Earth as a Sustainable Construction Material. Characterization of Different Mixtures and Implementation Using the Projected Earth System

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Abstract The use of the earth as a construction material has been carried out all over the world, in walls, ramparts, fortifications. For this reason, research of this type is necessary to implement current techniques in the restoration of rammed earth constructions with the rammed earth technique. In addition, it can be used for the construction of new works for both walls and cladding. The research of the earth as a construction material is presented here through the characterization of the earth itself, in this case, edaphic soils from the weathering of the Alhambra Formation (Spain), and its mixtures with aerial or hydraulic limes and cement of low resistance. In addition, natural or recycled aggregates and additives such as water repellents and ecological enzymes, to replace binders, and additions of powder rubber and textile from used tire waste have been used. The results obtained in all the mixtures, except the one added with rubber and textile powder, are ideal for use in restoration of earth works and new construction, placed on site using the projected earth system.

Keywords Earth · Projected earth system · Restoration of rammed earth · Lime · Ecological enzyme · Powder rubber and textile fibber

1 Introduction

Construction materials are considered environmental resources which have been obtained in order to be treated to shape the buildings that surround us. These materials undergo, to a greater or lesser extent, a series of natural processes that help us better understand how they are to be used and used, as well as their behavior throughout their useful life. Throughout history, the methods of extraction and treatment of these have changed, enhancing their virtues and facilitating adaptation to the different requirements to which they are going to be exposed.

All this great variety of materials that we find around us has a common component reinterpreted since the beginning of construction, we speak of a vernacular

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architecture, an architecture understood and based on the genesis of its environment, in which its components have that authenticity imprinted in their training. One of the materials that most corresponds to this comment is about the earth, this being one of the most used materials throughout history. It is a material present in practically all parts of the world, having been exploited by a multitude of civilizations which have used many techniques. All this set of practices provides us with information about how the land gives identity and shape to the constructions and elements in which it is used, arriving with this statement at the concept of heritage.

However, conserving the heritage built on land is not only considering the construction typology and its limitations, but it also consists of a task of research, rescue, and dissemination of the techniques used, which, since it is traditional architecture, depends on regional wisdom and presents the disadvantage that, since they are knowledge transferred orally, they do not appear in documents. To a certain extent, this problem has influenced the fact that currently the choice of the extraction area for the material is not an easy task, this being one of the main factors for the construction of walls.

The rammed earth is a constructive system used for millennia in places like Egypt, India, China, Syria, Peru, etc. In Spain, the land heritage built using this technique is quite extensive; in fact, it has remains belonging to 820 BC [16]. Specifically, in Granada (Spain) is one of the most extensive monuments built with rammed earth, the Alhambra, as well as domestic houses in the Albaicín and Sacromonte neighborhoods that give the city so much identity and name.

The rammed earth technique consists of filling a formwork with layers of earth of 10–15 cm compacting each one of them with a tamper. The formwork is made up of two separate parallel planks, joined by a crossbar. In compaction with techniques in which the mud is used in a more humid state, the rammed earth technique provides much lower shrinkage and greater resistance. The advantage in relation to adobe construction techniques is that brick constructions are monolithic and therefore have greater stability [20].

This earth system, as we have commented, consists of the tamping of the raw earth by layers inside a wooden formwork where the cohesive property of the clays is complemented by the mechanical compression of the material. Soil compaction is influenced by the degree of humidity. A soil that is too wet cannot be compacted properly just as one that is too dry will not work properly. For this reason, the optimum moisture content is essential so that it is just enough to activate the binding capacity of the clays, which ranges from approximately 0–10% [16]. It is therefore a system in which when using raw earth, the choice of raw material is essential, complementing it with the ideal degree of humidity, and the use of stabilizers to guarantee its durability.

Adobe was used on the Great Wall of China along with stone more than 5000 years ago and was subsequently used in houses and walls about 2700 years ago [18]. On the other hand, in North Africa and the Middle East, the most abundant material was and is earth, for this reason, there are also numerous examples of walls built with earth, a material that was erected as an easy, fast, and inexpensive way to build fortifications.

In addition, throughout the Mediterranean, there are Phoenician vestiges that used the earth in the form of adobe as a construction material, both in North Africa and on the Spanish coasts [3, 4, 17]. There are also descriptions of Roman writers who narrate the construction of clay towers in the invasion of the Iberian Peninsula carried out by the Carthaginians in 218 BC. In the context of pre-Columbian America, there is no evidence of the use of land as a building material, in fact, the first construction on land in North America was carried out by the Jesuit missionary Manuel Da Nobrega in 1549, which sent a request to Europe requesting craftsmen and carpenters to build clay and adobe walls.

In the same way, there is knowledge of earthen constructions carried out in early times in the area of Brazil [13, 22].

In the late Middle Ages, Spain was under Muslim rule, until the Catholic Monarchs, in 1492, took the last Muslim kingdom, the city of Granada (Spain). The Christian Kings implemented the earth building technique by hiring Muslim artisans. Later, the clay was mixed with fired brick, making stronger and more durable fortifications [2].

The proliferation of the earth as a building material was such that there are numerous cities that were built in this way, such as Babylon in Iraq, and the oldest known city, Catalhöyük, as has already been referred to, in Anatolia, from the seventh millennium BC, that it already had the houses built with adobe. In ancient Egypt, adobe, made with silt from the Nile, was frequently used in the construction of houses, tombs (mastabas), fortresses, and even palaces, although the Egyptians were also the first to use the carved stone to erect temples, pyramids, and other monumental buildings. In Peru, there is the citadel of Chan Chan, the largest mud city in America. In Jiayuguan, China, there is a wall partially built with rammed earth, the upper level finished with bricks, built during the Ming dynasty (1368–1644), and giant bearing wall like the Fujian Earth Building (TuLou) of the song-yuan dynasty (800 years ago) [29]. In our temples, this building material finds manifestations such as vestiges that patent its use by various civilizations such as the Roman or Muslim and samples of recent buildings that show that this material is part of a living earthen architecture [14, 19].

Clay, at the end of the Second World War, was once again a widely used construction material in East Germany due to its availability and low price [27]. The same happened in Australia, where his book "Build Your House of Earth" was until recently the accepted standard for construction on Australian soil [21].

All these different readings on the use of land under construction through the ramming technique coincide in one thing, during the development of the technique a series of problems arise about the use of soils of the geological formation of the area that has been used for so long for constructions through this method, since they are considered the best for such construction typology, this has made them be used for a long time, but the cited problems are such as access to extraction of the land and ease of obtaining it. For this reason, in this research, the main objective has been the behavior of colluvial and/or edaphic soils from the Alhambra Formation in Granada (Spain), which has provided a great development to the city, both in application and functionality.

As it has become clear, the use of the earth as a construction material has been carried out all over the world. For this reason, research of this type is necessary to implement current techniques in the restoration of rammed earth constructions with the rammed earth technique. In addition, it can be used for the construction of new works for both walls and cladding.

In this research, earth has been used as the main material, which has been mixed with different binders, aggregates, and additives. On the other hand, the technique of laying by projection has also been presented.

2 Materials and Method

2.1 Materials

2.1.1 Earth. Colluvial/Edaphic Soils

In this case, the chosen earth corresponds to the B horizon of the edaphic soil of the F. Alhambra (South of Spain, in Granada, Fig. 1) mixed with the roof of the C horizon. These soils are found in situ in the formation itself or accompanying the discharges that have been made in different nearby excavation areas, almost all for building projects.

The most superficial and altered soil formed by angular gravels and sandy silts where the vegetation corresponding to horizon A develops from the extraction zone. In horizon B, there are macroscopic vestiges of the mother material with rounded edges that are much cemented with less organic matter than in the upper level, made evident by the brownish hue of this layer. The C horizon would be the base material that is made up of very different rocks. These are colluvial sediments that make up the Alhambra Formation, characterized by its reddish color. All the results of the study of the physical–mechanical properties of edaphic soils will be compared with those obtained for the Alhambra Formation which is used in many of the surviving

Fig. 1 General view of the extraction area of the earth used (left) and soil collected in the laboratory (right)

rammed earth constructions in the city of Granada (Spain), including fortifications, dwellings, and walls [15].

The material was extracted in an area near the town of El Fargue, very close to Granada capital. Here, there are lands and orchards of anthropic spills or colluvial soils of the Alhambra Conglomerate that are easily accessible (Fig. 2).

X-ray diffraction tests have been carried out to obtain the mineralogical composition of this soil (Fig. 3), obtaining quartz (46–47%), dolomite (18–39%), and

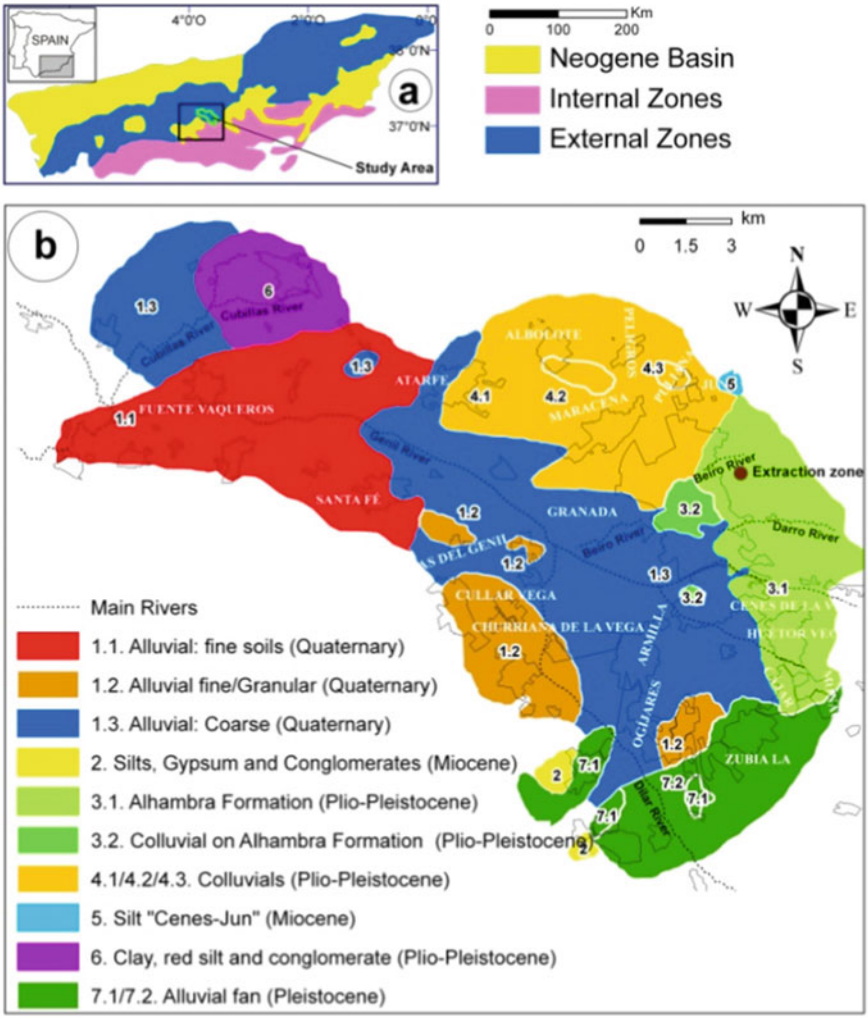

Fig. 2 General tectonic sketch of the central and eastern Betic Cordillera (**a**). The remarked zones show the location of Fig. 1b, (**b**) spatial location of soil units of the metropolitan Area of Granada. Town boundaries are shown with a thin polygonal line. Modified from Valverde-Palacios [28]

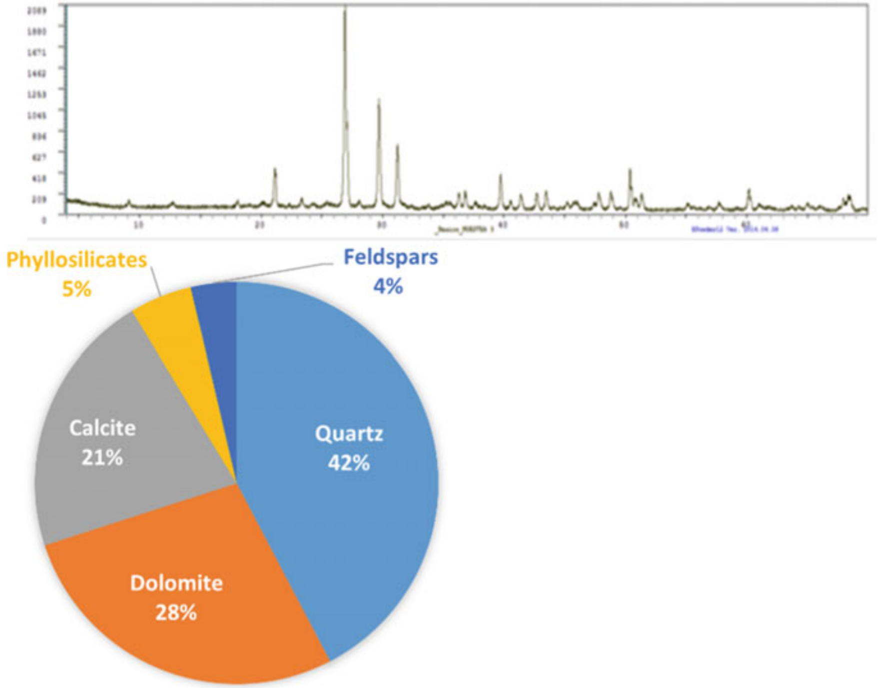

Fig. 3 Soil-sample powder-X-ray diffraction test results. The mean value of the three samples analyzed is presented

calcite (17–27%) as the dominant mineralogical elements. Feldspars (3–4%) and clay minerals, phyllosilicates (4–7%), such as chlorite and muscovite, are found to a lesser extent.

This mineralogical composition is very similar to the results obtained for soil samples from the Alhambra Formation (Ontiveros 1995, [14]), a result that confirms that the soil presented in this investigation comes from the weathering of level 2 of the F. Alhambra, on its edaphic horizon B with some C.

2.1.2 Binders

- CL90-S [7], hydrated calcium lime powder (>90% CaO + MgO). For the rehabilitation and restoration of the interior and exterior of emblematic and old buildings.
- NHL 5 [7], natural hydraulic lime. It is a type of lime widely used in restoration and green building. Its main characteristics include its low tendency to cracking, its great plasticity, and adherence to various surfaces. Regarding the most notable mechanical characteristics, we have a compressive strength of 2.0 MPa at 7 days and 5 MPa at 28.

- BL 22.5X [6], white masonry cement with a compressive strength greater than 10 and 22.5 MPa at 7 and 28 days, respectively, according to EN 413-1: 2011. In the case of cement, no mechanical tests have been carried out since this information was available through a quality certificate from the supplier, to which it must be added that the percentage used, with respect to the weight of the earth, is very low, so its importance as a binder is only in the short term until the main binder, lime, begins to carbonate, providing resistance.

2.1.3 Aggregates

- Dolomitic limestone natural aggregate (Fig. 4)

These aggregates come from dolomitic rocks that are basically composed of magnesium carbonate (Ca Mg $(CO_3)_2$), not reactive with the alkalis in cement. It is a well-processed material, which presents morphology like that resulting from aggregates from crushing. In this case, the high degree of micro-cracking of the mountain massif, due to tectonic phenomena, allows the rock to disintegrate when executing the extraction process, resulting in an aggregate equivalent to that of artificial crushing.

- Recycled aggregates from construction and demolition waste (Fig. 5)

They are waste from construction and demolitions that are transported to the plant to be treated through crushing and crushing processes, as well as a selection of the ideal material. In our case, we have a mixture of two types of fractions: fine fraction or sand (0/4 mm) and coarse fraction or gravel (4/8 mm). In its composition, we can find the following materials: concrete in a higher percentage, ceramic material, bricks, glass stoneware, porcelain, etc. These aggregates can be coded as 17 01 07 [23] according to the European waste list (Order MAM/304/2002, of February 8. Recovery and disposal operations of waste and European waste list. Chapter 17

Fig. 4 Dolomitic limestone natural aggregate

Fig. 5 Recycled aggregates

of the European waste list Annex 2 BOE, no. 43 (ref.: BOE-A-2002-3285)). They comply with the specifications established by the Spanish structural code. It is a well-processed material, with a suitable granulometry to be used in the earth projection technique and compatible with the earth used.

In both cases, their purpose is to correct the granulometric curves of the base material, the earth, in order to achieve greater compactness in the mixture as a whole; in the case of recycled materials, their use also has an ecological function, the elimination of waste.

2.1.4 Additive

Waterproofing: In the case of durability tests against rain, a water-repellent additive from SIKA, SikaProof L-100, was used.

Ecological enzyme as a by-product of sugar cane processing. The product is called COMPAT-TO®, produced and provided by nanosystems, and is composed of a mixture of organic enzymes that catalyze a binding action on plastic particles, for which a plasticity index greater than 10 and a content of clay greater than or equal to 20%.

2.1.5 Clays

The weathered soil of the Alhambra Formation has insufficient fines content for the ecological enzyme to bind the clay material. For this reason, two types of clays (Table 1, Fig. 6), from the company ARGILES COLADES S.A., have been used for the mixtures in which the enzyme has been used.

Table 1 Chemical composition of the two types of clays used

Chemical composition (%)	Micronized clay pen F gray	Micronized clay pen F beige
Al_2O_3	15	18,13
SiO_2	75,21	55,22
K_2O	0,64	3,59
CaO	0,40	4,62
Fe_2O_3	5,50	6,20

Modified from http://argilescolades.com/

Fig. 6 Micronized clay pen F gray (left), micronized clay pen F beige (right)

2.1.6 Rubber Powder and Textile Fibers

Material from used tire waste (Fig. 7), which is subjected to a mechanical crushing process in order to obtain different granulometries that serve us in our agglomerate of earth. This mechanical grinding is also responsible for separating all the components of the tires, so that the textiles, steel, and rubber are grouped independently, and the "rubber powder and granules" are free of impurities and can be used.

Fig. 7 Rubber powder and textile from tire waste

This material is divided into granules, with thicknesses of approximately 4 mm or rubber powder that turn out to be smaller particles, depending on the granulometry, the earth will have one use or another, either to make rammed mud or to use the projection technique.

2.2 Methodology

Once all the materials described in Sect. 2.1 had been received, the following tests were carried out:

Identification tests

- Determination of the particle size distribution by sieving [10]
- Determination of liquid and plastic limits [12]
- Soil type classification according to unified soil classification system [1]
- Qualitative determination of soluble sulfates content in a soil [25].
- Determination of the carbonate content of a soil [24]
- Organic matter content of a soil [26]

Physical-mechanical tests

- Compactation test. Standard proctor [6]
- Unconfined compression test [11]

One of the innovations of this research consists of the methodology of putting into work by projection of the earth with the proposed dosages. Specifically, a Tigre trademark plasterer (model P4 for walls) has been used. TIGRE ™ plastering machines have been used throughout the world for more than 50 years to spray concrete and mortars on all types of construction systems. The use of plastering machines not only generates significant savings in labor time and material waste, but also does not require specialized labor. The TIGRE ™ plastering machine connected to the compressor and loaded with mix in its bucket manages to apply the material at a speed and with adherence impossible to achieve with manual installation.

In addition, accelerated carbonation tests have been carried out, adopting the regulations for the case of concrete [8]. On the other hand, durability tests against rain, with a device designed in the construction materials laboratory of the Department of Architectural Constructions of the University of Granada, have been carried out.

3 Results and Discussion

This section presents the most relevant results obtained in the most suitable proportions of each of the mixtures that will be compared with the standard mixture established by only soil for the Proctor tests and resistance to compression or by soil + natural dolomitic aggregate + aerial lime + cement in the case of projection tests. Specifically, the materials that make up the studied mixtures are the following:

- Earth
- Earth + natural dolomitic aggregate
- Earth + recycled aggregate
- Earth + aerial lime + white cement
- Earth + natural hydraulic lime + white cement
- Earth + natural dolomitic aggregate + aerial lime + white cement
- Earth + recycled aggregate + aerial lime + white cement
- Earth + ecological enzymes + clay
- Earth + rubber powder and textile fibber
- Earth + rubber powder and textile fibers + aerial lime + white cement.

However, the results of those mixtures that have finally been used to put them into work through the earth project system are presented here, so the rest of the mixtures should be understood as intermediate tests for better characterization.

3.1 Size Distribution, Atterberg Limits, Soil Type Classification, Carbonate, and Sulfate Content

In the case of the base material, the earth, the sample under analysis (Fig. 8) is characterized by having between 6 and 10% in fines (sizes smaller than 0.088 mm sieve), a percentage of gravel that ranges from 3 to 9% (sizes larger than 10 mm sieve). The percentages of sand vary between 53 and 72%, those of gravel between 13 and

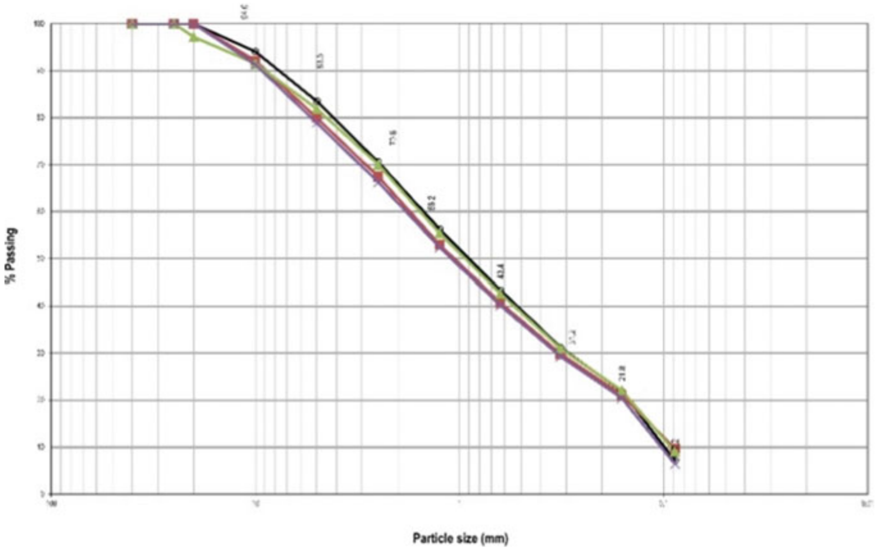

Fig. 8 Granulometric distribution of the earth used

35% and those under 0.08 (silts and clays) between 12 and 22%. The uniformity coefficient varies between 15 and 18, indicating that it is fairly uniform. As for the curvature coefficient, it is between 1 and 3 classifying it as a well graded soil.

On the other hand, the Atterberg limits for the earth were determined in the laboratory on the fine particles (passing through the ASTM 40 sieve) obtaining the following results: silts and inorganic clays of low-medium compressibility and plasticity, respectively, that is, CL-ML, ML, or CL, with LL between 21–24% and PL between 18–20%.

Both size distribution and Atterberg limits establish an SM or SC-SM classification [1] with different percentages of gravel for the soil used. If we compare with the results in samples from level 2 of the "Alhambra Formation" [15], which corresponds to the parental sample of this edaphic soil, the lack of fines in the soil of this investigation is corroborated, since that we lack samples classified as SC, as well as the significant presence of coarse (gravel) that at the aforementioned level provides GC and GC-GM classifications. Therefore, the edaphic soil in question differs fundamentally from its parent soil in that the clay content is very low, and the coarse sizes are also poorly represented. This is a consequence of the weathering process of the parent soil from which the edaphic soil originates.

The carbonate content varies between 15.50 and 32.50%, resulting in a characteristic average value of 22%, taking into account that two of the dominant components of the soil are carbonates (calcite, dolomite), which explains why the highest values are found between 5 and 16 mm where calcite and dolomite grains should be especially concentrated, also, in the finest particles of this level (0.16–0.18 mm), the carbonate content is also elevated, which is quite normal in the B horizon of edaphic soils due to the washing out of salts in the upper horizon. Compared to Alhambra Formation (level 2), carbonates range between 13.5 and 17.1%, essentially concentrated in fines [15].

A qualitative determination of sulfates has been carried out, and it has been determined that they are absent. The Alhambra Formation also lacks sulfates in its composition, as does the soil under study (Ontiveros 1995, [15]). The organic matter content is very low, not exceeding 0.13%, so it is a soil with a low-organic content of less than 1%. These results are similar to those obtained for the levels of the Alhambra Formation, which in general tends to be null as it is not affected by edaphogenesis processes.

3.2 Compactation Test. Standard Proctor

In the standard proctor test (Fig. 9), the maximum density and optimum moisture content, for the earth, vary between 2.01 and 2.17 g/cm^3 and 8.1–8.5%, respectively, and 2.10 g/cm^3 and 8.0% are adopted as the most characteristic values for the edaphic soil of the Alhambra Formation in its B horizon with some mixing of the parent material (C). The Proctor densities of level 2 of the Alhambra Formation [15] vary between 2.0 and 2.06 g/cm^3. In the case of the research by Ontiveros (1995) and Fuentes et al. [15], the Alhambra Formation presents values of 2.21 g/cm^3 at level

Fig. 9 Pictures show an example of the performance of a standard proctor test

Table 2 Results of the standard Proctor test (the percentages of binders, aggregates, and rubber are referred to the weight of the earth)

Material or mix	Maximum density (g/cm^3)	Optimal humidity (%)
Earth	2.02	8.5
Earth + 20% dolomitic natural aggregate	2.02	10
Earth + 8% aerial lime + 1%white cement	2.04	12.7[a]
Earth + 8% natural hydraulic lime + 1% white cement	2.02	13.5[a]
Earth + 20% recycling aggregate	1.91	13[b]
Earth + 6% beige clay	2.05	8.5
Earth + 7.5 ml enzymes	2.03	8.5
Earth + 7.5 ml enzymes + 6% gray clay	2.01	8.5
Earth + 7.5 ml enzymes + 6% beige clay	2.04	8.5
Earth + 10% powder and textile rubber fibers	1.83	11.3

[a] 22% (relative to the weight of the cement) more water has been added
[b] 4.5% more water has been added

1, 2.16 g/cm^3 at level 2, and 1.87 g/cm^3 at level 3, for optimum moistures of 8.4%, 7.7%, and 9.5%, respectively.

In addition, standard proctor tests have been carried out on the main mixtures, that is, with natural dolomitic aggregates, with recycled aggregates, with enzymes, with enzymes and clays, and with powder rubber and textile fibers from tire waste. Table 2 shows the results obtained for maximum density and optimal humidity.

According to the results shown in Table 2, it is observed that the lowest proctor densities are obtained in the case of the mixtures of soil + powder and textile rubber fibers (1.83 g/cm^3) and for soil with recycled aggregate (1.91 g/cm^3), a question that is logical given the low density of used tire dust and textile and the lower density of recycled aggregate. On the other hand, it is observed that in these two mixtures, the optimum humidity increases, an issue that needs to be corrected later with the use of fluidizers that reduce the amount of water to minimize shrinkage cracks for installation using the projection technique. The maximum density of all mixes and additives, earth with aerial lime and white cement, earth with natural hydraulic lime and white cement, hardly varies, ranging between 2.03 and 2.11 g/cm^3 for proctor compaction moistures between 8 and 13%, increasing with the addition of binders and especially for natural hydraulic lime (NHL 5).

On the other hand, it is well known that lime, and especially airborne lime, is a binder that does not provide significant resistance in the very short term, so in this case, it is necessary to complement, for putting into work, whatever the methodology used, with the addition of another type of binder, in this case white cement, which was used in 1% with respect to the weight of the earth; this new addition requires 22% (of the weight of the cement) more water added to hydrate it.

As previously mentioned, the data obtained are like those provided by other works in the tests carried out on level 2 of the Alhambra Formation and to those obtained for the materials of the Alhambra Formation, which have been the most widely used to build part of Granada's earthen heritage [15].

3.3 Unconfined Compression Test

Once the main materials have been characterized in terms of grain size, plasticity, and proctor density, compacted samples have been made at the maximum density and with the optimal humidity that resulted from the referred standard proctor test.

The mean compressive strengths of the earth (maximum density is 2.02 g/cm^3 and optimal humidity 8.5%) are 1.90 MPa (Figs. 10 and 11). These results are low if compared with others belonging to an outcrop of the Alhambra Formation level 2, which indicate that the compressive strengths of this type of material are of the order of 3.7 MPa for a density of 2.05 g/cm^3 and a humidity of 9.55% [15]. However, if we compare it with a fine level of the Guadix Formation, we obtain values of 0.8 MPa for a maximum proctor density of 2.15 g/cm^3 and optimum humidity of 8.46%; this research was carried out for the construction of an information office in a vault, built with soil with walls of 0.40 m thick, in the cave complex of Trópoli in Alcudia de Guadix, Granada, Spain [28].

Comparing the compressive strengths obtained with only earth, in terms of earth mixed with natural dolomitic aggregates and with 10% air lime—CL90S- or natural hydraulic lime (NHL 5) and 1% white cement—BL 22.5 x—(all the percentages of the binders are referred to the weight of the earth) and subjected to seven days of forced carbonation (Fig. 11) (1–3% CO_2), an increase of the order of 50% is observed. On the other hand, when using recycled aggregates, the problem they have in terms of greater absorption compared to the natural dolomitic aggregate has been

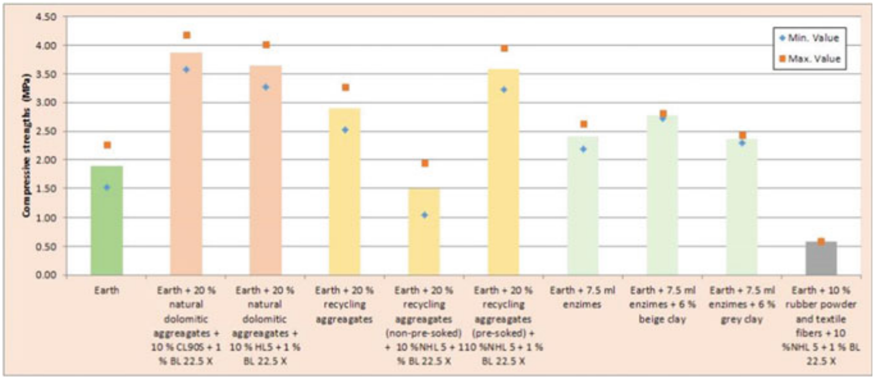

Fig. 10 Compressive strength results in compacted dry samples at standard proctor density

Fig. 11 Electric compression multi-test machine used (left). Forced carbonation chamber (top right) and sample after unconfined compression test and depth of carbonation test with phenolphthalein (bottom right)

appreciated; for this reason, the low resistance obtained, 26% less, makes it necessary to pre-wet the aggregate with 5% of water with respect to the weight of the dry mass of recycled aggregate added according to the investigations of Cuenca-Moyano et al. [5]; with this pre-wet method, and also after seven days of forced carbonation, an increase in compressive strength of around 47% was achieved.

The mixtures of earth with ecological enzymes, to replace binders, have been very satisfactory in the case of the addition of clay (6% with respect to the weight of the earth), and even more so for the type micronized clay pen F beige in which 31% more is achieved compressive strength compared to ground only.

On the contrary, the use of rubber powder and textile fibers has revealed a notable drop in compressive strengths (~200%), an issue that was to be expected given the low density of the one with this residue. However, this mixture opens up a new line of research for the use of this product as a thermal insulating material put into work using the Projected Earth ™ technique.

Regarding the durability in simulated rain test, after 90 min (Fig. 12), the compact specimens at standard proctor density of the different mixtures have a heterogeneous behavior with mass losses of between 10 and 25% for those of only earth, between 2 and 5% for earth + natural aggregate + lime + cement, the most suitable result is aerial lime, a very similar result in the case of substitution of natural aggregate for recycled aggregate. On the other hand, the mass losses measured in the other mixtures, with ecological enzymes and with powder and textile fibers, the weight loss reached 40–50%, an issue that was not later reflected in the projected mixtures that are developed in the next section.

Fig. 12 Example of cylindrical samples compacted to standard proctor density placed in rain test machine

3.4 Commissioning Test Using the Projected Earth System

The system presented is a patent and registered trademark owned by the University of Granada (Spain) and by the inventors, Fuentes-Gracía, R., Valverde-Espinosa, I and Valverde-Palacios, I. [14, 15]. However, this technique began with a type of machinery similar to that used to spray concrete by wet means that requires great specialization and high-capacity compressors. For this reason, the projection of four mixes with a Tigre ™ plastering machine (Fig. 13) is now presented as an innovation, which does not require much experience and is much more versatile.

Specifically, the mixtures that have been projected are the following (Fig. 14):

- Earth + natural dolomitic aggregate (NA) + aerial lime (CL90S) + white cement (BL22.5X) + water-repellent additive (WRA)
- Earth + recycled aggregate (RA) + aerial lime (CL90S) + white cement (BL22.5X) + water-repellent additive (WRA)
- Earth + ecological enzymes (EE) + beige clay (C) + water-repellent additive (WRA)
- Earth + rubber powder and textile fibers (RPT) + CL90S) + white cement (BL22.5X) + water-repellent additive (WRA)

The mixtures were prepared in a concrete mixer with a pre-established order of filling, according to the previous investigations carried out by Fuentes-García [14], to achieve the greatest possible homogeneity. Tables 3 and 4 show the ideal filling orders for the different mixtures:

The result of the projection of the different mixtures is shown in Fig. 13 in which it can be seen that the texture and adherence to the ceramic support have been very satisfactory. Subsequently, samples were extracted to test them under compression, obtaining as a result, the values shown in Table 5. In this case, durability tests have not been carried out but it should be noted that after two and a half years, in a climate such as Granada (Spain) with annual average temperatures between 0 and 34 °C and

Fig. 13 **a** Ceramic brick factory wall that will serve as a support to project the mixtures. **b** Example of materials dosed by weight prepared for projection. **c** Tigre plaster sprayer plugged into compressor

a precipitation around 300 mm/year, the projected mixtures are in perfect condition and no mass loss.

Regarding the results of compressive strength on carved samples extracted from the projected mixtures, a decrease of the order of between 46 and 60% is observed with respect to the cylindrical specimens compacted to the density of the standard proctor test. These decrease percentages are consistent with those obtained in the previous research such as Fuentes-García [14]. The concrete results can be seen in Table 5.

4 Conclusions

After the results of all the tests that have been presented for the characterization of the proposed mixtures, it can be concluded in a general way that all except the one added with dust and textile from tire waste are suitable for use both in new construction and for rehabilitation of rammed earth-based constructions using the Tapial technique.

In addition, the “projected earth system” laying technique using a plastering machine is viable as a construction technique, achieving adequate strength and durability while saving time and manpower.

Fig. 14 Result of the projection of the different mixtures. **a** Earth + natural dolomitic aggregate + aerial lime + white cement. **b** Earth + recycled aggregate + aerial lime + white cement. **c** Earth + ecological enzymes + clay. **d** Earth + rubber powder and textile fibers + aerial lime + white cement

Table 3 Ideal filling order for the case of earth + dolomitic natural aggregate and for earth + recycled aggregate

	Earth + NA		Earth + RA	
	Fill order	Quantity	Fill order	Quantity
1°	Water	All	Water	All
	CL90S or NHL 5	All	CL90S or NHL 5	All
	BL 22,5x	All	BL 52,5	All
2°	Earth	1/2	Earth	1/2
	NA	1/2	RA	1/2
3°	Earth	1/2	Earth	1/2
	NA	1/2	RA	1/2
	WRA	All	WRA	All

Table 4 Order of filling suitable for the case of earth + ecological enzymes and for earth + rubber powder and textile fibers

	Earth + RPT		Earth + EE	
	Fill order	Quantity	Fill order	Quantity
1°	Water	All	Water	Todo
	CL90S	All	EE	Todo
	BL 52,5	All	Earth	1/2
2°	Earth	1/2	C	Todo
	Cuacho	1/2	NA	1/2
	NA	1/2	Earth	1/2
3°	Earth	1/2	NA	1/2
	RPT	1/2	WRA	Todo
	NA	1/2		
	WRA	All		

The use of construction and demolition waste, specifically recycled aggregate, and rubber powder and textile fibers from tire waste lengthens the life cycle of these products, fully entering the field of circular economy.

Table 5 Results of the tests of mean resistance to compression of the samples of the different projected mixtures in comparison with those obtained of the compacted samples at the density of standard proctor tests

	Mean value compressive strength (Mpa)	
	Samples standard Proctor tests	Samples from projected mixtures
Earth + 20% natural dolomitic aggreagates + 10% CL90S + 1% BL 22.5 X	3.88	1.71
Earth + 20% recycling aggreagates (pre-soked) + 10%NHL 5 + 1% BL 22.5 X	3.59	1.42
Earth + 7.5 ml enzimes + 6% beige clay	2.78	1.25
Earth + 10% rubber powder and textile fibers + 10%NHL 5 + 1% BL 22.5 X	0.58	0.31

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References

1. American Standard ASTM D2487–11. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)
2. Ballesteros P, Kirchner H, Fernández M, Ortega J, Quirós JA, Retamero F, Sitjes E, Torró J, Vigil A (2010) Por una arqueología agraria de las sociedades medievales hispánicas. Propuesta de un protocolo de investigación. In Por una arqueología agraria. Perspectivas de investigación en las sociedades medievales hispánicas, pp 185–202. http://www.rmoa.unina.it/id/eprint/143
3. Chazelles CAD (1993) Savoir-faire indigènes et influences coloniales dans l'architecture de terre antique de l'extrême-occident (Afrique du Nord, Espagne, France méridionale). In: Conferência internacional sobre o estudo e conservaçao da arquitectura de terra (7a). Silves (Portugal), 24 a 29 de Outubro 1993, pp 159–165
4. Costa C, Cerqueira Â, Rocha F, Velosa A (2019) The sustainability of adobe construction: past to future. Int J Archit Heritage 13(5):639–647. https://doi.org/10.1080/15583058.2018.1459954
5. Cuenca-Moyano GM, Martín-Morales M, Valverde-Palacios I, Valverde-Espinosa I, Zamorano M (2014) Influence of pre-soaked recycled fine aggregate on the properties of masonry mortar. Constr Build Mater 70:71–79. https://doi.org/10.1016/j.conbuildmat.2014.07.098
6. European standard EN 413-1:2011. Masonry cement—Part 1: composition, specifications and conformity criteria
7. European standard EN 459-1:2016. Building lime—Part 1: definitions, specifications and conformity criteria
8. European standard EN 13295:2005. Products and systems for the protection and repair of concrete structures—test methods—determination of resistance to carbonation

9. European standard EN ISO 17892-1:2014. Geotechnical investigation and testing—laboratory testing of soil—Part 1: determination of water content
10. European standard EN ISO 17892-4:2016. Geotechnical investigation and testing—laboratory testing of soil—Part 4: determination of particle size distribution
11. European standard EN ISO 17892-7:2017. Geotechnical investigation and testing—laboratory testing of soil—Part 7: unconfined compression test
12. European standard EN ISO 17892-12:2018. Geotechnical investigation and testing—laboratory testing of soil—Part 12: determination of liquid and plastic limits
13. Flores R (2005) A construção em taipa de pilão no Brasil: as Casas Bandeiristas de São Paulo. Arquitectura de Terra Em Portugal, pp 92–95
14. Fuentes-García R (2010) Construcciones de tierra. El tapial. Nuevo sistema para construcción y restauración mediante la técnica de "Tierra Proyectada". Tesis Doctoral. Granada, Spain
15. Fuentes-García R, Valverde-Palacios I, Valverde-Espinosa I (2015) A new procedure to adapt any type of soil for the consolidation and construction of earthen structures: projected earth system. Mater Constr 65(319):e063–e063
16. Guerrero Baca LF (2007) Arquitectura en tierra. Hacia la recuperación de una cultura constructiva. Apuntes: Revista de estudios sobre patrimonio cultural. J Cultural Heritage Stud 20(2): 182–201. ISSN 2011-9003. (Ejemplar dedicado a: Arquitectura en tierra)
17. Houben H, Guillaud H (2001) Earth construction. A comprehensive guide. itdg Publishing, London
18. Keefe L (2012) Earth building: methods and materials, repair and conservation. Taylor and Francis, London
19. Marchiori C (2015) Arquitectura en tierra de la prehistoria y protohistoria en el Próximo Oriente. Estudio arqueométrico del adobe en los yacimientos de Tell Halula, Yumuktepe y Tell Tuqan. Universitat Autònoma de Barcelona
20. Minke G (2001) Manual de construcción para viviendas antisísmicas de tierra. Forschungslabor für Experimentelles Bauen Universidad de Kassel
21. Moor M, Heathcote K (2002) Earth building in Australia—durability research. In: Proceedings of Modern Earth Building, Berlin, Germany, 19–21 April 2002, pp 129–139
22. Puccioni S, Lyra CC (1993) O uso da Taipa-de-Pilao em construcoes Luso-Brasileiras. In: Conferência internacional sobre o estudo e conservaçao da arquitectura de terra (7a). Silves (Portugal), 24 a 29 de Outubro 1993, pp 296–298
23. Sanchez-Roldan Z, Martin-Morales M, Valverde-Espinosa I, Zamorano M (2020) Technical feasibility of using recycled aggregates to produce eco-friendly urban furniture. Constr Build Mater 250:118890
24. Spanish standard UNE 103200:2021. Determination of the carbonate content of a soil
25. Spanish standard UNE 103202:2019. Qualitative determination of soluble sulphates (in water) content in a soil
26. Spanish standard UNE 103204:2019. Organic matter content of a soil by the potassium permanganate method
27. Steingass P (2004) New chances for modern earth building. In: Actas del II Seminario Iberoamericano de construcción con tierra [Recurso electrónico]: Escuela Técnica Superior de Arquitectura de Madrid, 18 y 19 de septiembre de 2003. Mairea Libros, pp 417–425
28. Valverde-Palacios I, Fuentes R, Valverde-Espinosa I, Martín-Morales M, Del Moral Ávila C, Delgado Méndez L, Santos J, Canals Peres E (2012) Projected Earth System®. Aplicación de esta técnica a la construcción de viviendas sostenibles y ecológicas: Ecodome. XI Congreso Internacional de Rehabilitación del Patrimonio Arquitectónico y Edificación (El Patrimonio Ibérico). Cascais (Portugal). Libro de actas digital
29. Zhang PC, Luo K, Liao WB (2012) Study on the material and the structure of Earth building in Fujian. In: Advanced materials research. Trans Tech Publications Ltd., vol 368, pp 3567–3570