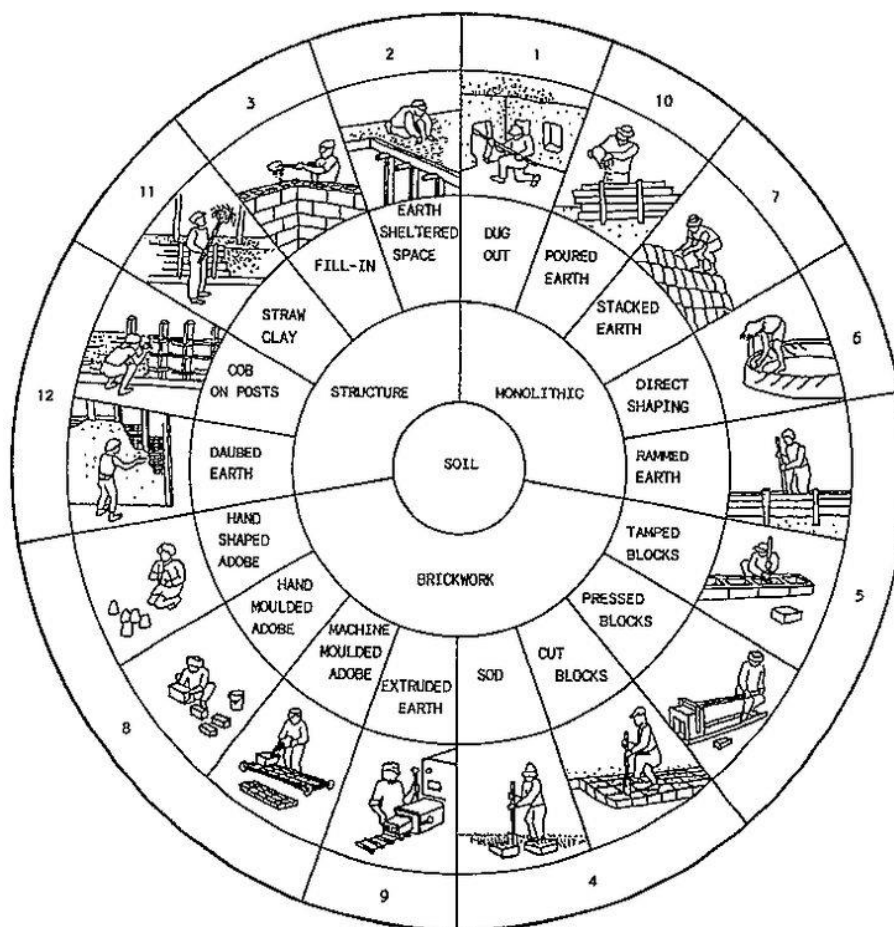
Raw earth is a traditional constructive material that has been used through centuries all over the world. As Houben and Guillaud [1] point out, earthen dwellings show features of universality and diversity: vernacular and monumental historic architectures are spread from Latin America to Africa, from Central Europe to Middle East, so that nowadays one in three inhabitant lives in earthen dwellings [2].

Earth buildings have indubitable environmentally friendly properties. First, the base material is available almost everywhere and it can be transformed in a way it can be used in construction. Soils to be processed can be directly extracted in the building site, reducing the environmental costs of transportation and pollution derived from it. Raw earth is a nontoxic and non-polluting material, with a large absorption capacity of volatile compounds. When no additives are added to it, natural soil used in buildings can be reused in an infinite recyclable chain.



From a thermophysical comfort point of view, raw earth behaves as a thermo-hygrometric regulator, stabilizing the levels of vapor and mitigating the effects of heat waves during the day, creating comfortable interior environments due to the breathability and high thermal mass of the walls.

Basically, 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, historically, 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 [1] on earthen techniques is a good summarising tool to understand the applicative possibilities of soil in construction (Figure 1).



**Figure 1.** CRATerre wheel on raw earth applications (Houben H, Guillaud H, 2006, *Traité de construction en terre*, Éditions Parenthèses).

As mentioned above, in the past, the composition of soils suggested a preferential use and, consequently, a constructive system to be used.

Nowadays, material science has produced big progresses on the *engineering* [3] of natural soils for earth building technologies, especially for rammed earth applications, borrowing knowledges and performance evaluating procedures from different investigation fields: geotechnical and transport engineering (for the characterization and the optimization of natural soils), structural and technical physic engineering (for the evaluation of mechanical characteristics, physical and thermal properties).

This huge cognitive apparatus is necessary because an independent raw earth material science has not been organically developed yet but the use of this tools ensures a good assessment of the material properties which obviously influences the final performances of raw earth products.

## 2. National and International regulation and productive context

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. Del Rio Muñoz and Esteban [4] make a division between these practices putting them in relation with the geographic areas where they rise.

In Asia, Latin America, Africa and Middle East raw earth technologies are used for social and emergency housing, with strong efforts made in training local communities in self - building practices of low-tech raw earth dwellings. 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 light environmental impact, small embodied energy and low energetic costs in constructions 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, in order to improve their mechanical characteristics and speed up their production.

Traditionally RE 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. Another contemporary raw earth technique is compressed earth block (from now on CEB), small prefabricated bricks with almost the same composition of RE, 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, guidelines or practices on earth buildings.

Jiménez e Cañas [5] give an interesting contribution to the reorganization of knowledge on raw earth regulations, distinguishing if the sources are national standards/regulations, guidelines or technical documents. In their article, each regulation is related to the analysed technique, to the material properties they recommend to test and how to run these tests.

Usually these 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 is always to be double-checked using mechanical, visual and physical tests.

The most important mechanical test to be ran is the unconfined compressive strength test where the RE samples (prisms or cylinders, depending on the standard) should exceed basic resistances going from 1.3 MPa (value in the New Zealand Code [6]) to 2.1 MPa (as in the New Mexico Building Code [7]); indeed, according to some of these standards, the use of stabilizers such as Portland cement and lime is explicitly recommended. The use of these products should be avoided when possible because they reduce the recyclability properties of natural earths.

Visual tests usually refer to cracking and shrinkage phenomena that can be observed on the final mixes: usually standards and guidelines provide limits which are stringent depending on the raw earth technology. Usually damp technologies as RE do not show too much crack or shrinkage, because of the low amount of water used.

Finally, physical tests such as the absorption and the erosion ones are more differentiated among the guidelines, and rarely reflect the operating conditions of rammed earth structures.

Not surprisingly, countries which are endowed of Earth building codes, show also a good amount of raw earth (especially RE ones) dwellings, as 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. A brief resume of the contents of the most recent regulations on earthen technique can be found in table 1. [4][8]

**Table 1.** Earth architecture contemporary regulation.

Nation	Standards	Guidelines	Earth technique			
			RE	CEB	Adobe	COB
<b>Australia</b>		HB 195 (2002)	x	x	x	-
<b>France</b>	XP P 13-901 (2001)		-	x	-	-
<b>Germany</b>		Lehmbau Regeln (1999)	x	x	x	-
<b>New Mexico</b>	NMAC (2000)	14.7.4	x	x	x	-
<b>New Zealand</b>	NZS 4297 (1998) NZS 4298 (1998) NZS 4299 (1998)		x	x	x	-
<b>Peru</b>	N E.080		x	-	x	-
<b>Regional Africa</b>	ARSO (1996)		-	x	-	-
<b>Spain</b>	UNE 41410(2008)		-	x	-	-
<b>United Kingdom</b>		Rammed Earth Design and Construction Guideline (2004)	x	-	-	-
<b>Zimbabwe</b>	SAZS 724 (2001)		x	-	-	-

A market research that we have carried out on contemporary raw earth construction products, showed that the main earth products suppliers are United States and European countries as Germany, Austria, Spain and France. These countries provide a wide range of earth products such as:

- cladding raw earth panels for counterwalls, false ceilings and partitions;
- insulating raw earth panels (in combination with artificial and natural fibers and reinforcing meshes);
- radiating raw earth panels (with coils or electrically powered);
- compressed earth blocks;
- ready-made mixed for RE;
- prefabricated RE panels.







Some example of these products can be found in table 2.

This brief overview on raw earth contemporary production shows the wide use of raw and rammed earth-based products for cladding and coating purposes, 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. The same mechanism has been used in Martin Rauch's Lehm Ton Erde production, in which massive panels have been usually integrated inside concrete or steel framed buildings and sometimes used with insulations as granular foam glass. In some cases, companies sell a complete constructive system: this is the case of the Canadian Sirewall, which promotes an insulated anti-seismic rammed earth system. The Sirewall RE system uses a double wythe of cement stabilized RE, reinforced with vertical and horizontal steel rebars to prevent failure from earthquakes, with an EPS rigid insulation interposed. This system represents one of the most outstanding attempts to adequate traditional RE 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 and EPS.

In conclusion it's possible to infer that contemporary rammed earth technologies are often linked to cement - based ones. Rarely contemporary rammed earth seems to maintain its original characteristics of ecological and low carbon footprint technology.

**Table 2.** Contemporary construction earth products: comparison on type, uses and base materials of raw earth products.

Type of Product	Use	Picture of the product	Materials
<b>Cladding earth panels</b>	Counterwalls, false ceilings and partitions		Matrix: clay, sand, natural fibers Reinforcement: glass fiber net or juta net
<b>Insulations earth panels</b>	Insulation panels for walls		Matrix: clay, sand, natural fibers Reinforcement: glass fiber net or juta net
<b>Radiating earth panels</b>	Radiating Panels with coils, for walls and ceilings		Matrix: clay, sand, natural fibers Reinforcement: glass fiber net Internal multilayer pipe
<b>Radiating earth panels</b>	Electrically powered radiating panels		Matrix: clay, sand, natural fibers Reinforcement: glass fiber net Internal pierced carbon fiber film
<b>Ready-made mixed for RE</b>	Rammed earth walls or cladding made on site		Matrix: clay, sand, gravel Stabilizers: Portland Cement, Lime, Aluminosilicates
<b>Prefabricated RE panels</b>	Rammed earth walls or cladding		Matrix: clay, sand, gravel Stabilizers: Portland Cement, Lime, GGBS (Ground granulated blast furnace slag), Aluminosilicates

### 2.1. Italian delay in raw earth construction legislation

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 rammed 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] doesn't refer to new earth-based constructive systems, and poor attention is given to historical raw earth heritage. Earthen architecture heritage is rich in variety and spread all over the Peninsula, from Piedmont, Lombardy and Veneto (where *casolari* and *rustici* dwellings are realized with RE technology), to Abruzzo and Marche (where countryside buildings

called *pinciare* are realized with the *massone*, a technique similar to cob) and Sardinia (houses realized with *ladiri*, the traditional adobe name in Campidani, Cixerri and Sarrabus areas [10]).

While Piedmont is endowed with some guidelines for the rehabilitation of rammed earth vernacular structures, Sardinia and first the University of Cagliari, has been carrying out a careful research activity on this fragile heritage, producing both scientific issues and maintenance manuals for the inhabitants [10] [11] [12]. In these documents the main characterization procedures on soils and tests on final products are explained. Some of these procedures are based on New Zealand Earth building codes and some CRATerre guidelines; some Italian contemporary researches on raw earth technology have international impact mainly on the topics of characterization and optimization of the mechanical properties of earth products [13][14].

The lack in standards produce 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 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).

Even so, the progresses in production are meant to be forgotten if there is no holistic view on the possibilities of the innovation of a historic building technique. The delay of Italy can help in rethinking 21th century rammed earth buildings as more sustainable and more performing, using materials and processes able to guarantee excellent thermal and seismic behaviour but with a lower carbon footprint compared to those that already exist.

### **3. Performance-oriented design for rammed earth products**

The idea of working on a more sustainable and environmentally friendly RE system does not mean dealing with low mechanical and thermal performances, as well as low-tech does not mean absence of technology. The importance of performance oriented-design for RE production 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 RE products as confident building materials. This can be achieved monitoring the production through a low-tech prefabrication process.

The core idea of the research is to partially industrialize the production of RE, in order to improve the final performance of the product. The prefabrication under controlled conditions can solve many issues related to earth construction:

- Correction and optimization of the base material (soil) when it is not suitable for rammed earth construction;
- Control on the combination of different natural base materials (soils, sands, other aggregates) for the rammed earth products;
- Repeatability of the manufacturing process;
- Control on the physical, thermal and mechanical characteristics of materials and products through experimental tests;
- Control of real durability using experimental tests;
- Performance certification by product data sheets.

Prefabrication is also helpful because it reduces RE long construction times as well as the issues connected to the fact that RE is a labour-intensive technology with high risks of technological faults. In this way, natural and low-cost materials (local soils), used in combinations with waste and recycled materials (like volcanic sands and opus signinum, as aggregates inside the mix) can be combined through innovative processes, ensuring high materials performances because of the control on the production chains. After that, the final product would be transported to the building site and assembled.

Due to the strict Italian Building code which does not allow RE to be load-bearing, our system uses improved prefabricated RE elements to be assembled in combination with a reinforcing timber structure with seismic-resistant function, while RE wallings work as dissipating layers.

The timber reinforcement works as an anti-seismic and load-bearing structure and it is interposed between the massive prefabricated RE elements. Wood and raw earth have been historically combined in vernacular architectures [15], showing similar behaviours for breathability, moisture content and hygroscopicity. In the system, the RE massive elements are designed both to cooperate in the load-bearing function and to guarantee good thermophysical and hygrometric conditions.

The high thermal mass of rammed earth walls has already proved to have good performances in Mediterranean climates [16], without adding insulations. Indeed, use of insulation is suggested when the RE thickness decreases. High thermal mass of rammed earth is consequent to the high density of the material, usually ranging between 1800 – 2000 kg/m<sup>3</sup>, so that a 300 mm rammed earth wall can provide comfortable living conditions without need of HVAC control. As Ciancio, Beckett [3] and many other authors point out, rammed earth buildings have low thermal diffusivity (thermal diffusivity is calculated by dividing thermal conductivity by the thermal mass,  $mCp$ , where  $m$  is the material's mass and the  $Cp$  is the specific heat capacity), which prevents from high rates of heat transfer through the envelope because of heat absorption and storage inside the walls.

The main steps of the research are related to the optimization of the raw material, the definition of the constructive system and the modelling of its thermophysical performance.

In the first stage of the research we work on the base material that is used to manufacture the rammed earth mixes. An effort has been done in order to achieve good mechanical strength without adding additives.

### 3.1. Rammed earth material science

The first step of the research concerns the study of the base material and the optimization of the mix in order 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, in order to find a suitable soil for earth construction. The variables considered for the choice of the raw material were the dry resistance of the material (which is expression of the internal cohesion provided by clay fraction), the texture (through sieving and a simplified sedimentation test) and the linear shrinkage. While the evaluation of the dry resistance of the material is coded by several earth construction manuals, besides other qualitative assessment like the simplified sedimentation test, the combination of the pieces of information coming from the sieving analysis and the linear shrinkage test were done following the procedure proposed by Burroughs [17]. 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) and the procedure of bringing the material to the factory was not considered sustainable.

The Particle Size Distribution (from now on PSD) of the two remaining soils was determined through a laboratory test following the ASTM D7928 – 17 and the Atterberg limits. 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, was subjected to different optimization processes to improve its properties, through several stabilization process.

As it is known, stabilizing means to change the natural composition of the base material in order to regularize its behaviour. 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, in order to reduce excessive porosity, or we could add additives which can improve internal cohesion between the components of the mix.

There are three procedures of stabilization [1]:

- Mechanical stabilization: through a compaction process, soil can be densified, improving mechanical strength and reducing permeability and porosity
- Physical stabilization: through the mix of different particle sizes, texture is modified, and mechanical strength is enhanced
- Chemical stabilization: using some materials or chemical products a new binding matrix can be added besides the clay one, that link together the particles of the mix, creating new materials.



Through these procedures many results can be achieved: improvement of mechanical characteristics and cohesion, reduction of absorption and shrinkage effects, enhancement of erosion resistance to wind and waterproofing toward capillarity water.

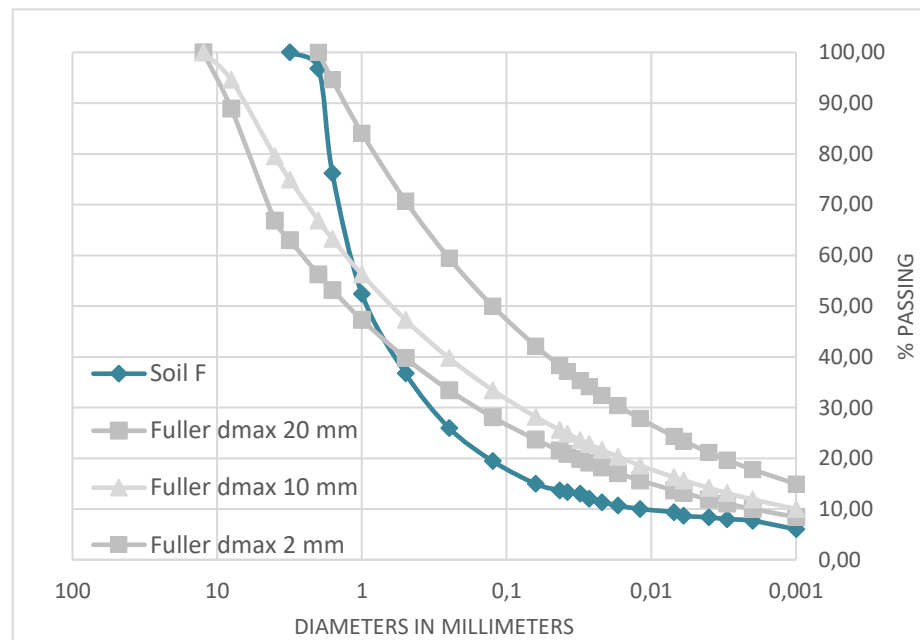
Chemical stabilization through Portland Cement is nowadays regarded as a common practice in many areas, as Australia and United States, and explicitly recommended in some earth building codes, as the NMAC or the HB195. Obviously, the addition of Portland cement increases the embodied energy of cement stabilized rammed earth, as Reddy [18] calculated amounting to  $500 \text{ MJ/m}^3$ , which is by the way only the 15 – 25% of the embodied energy of conventional burnt clay brick. Obviously, the addition of cement reduces also the recyclability of the raw earth, and therefore also the environmental impact of contemporary rammed earth technology. Prior to realize a chemical stabilization with these agents, it would be better to operate a physical correction of the base material.

The soil adopted for optimization is a Sicilian soil quarried in the area of Syracuse (figure 2). The particle size distribution is shown in figure 3. 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 clay and silt.



**Figure 2.** F soil quarried in Florida (Syracuse area).



**Figure 3.** Particle size distribution of the F soil and comparison with ideal Fuller distribution for rammed earth application [1].

In table 3 is shown the result of the plasticity test (obtained by determining Atterberg limits on the fine fraction): Liquid limit (LL), Plastic limit (PL) and Plasticity index (PI= LL - PL). In the same table are reported the acceptable limits of these values for rammed earth application, as defined by HB195, Walker and Houben & Guillaud. Comparing these results to the reference values, the mineralogy of the clay contained in Soil F is identified as a kaolinite.

**Table 3.** Atterberg limits of F soil.

Reference	Atterberg Limits		
	LL (%)	PL (%)	PI (%)
<b>HB195</b>	<35–45	-	<10–30
<b>Walker</b>	<45	-	<2–30
<b>Houben &amp; Guillaud</b>	25-50	-	2–30
<b>F Soil</b>	<b>47.30</b>	<b>30.68</b>	<b>16.62</b>

The comparison between these basic pieces of information and the current average PSD composition values (found in literature) brought us to elaborate several unstabilized rammed earth (from now on URE) mixes where the natural soil has been mixed with increasing amount of gravel and sand, following the methodology indicated by Hall & Djerbib [19]. This physical stabilization is the first experimental step in order to reach a minimum characteristic unconfined compressive strength of 1.3 MPa, in accordance with many standards like NZS, HB195, NTE E080 [20].

The particle size distribution has been changed through the addition of local pyroclastic rocks available in whole Etna volcano area. The added aggregates have different sizes: the bigger particles are gravels with diameters ranging from 12.5 mm to 4 mm, while the smaller pyroclastic sand ranges from 4 mm to 0.5 mm. Different mixes have been test, with increasing amount of gravel and sand, decreasing in the meanwhile the amount of F soil. Every mixed is identified with a code following the scheme in table 4.

**Table 4.** Rammed earth mixes.

Type of Sample	% F soil	% Gravel	% Sand	Mix code
URE	85	15	0	<b>URE810</b>
URE	70	30	0	<b>URE370</b>
URE	50	30	20	<b>URE532</b>
URE	40	30	30	<b>URE433</b>
URE	30	30	40	<b>URE334</b>

The samples for unconfined compressive strength test have been manufactured in cube shape, with dimension 150 x 150 x 150 mm (figure 4). The design density of the sample was 1900 kg/m<sup>3</sup>, so a constant amount of mix was compacted inside every formwork, at a moisture content near to its Optimum Moisture Content (usually ranging from 8 to 10% of the dry volume of the mix) to reach the design density. The compaction has been done with 3.5 kg heavy manual rammers, compacting layers of 100 mm in 50 mm ones, following operative indications provided by earth builders and producers. Every sample has been finished with a thin top layer of moist soil passing through a 2 mm sieve, in order to produce a perfectly flat surface for the mechanic press of the unconfined compressive strength test. At the end of the compaction process the samples were put in dry and aired storage rooms and cured until their weight was constant (in normal conditions this happens in 12 – 20 days, depending on the weather conditions and humidity percentage).



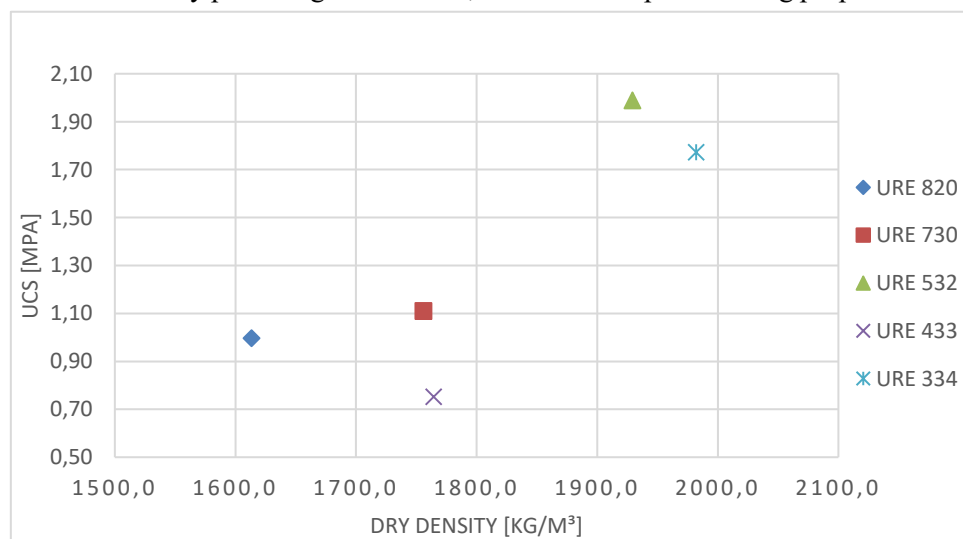
**Figure 4.** URE532 samples.

After curing, samples were crushed in a mechanical press, with an applied load rate set to 30 kN/min. Results of the average unconfined compressive strength (from now on UCS) of the cubes can be find in table 5.

**Table 5.** Average density and UCS for URE samples.

Sample	Average Dry Density [kg/m <sup>3</sup> ]	Average UCS [MPa]
<b>URE810</b>	1613.4	1.00
<b>URE370</b>	1756.0	1.11
<b>URE532</b>	1764.3	1.99
<b>URE433</b>	1982.1	0.75
<b>URE334</b>	1929.3	1.77

In figure 5 the correspondence between dry density and unconfined compressive strength values is shown. The UCS values increase when samples are compacted at higher densities, through a densification obtained by adding a variable amount of sand; in this regard we remark that a 100 kg/m<sup>3</sup> gap in dry density implies an increase of UCS of at least 1 MPa. Even so, this pattern is not confirmed by the URE433 and URE820 values. Indeed, the URE 433 shows low and out of the tendency compressive strengths, so that we must assume that some irregularities have occurred in the manufacturing process of the specimens and this batch must be discarded. On the other hand, the URE334 samples, despite having a higher dry density, do not reach the maximum  $f_{cm}$ . Probably it's due to the small amount of clay percentage in this mix, which lead to poor binding properties of the material.



**Figure 5.** Dry density vs UCS of Unstabilized Rammed Earth samples.

Based on these observations it is possible to confirm Ciancio [2] thesis on the impossibility of proving a correlation between Dry Density and strength for the URE samples. URE532 and URE334 are the only mixes that satisfy the minimum UCS set by abovementioned international standards. These UCS are homogeneous with the one found in the literature review.

#### 4. Conclusion

The use of raw earth as a contemporary construction material has several fields of application in developing countries and in developed ones. In the former ones, raw earth architecture is nowadays used for emergency architecture and in social housing interventions, using also self-building practices.

Developed and more industrialized countries in North America, Oceania and Europe are taking other directions. North America and Oceania are developing standards and building codes for earth constructions, which are helping in the progressive adaptation of raw earth products to industrial quality target for building production. This process is still ongoing, so that raw earth technologies have frequently been adapted to existing cement-based constructive technologies, through the massive use of Portland Cement, steel and artificial synthetic insulations, which obviously increase the environmental impact of the whole systems.

The lack in production of proper earth building standards generated, in European countries, a higher focus in the development of raw earth products which can improve the indoor quality of buildings, through their control of thermo-hygrometric conditions and the use of healthy natural materials. Indeed, European raw earth production is specializing in manufacturing cladding elements for internal walls and less commonly, element for exterior envelopes.

Our research moves on the definition of a contemporary rammed earth constructive system. The system aims to bring rammed earth building technologies to the quality target required by the actual building sector, without losing the positive advantages of working with natural – based and low embodied energy materials. For this reason, a prefabrication process is implemented in order to manufacture RE panels with high physical, mechanical and thermal performances, which can create comfortable indoor thermal and humidity conditions. The RE prefabricated envelope is afterward combined with a reinforcing timber structure, which performs the function of resisting to horizontal loads from earthquakes. The constructive system will be lately validated by a thermal simulation.

This paper shows the first steps of the research, which starts from the choice of the best material to use. For this aim, an analysis of the composition of 5 different natural soils was carried out, concerning their texture (through a particle size distribution test), their linear shrinkage and their plasticity (through the determination of Atterberg limits). The best natural soil was subsequently mixed with natural pyroclastic aggregates from Etna volcano area, which are an abundant resource of Eastern Sicily area, in order to correct the texture and to improve the mechanical properties of the mix. Then, encouraging results on the physical stabilization of the engineered soil were obtained.

The next step of the research on the material will concern the analysis of physical and thermal characteristics of the most performant URE samples, and the evaluation of their resistance to abrasion, in order to characterize a mix which can be used for the prefabricated RE panels. These analyses aim to answer to the quality criteria which contemporary building products must respect. It is worth noting that the effort put in the stabilization of the soil via mechanical and physical processes, without adding chemical stabilizers, follows the approach of improving natural materials without denaturing their composition, maintaining the concept of low tech and low embodied energy technologies.

New efforts must be made in order to find suitable performance evaluating indicators for natural and traditional materials which are generally penalised by industrial ones. Only through an integrated and holistic approach the innovation of historic building techniques and the contemporary earth construction could succeed in creating smarter, more adaptive, efficient and sustainable buildings.

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#### References

- [1] Houben H, Guillaud H CRATerre 2006 *Traité de construction en terre* Éd Parenthèses
- [2] Eloundou L, Joffroy T 2013 *Earthen Architecture in today's World: UNESCO International Colloquium on the Conservation of World Heritage Earthen Architecture* (UNESCO headquarters, Paris)

- [3] Ciancio D, Jaquin P and Walker P 2013 Advances on the assessment of soil suitability for rammed earth. *Constr. Build. Mater.* **42** 40-47
- [4] Del Río Muñoz M and Sainz Esteban A 2011 La evolución de los sistemas constructivos en tierra. *Construcción con tierra: Tecnología y Arquitectura. Congresos de arquitectura de tierra en Cuenca de Campos 2010/2011* 57-68
- [5] Jiménez Delgado MC, Cañas Guerrero IC 2005 The selection of soils for unstabilised earth building: a normative review. *Constr. Build. Mater.* **21** 237–251
- [6] SNZ. New Zealand Standard 4298: 1998. Materials and workmanship for earth buildings (New Zealand: Wellington)
- [7] NMAC 2003 New Mexico Earthen Building Materials Code. Construction Industries Division (CID) of the Regulation and Licensing Department (Santa Fe', NM)
- [8] Cid J, Mazarrón FR, Cañas I 2011 Las Normativas de construcción con tierra en el mundo. *Informes de la Construcción* **63** 159-169
- [9] Norme tecniche per le costruzioni 2018, DM 17 gennaio 2018
- [10] Sanna U and Atzeni C 2008 Architettura in terra cruda dei Campidani, del Cixerri e del Sarrabus, Dei Tipografia del Genio Civile
- [11] Achenza M and Sanna U 2009 Il Manuale tematico della Terra Cruda, Dei Tipografia del Genio Civile
- [12] Achenza M and Cocco C 2015 A web map for Italian earthen architecture. *Earthen Architecture: Past, Present and Future* ed Mileto C, Vegas F, García Soriano L, Cristini V (CRC press), 11-16
- [13] Miccoli L, Müller U and Fontana P 2014 Mechanical behaviour of earthen materials: a comparison between earth block masonry, rammed earth and cob. *Constr. Build. Mater.* **61** 327–39
- [14] Briccoli Bati S, Fagone M, Loccarini F and Ranocchii G 2014 Jute fabric to improve the mechanical properties of rammed earth constructions *Earthen Architecture: Past, Present and Future* ed Mileto C, Vegas F, García Soriano L, Cristini V (CRC press) 55-60
- [15] Mileto C and Vegas López Manzanares F 2017 Proyecto COREMANS: Criterios de intervención en la arquitectura de tierra, Ministerio de educación, cultura y deporte
- [16] Serrano S, De Gracia A and Cabeza LF 2016 Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions. *Appl. Energy* **175** 180-88
- [17] Burroughs S 2010 Recommendations for the selection, stabilization and compaction of soil for rammed earth wall construction. *J. Green Build.* **5(1)** 101-14
- [18] Venkatarama Reddy BV and Prasanna Kumar P 2010 Embodied energy in cement stabilised rammed earth walls. *Energy Build.* **42(3)** 380-85
- [19] Hall M and Djerbib Y 2004 Rammed earth sample production: context, recommendations and consistency. *Constr. Build. Mater.* **18(4)** 281–86
- [20] Norma E.080 Diseño y construcción con tierra reforzada 2017 Ministerio de vivienda, construcción y saneamiento. *El Peruano*