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A Proposed Experimental Method for the Preparation of Rammed Earth Material

Application of the Method to A Case Study

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***Abstract* — To build with raw earth, several methods can be applied. The most common of them are: adobe, compressed earth blocks and rammed earth. However, not all earth types are suitable for these construction methods. Indeed, for each construction technique, there are requirements to fulfilled, particularly regarding grain-size distribution and plasticity proprieties of the earth chosen to be used. This paper presents a case study on a clayey earth. The aim is to check its suitability for rammed earth technique. an experimental method has therefore been adopted to achieve this purpose. As a first step of this approach, the earth has been identified by analyzing its grain-size and its plasticity. Then, and based on the results of these analysis, which show that the material does not satisfy the requirements so that it can be used in rammed earth, texture modification by adding sand and gravel has been carried out. As a result, clay activity and shrinkage-swelling potential has significantly decreased. In the second step, several compaction tests bas been carried out, which showed a decrease in the optimum compaction moisture content and an increase in the maximum dry density of the material after sand was added. These improvements are even greater after adding gravel. The quantities of sand and gravel added to raw earth are determined in order to increase the compactness of the material thus formulated. In the final step, and to assess the relevance of the stabilizations applied, uniaxial compression tests are carried out on dry specimens made from the materials formulated. The results show slight but beneficial impact on dry compressive strength.**

Keywords* — *Rammed earth, Compaction, Gradation, Shrinkage, Compressive strength.

1. INTRODUCTION

The methods used around the world to build with raw earth vary from region to region depending on the nature of the locally available earth, climatic conditions and local know-how. The question is: what materials can be used to build sustainable earthen constructions?
In general, any earth with a sufficient cohesion can be used to build earthen constructions. Thus, clayey earths can be used in adobe, while sandy earths are more suitable for the compressed earth block technique. Concerning rammed earth method, the most suitable earths the well graded ones containing clay, silt, sand and gravel [1].
In the case where the construction technique is not prescribed, the construction method should be chosen according to the nature of the locally available earth. Otherwise, it is either try to find, as far as possible, the most suitable earth for the chosen method, or to modify and stabilize the locally available earth to improve its quality.
As earth is a complex and natural material, the same formulation may not necessarily give the same results in terms of characteristics. Therefore, no standard formulation is feasible. However, a standard method can be established for the formulation of earth-based materials in order to obtain predefined characteristic properties. It is this approach that we have followed in the case study covered in this paper.
As for the state of the art on this subject, some references are discussed in the 3rd part in which the proposed experimental method is described.

2. OBJECT AND AIMS

This paper deals with a case where the rammed earth construction technique is imposed by the project owner and where, at the same time, it is required to use local earth from the project's earthworks. The aim is to develop an eco-material suitable for the rammed earth technique. Stabilization using additives such as cement, lime or vegetable fibers must be justified. The material, once elaborated, must meet the following requirements:

Tab. 1 : Required characteristics for the material to be developed

Dry density [a]	Com. strength [b]	Optimum CMC [c]
$\geq 1.85\ Mg/m^3$	$\geq 2.0\ MPa$	$\leq 15\%$

[a] Dry density obtained from cylindrical specimens according to the European Standard EN 12390-7. It is the average of the densities of the three dried specimens. The value obtained will be used to estimate the weight of the wall studied.

[b] Dry uniaxial compressive strength, in the direction perpendicular to the layers, obtained from earth blocks or cylindrical specimens according to the European Standard EN 12390-3. This value is the average failure stress of at least three specimens. Taking into account the scale effect, a partial safety factor of 0.40 will be applied when designing the wall studied.

[c] Optimum compaction moisture content obtained by the Standard Proctor Test according to the European Standard EN 13286-2. This threshold is imposed for two reasons: to reduce shrinkage deformations and to save water.

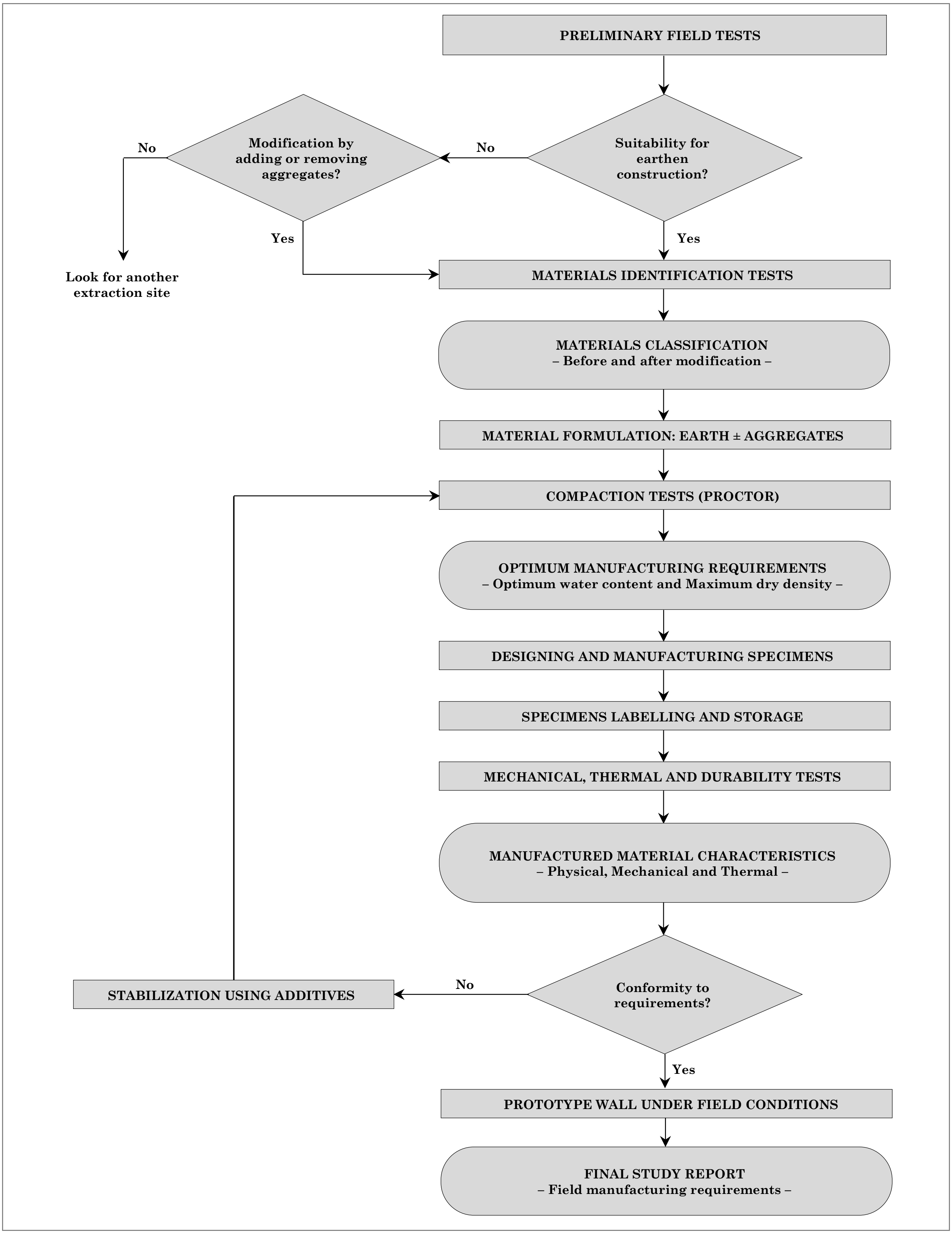

Fig. 1 : Summary of the experimental method applied in this case study

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The project is a tourist complex. The project's building has a combination of reinforced concrete structures and rammed earth walls. The walls thicknesses are determined by the engineering design office using the characteristics given in table (tab. 1). The material to be processed must therefore comply with these characteristics. To achieve these results, an experimental method was adopted. This method shown in the figure (fig. 1) has been developed with the aim of minimizing the number of formulations to be tested.

3. METHODOLOGY

As summarized in the previous figure (fig. 1), the first phase of the study consists of preliminary tests such as « Smell test », « Nibble test », « Wash test », « Cutting test », « Sedimentation test », « Ball dropping test », « Ribbon test », « Linear shrinkage test », « Dry strength test », etc. The aim is to assess the suitability of the material for earthen construction [2]. Some of these tests are illustrated in a research article from R. A. Silva (2013) [3].

Note that these tests are only useful when looking for a suitable location to extract earth whose suitability must be assessed. Otherwise, one can skip directly to the next phase of the proposed approach. As the earth to be used is imposed by the project owner, partly due to environmental reasons, the preliminary tests are therefore not to be considered in this case study. Once the earth to be used has been chosen, the next phase of laboratory identification tests can be started.

One of the most important of these identification tests are grain-size test and plasticity test, because it allow to check the suitability of the material for the chosen construction technique. As for rammed earth technique, Hugo Houben and Hubert Guillaud recommend, in their book « Traité de Construction en Terre », to use earth characterized by a grain-size curve belonging to a specific spindle – R. E. Spindle: Rammed Earth Spindle – (fig. 2) and by a low to medium plasticity with a plasticity index around 25% [1].

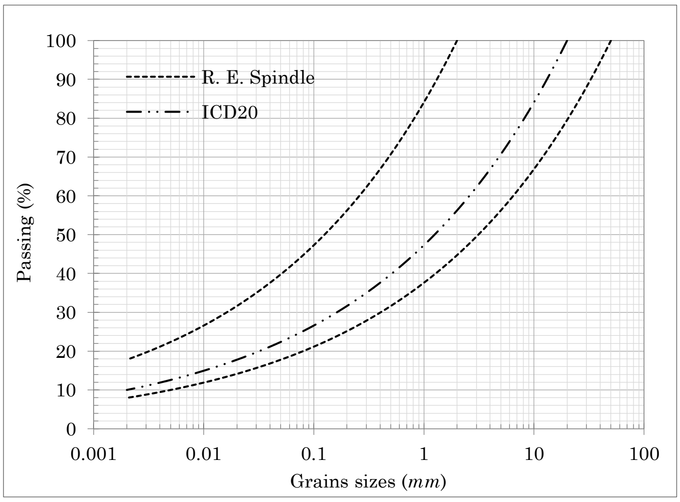


Fig. 2 : Recommended grain-size spindle for rammed earth (ICD20: *Ideal grain-size curve of earth with* $20\ mm$ *as maximum grain size | R. E. Spindle: Rammed Earth Spindle*).

The quality of the material thus produced is considered suitable if its maximum dry density is at least $1.75\ Mg/m^3$ obtained after compaction at an optimum water content of between 5 and 15% [1].

Theoretically, the curve above (ICD20) is the ideal one to produce the densest material possible.

Indeed, Fuller and Thompson developed in the early 1900s, for a material made from perfectly rounded grains, a formula describing the optimum grain size curve for this purpose [4]. This formula is written as follows:

$$P(\%) = 100\sqrt{\frac{d}{D}} \qquad (1.a)$$

Where "D" represents the maximum grains size and "P" the percentage of grains with a size smaller than the size "d".

This formula can be written in the following general form:

$$P(\%) = 100\left(\frac{d}{D}\right)^n \qquad (1.b)$$

Where "n" is the gradation index, which a parameter depending on the shape of the aggregate (0.5 for perfectly rounded grains). It can also be expressed as follows:

$$P_i = P_j\left(\frac{d_i}{d_j}\right)^n \qquad (1.c)$$

Where "P_i" and "P_j" are respectively the percentages of grains with sizes which are smaller than the size "d_i" and "d_j" ($d_i < d_j$).

As earth grains are not perfectly rounded, the value of "n" is necessarily different from the one of Fuller and Thompson. For example, the American Standards use 0.45 as value for this index, for aggregates used in asphalt pavement for US federal highways [5].

In the case of sandy earths, used to make road pavement structures, "n" is generally taken equal to 0.33 [6].

As for earths suitability for buildings, which must contain a significant quantity of clays, Hugo Houben and Hubert Guillaud recommend for "n" values varying from 0.20 to 0.25 [6].

Knowing that the earths used in rammed earth have very well graded texture, the value 0.25 seems to be the most adequate for "n". Therefore, the optimum grain-size curve above (fig. 2) is defined by the following equation:

$$P(\%) = 100\left(\frac{d}{D}\right)^{0.25} \qquad (1.d)$$

3.1. Raw earth identification

The earth used is poorly graded (fig. 3). This curve is obtained by sieving analysis of particles with dimensions over 80 μm [7] and by sedimentation analysis of the rest of the particles [8].

This curve is used to determine a series of parameters useful to analyze the texture of the earth and to define its classification.

These parameters are mainly: the effective size "d_{10}", the clay content "$C_{2\mu}$", the coefficient of uniformity "C_u" and the coefficient of curvature "C_c" defined by the following formulas:

$$C_u = \frac{d_{60}}{d_{10}} \quad ; \quad C_c = \frac{(d_{30})^2}{d_{60} \times d_{10}} \qquad (2)$$

Where "d_x" is the size corresponding to "$x\%$" of passing.

These two parameters are required to analyze the uniformity and gradation of earth texture.

Concerning earth plasticity, there are three limits (Atterberg limits): liquid limit "ω_l" [9], plasticity limit "ω_p" [9] and shrinkage limit "ω_s" [10]. Other parameters can be calculated, such as the plasticity index "I_P" and the shrinkage index "I_s":

$$I_P(\%) = \omega_l - \omega_p \qquad (3.a)$$
$$I_s(\%) = \omega_l - \omega_s \qquad (3.b)$$

These parameters can be used to interpret the plasticity of the fine earth fraction and to evaluate its shrinkage and swelling potential [11].

It is also used to determine the activity coefficient of clay defined by:

$$C_a = \frac{I_P}{C_{2\mu}} \qquad (4)$$

This coefficient is a parameter used to analyze the activity of clays, this activity does not only depend on the plasticity of clay (quality), but also on its proportion in the earth composition (quantity).

For more details on the Atterberg limits as intrinsic soil properties, one can see a paper on the subject written by Sridharan et al. (published in 2000) [12].

3.2. Densification by « $gradation$ »

The principle of densification by « $gradation$ » is to determine the proportion of each granular fraction in the material, in order to reduce the void ratio and form a more stable material.

By comparing the grain-size curve of the available earth, the adjustments to be made can be easily identified. Indeed, If the grain-size curve does not fit into the spindle, then it should be required to:

- Or remove by sieving the granular fraction which is present in significant quantity;
- Either add the fraction whose quantity is insufficient.

Note that these two actions are easier to carry out when it comes to removing or adding a coarse fraction (gravel and sand). Another possibility is to mix two earths with different textures to achieve the same purpose.

These adjustments require determination of grain-size curves of all ingredients to be mixed, in order to find the appropriate proportion of each one of them in the final mixture.

If "a" is the proportion of aggregate to be added to earth, in order to be used in rammed earth, then the mixture passing is:

$$P_M(\%) = a.P_A(\%) + (1-a).P_E(\%) \qquad (5)$$

Where "$P_A(\%)$" and "$P_E(\%)$" are respectively aggregate passing and earth passing.

The optimum value of "a" to use, so that the differences between the mixture grain-size curve is as close as possible to the ideal curve, can be determined using graphical methods [1].

3.3. Densification by compaction

In order to obtain the best possible compaction, compaction tests are carried out by compacting the earth at different water contents and measuring the respective dry densities.

The aim is to determine the optimum moisture content to achieve the maximum dry density. The procedures applied are those of Standard Proctor Test, which is well known in the geotechnical engineering field [13].

Once determined, these two parameters will serve as required conditions for the execution of eventual rammed earth walls, and also to produce specimens.

3.4. Compressive strength test

The aim is to determine the compressive strength of each formulated material in order to compare them and conclude the most appropriate stabilization to choose.

- Manufacturing process

Since there are no standards specifically developed for testing rammed earth, compression tests are carried out on cylindrical specimens of dimensions according to concrete standards [14]. Therefore, the specimen height must be equal to twice its diameter, which must be at least equal to five times the greatest grain size of the material concerned.

In this case study, the greatest grain size is $20\,mm$, so the dimensions of the specimens are $100\,mm$ for diameter and $200\,mm$ for height. Theses dimensions are the same adopted by some researchers such as Rui A. Silva et al. [3].

To manufacture these specimens, an average dry density equal to that obtained in the Standard Proctor Test $\pm 5\%$ was targeted. Taking into account the dimensions of the mold for specimen making compared to those of the Proctor mold, the same compaction methods as those of the Proctor test were adopted with 5 layers for a height of $200\,mm$ instead of 3 layers for a height of $116.5\,mm$.

Each layer is approximately $3.6\,cm$ thick, except the first and last layer whose thickness is $4.6\,cm$ ($3.6\,cm$ of material plus a thin layer of $1\,cm$ thick made up only from grains with size less than $5\,mm$, so as to facilitate the preparation of the bearing surfaces of the specimens). The demolding is done immediately after compaction.

- « Drying » conditions

Concerning drying conditions, specimens were then stored in a room with temperatures varying from 20 to 25 °C and relative humidity of about 60%.

After four weeks, the weights and dimensions of each specimen are measured, then the densities are determined, according current European Standards on concrete material [15], and compared to the aimed dry densities.

These comparisons are used to check the drying of the specimens. The drying of a specimen is achieved if its density is equal to the one targeted by compaction $\pm 5\%$ and if the weight of the specimen does not decrease by more than 2/1000 after 48 hours under the drying conditions above.

Note that the dry state of the compacted material means that the water content has reached its equilibrium value close to and not equal to zero.

- Compression procedure

After preparing their bearing surfaces of the specimens making them parallel and flat, the dry specimens are compressed using a press that complies with the current European Standard EN 12390-4 [16] and has a constant loading speed of $0.05\,MPa/s$ according to the European Standard on concrete EN 12390-3 [17].

Each formulated material's compressive strength is determined by calculating the arithmetic average of the failure stresses of three specimens.

3.5. Remarks

Tensile and flexural tests are not included in this case study, since the only strength required to be tested is the compressive strength. In fact, and for safety reasons, the tensile strength is taken to be zero.

Taking into account the nature of the walls thickness (40 to 50 cm), thermal tests seem to be unnecessary. As for durability tests such as erosion and abrasion tests, they are not carried out in this project as it is expected that the wall facades will be covered with lime plaster.

4. RESULTS AND DISCUSSIONS

4.1. Materials identification

The earth studied is sieved to remove some big particles. Therefore, the maximum grain size "D" is 20 mm.

As shown in the figure (fig. 4), the grain-size curve characterizing this earth does not fit into the spindle specific to rammed earth construction technique. Indeed, the fine granular fraction (silt and clay) is quite important. This curve can be adjusted by adding sand, the proportion of which depends on its own grain-size curve.

The values of the Atterberg limits show that the raw earth used is highly plastic with a high swelling-shrinking potential (tab. 5). This plasticity proprieties are not the ones that are recommended for rammed earth construction technique [1].

In order to ensure that this mixture grain-size curve is perfectly in conformity with the spindle specific to rammed earth technique, the mixture is made with weight ratio of 1/3 sand and 2/3 earth.

The grain-size curve of the mixture produced (fig. 4) can be improved to approach the ideal curve by adding gravel. This is a stabilization proposal that can be relevant if the improvements in the material's mechanical performances are significant.

The gravel used for this stabilization is rounded gravel from local alluvial deposits (fig. 3). The mixture obtained is produced with weight ratio of 1/4 gravel, 1/4 sand and 2/4 earth.

The sand available to densify the earth by gradation is a 0/5 semi-crushed sand whose grain-size curve is given in the figure (fig. 3).

Pic. 1 : Photos showing the three materials used (Raw earth on the left, Sand in the middle and Gravel on the right).

As shown in the figure (fig. 3), raw earth studied is non-uniform with a fine granular fraction of more than 50%. Sand, however, has a relatively uniform texture with a fine granular fraction of 8%. As for gravel, it is clear and of a perfectly uniform texture.

Tab. 2 : A brief description of the three materials used to formulate rammed earth.

Material	Brief description (pic. 1)
Earth 0/20	Raw *marly* earth of a whitish color, whose main granular fraction is the fine one with an absolute density of 2.50 Mg/m^3. The earth was extracted near Agadir city from 0.50 to 3.00 meters deep using an excavator.
Sand 0/5	Semi-crushed sand from local alluvial deposits, containing a significant quantity of fines, and whose grains absolute density is 2.70 Mg/m^3.
Gravel 5/20	Rounded gravel, with heterogeneous petrography, extracted from alluvial deposits of a local river, composed of almost spherical grains whose absolute density is 2.70 Mg/m^3.

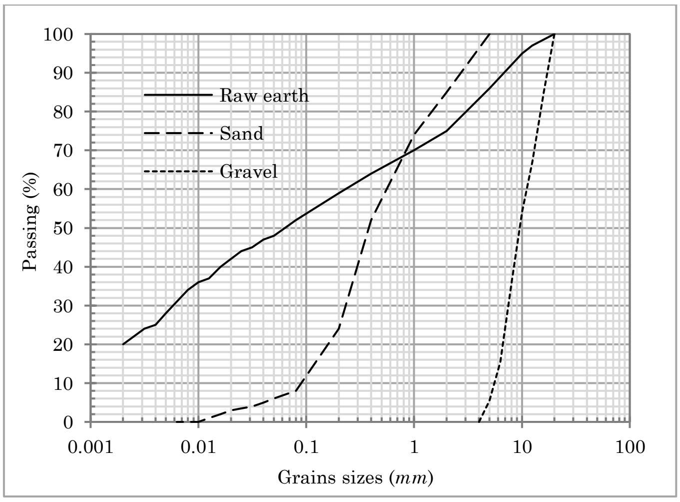


Fig. 3 : Grain-size curves of studied materials (earth, sand and gravel).

Starting from this paragraph and in order to make it easier to draft this paper, the following designations will be used:

— MIX0: Raw earth;
— MIX1: Earth mixed with sand;
— MIX2: Earth mixed with sand and gravel.

Tab. 3 : Formulation of the three materials to be studied (MIX0, MIX1 and MIX2).

Material	MIX0	MIX1	MIX2
Raw earth (%)	100	67	50
Semi-crushed sand (%)	0	33	25
Rounded gravel (%)	0	0	25

Sieving and sedimentation analysis was carried out and the above curves are obtained (fig. 4).

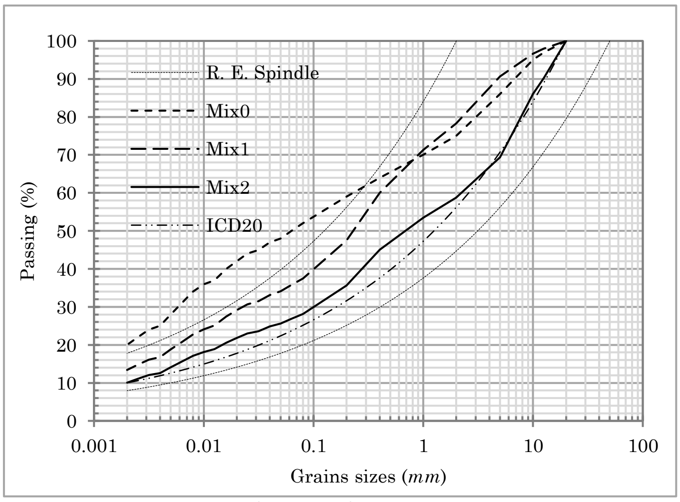


Fig. 4 : Grain-size curves of the three formulated materials (MIX0, MIX1 and MIX2).

These curves show that, unlike the grain-size curve characterizing raw earth (MIX.0), the curve of the earth-sand mixture (MIX1) is well within the spindle specific to rammed earth construction technique, but is still far from the optimum curve (icd20). However, the third curve representing the earth-sand-gravel mixture (MIX2) is more in line with this optimum curve. From these curves, it is easy to read or calculate the following parameters:

Tab. 4 : Parameters describing the textures of the materials formulated (MIX0, MIX1 and MIX2).

Material	MIX0	MIX1	MIX2
d_{10} (mm)	< 0.001	$0.001^{(*)}$	0.002
d_{30} (mm)	0.006	0.025	0.100
d_{60} (mm)	0.250	0.400	2.50
C_u	--	400	1250
C_c	--	1.56	2.00
C_2 (%)	78	75	59
$C_{0.4}$ (%)	64	60	45
$C_{80\mu}$ (%)	52	37	28
$C_{2\mu}$ (%)	20	13	10

$^{(*)}$ *value estimated by extending the grain-size curve*.

Tab. 5 : Atterberg limits of the three formulated materials (MIX0, MIX1 and MIX2).

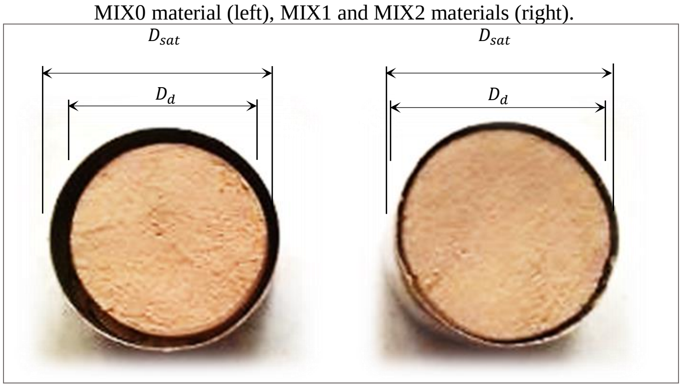
Material	MIX0	MIX1	MIX2
ω_l (%)	51.8	32.8	32.8
ω_p (%)	26.7	22.2	22.2
ω_s (%)	11.1	16.8	16.8
I_p (%)	25.1	10.6	10.6
I_s (%)	40.7	16.0	16.0
C_a	1.26	0.82	1.06

Raw earth material (MIX0) is mainly fine-grained, with more than 50% of its grains having a size of less than 80 μm.
The behavior of this material will therefore be largely influenced by that of its fine fraction, in particular clays, which represent a significant proportion of around 20%.
As for the grain texture of the other two materials (MIX1 and MIX2), they are coarse-grained earths, whose uniformity coefficient ($C_u \gg 2$) and curvature coefficient ($1 < C_c < 3$) values show that they are well graded.
Concerning Atterberg limits, obtained after these changes in the earth's grain-size, they show a decrease in plasticity and swelling potential (tab. 5).
In fact, there is a decrease in both liquid limit and plasticity index, with an increase of almost 5% in shrinkage limit, meaning that shrinkage index is decreased by about 13%.
The two materials MIX1 and MIX2 are characterized by the same plasticity because their granular fraction 0/0.4 is the same.
There is also a decrease in clay activity from high activity ($1.25 < C_a < 2$) in the case of MIX0 material to medium activity ($0.75 < C_a < 1.25$) in the cases of MIX1 and MIX2 materials [18].
Note that MIX1 material has the lowest clay activity ($C_a = 0.82$). Which means that it is the most stable material facing water content changes (i.e. less volume change when wetted and less shrinkage when dried).
These results are actually well-known by the scientific community. Liquid limit and plasticity index increases with the specific surface area of the grains [19], which is important in the case of fine earths, clayey earths in particular, compared to that of coarse earths.
Also, the impact of the addition of sand and/or gravel on the shrinkage limit is confirmed by some studies [20].
Supposing that shrinkage phenomenon is isotropic, the volumetric shrinkage of the 0/0.4 granular fraction of earth material can be estimated, before and after its stabilization, using the following formula:

$$S_V(\%) = 100\% - \left(\frac{D_d}{D_{sat}}\right)^3 \times 100 \qquad (6)$$

Where D_d and D_{sat} are respectively the diameter of sample in its dried state and in a state approaching saturation, which corresponds to the liquid limit.

Pic. 2 : Photo showing the volumetric shrinkage of the 0/0.4 fraction of MIX0 material (left), MIX1 and MIX2 materials (right).



As a result, the volumetric shrinkage of the earth studied decreases from 38% before stabilization to 17% after stabilization.

Tab. 6 : Classification of the three materials formulated (MIX0, MIX1 and MIX2).

Material	MIX0	MIX1	MIX2
AASHTO *System*	A-7	A-6	A-6
USCS *System*	CH	SC	GC

AASHTO *System is the American Association of State Highway and Transportation Officials Classification System* [21] *and* USCS *System* is the *Unified Soil Classification System* [22].

According to USCS System, the raw earth material (MIX0) is a Fat Clay with a high plasticity « CH », which is rarely suitable for unstabilized earth construction. As for the earth-sand mixture (Clayey Sand « SC ») and the earth-sand-gravel mixture (Clayey Gravel « GC »), they are suitable and sometimes need fine earth to be added [23].

4.2. Optimum compaction characteristics

The compaction tests on the three materials MIX0, MIX1 and MIX2 were carried out according to the terms of the Standard Proctor Test [13].

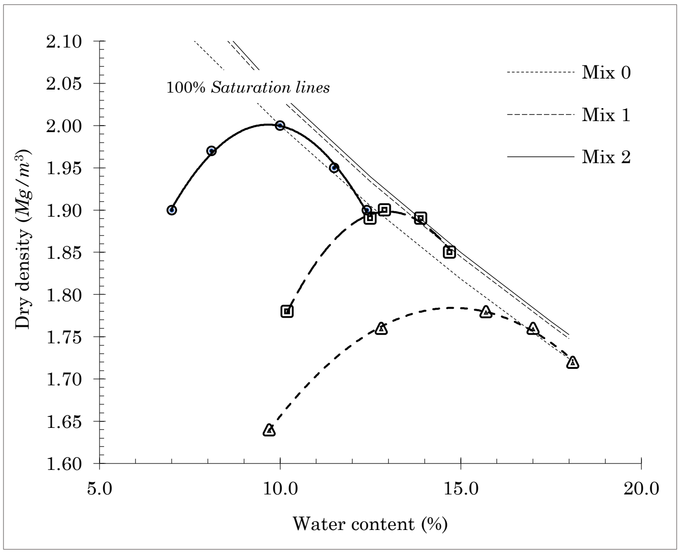


Fig. 5 : Compaction test curves according to Standard Proctor Test of the three materials formulated (MIX0, MIX1 and MIX2).

Tab. 7 : Maximum dry density (ρ_{dmax}) and optimum moisture content (ω_{OMC}) of the three materials formulated (MIX0, MIX1 and MIX2).

Material	MIX0	MIX1	MIX2
ω_{OMC} (%)	14.8	13.0	9.5
ρ_{dmax} (Mg/m^3)	1.78	1.90	2.00

The curves obtained from these tests are given below (fig. 5).
As shown in the previous results, there is an increase in the dry density of earth-sand material (MIX1) by 0.12 Mg/m^3 compared to raw earth (MIX0). This increase in density is associated with a decrease in the optimum compaction moisture content from 14.8% to 13.0%, meaning that about 12% of water has been saved.
The results concerning the earth-sand-gravel material (MIX2) are much more significant. Indeed, there is an increase in dry density from 1.78 Mg/m^3 to 2.00 Mg/m^3, which represents more than 0.22 Mg/m^3 increase. As for the optimum moisture content, it has been decreased to 9.5%, which means a water saving of about 36% compared to raw earth (MIX0). These curves show an increase in dry density and a decrease in the optimum compaction moisture content (tab. 7).
The maximum dry density increases for two reasons: first, because absolute density of aggregates is higher than the one of substituted earth ($2.70\, Mg/m^3 > 2.50\, Mg/m^3$), second, because the mixture grain-size curve is closer to the ideal curve described in the figure (fig. 4).
As for the optimum compaction moisture content, its decrease can be explained by the same factors that have reduced plasticity and liquid limits. Moreover, some studies (A. Sridharan, 2005 [24] ; T. Tsegaye, 2017 [25]) show that there is a correlation between the Atterberg limits of earths and their compaction characteristics.

Comparing the optimum compaction moisture contents of each of the three formulated materials with their respective shrinkage limits, it appears that, contrary to raw earth (MIX0), the use of the two materials MIX1 and MIX2 can be in the solid state under shrinkage limit ($\omega_{OMC} < \omega_s$). As a result, cracks caused by shrinkage can be avoided.

4.3. Compressive strength

The compaction of the specimens was carried out in their optimum moisture contents as previously estimated. Immediately after compaction, each specimen weight and sizes are measured to calculate its wet density (ρ_h).
Three specimens per formulation were manufactured using the same procedure described in the 3rd part of the present paper. The specimens manufactured are then kept in the conditions previously described for at least four weeks before checking their drying. Once they are "completely dry", compressive tests are carried out according to the methods described before.
Concerning compaction, results show that specimens' dry densities are slightly greater than the maximum density achieved by compaction test (1.04 to 1.07 times greater). This is because the thickness of layers used to make specimens (about 3.6 cm) is less than that one used in compaction test (about 4.6 cm), while the compaction energy remains the same.

Pic. 3 : Photo showing some of specimens prepared for compressive test (MIX0 material).

As for compressive strength of specimens, there is an increase of 0.09 MPa for MIX1 material compared to MIX0 material, and an increase of 0.10 MPa for MIX2 material compared to MIX1 material.
Measurements also show improvements in absolute and bulk density and compactness of the material because of densification performed.
To assess the efficiency of the formulations selected and the manufacturing processes applied in this case study, the compressive strength obtained can be compared to the values recommended by documents regulating rammed earth construction.

One of these documents is « The Australian earth building handbook » (HB 195, 2002), which recommend a dry unconfined characteristic strength obtained from earth blocks or cylindrical earth specimens of at least 2.0 MPa [26].
The compressive strength obtained can also be compared to results of similar research studies. Some of these results were summarized in an article of L. Miccoli et al. (2014) [27]. Thus, one of these studies (V. Maniatidis and P. Walker, 2008), was carried out on a earth with physical and compaction properties relatively close to those of the MIX2 material, and has obtained an average compressive strength equal to 2.46 MPa determined on cylinders with the same dimensions as those used in the present case study [28].
In another case study carried out on a clayey sand (Soil S4) in northern Portugal, the compressive strength obtained, for an unstabilized rammed earth, is about 0.41 MPa [3].
There is also a case study conducted by L. Miccoli et al., in 2017, to investigate decay in historic rammed earth structures, in which the compressive strengths obtained are 0.67 MPa for extracted samples from ancient walls, 2.07 MPa for remixed samples and 1.67 MPa for local earth [29].

Tab. 8 : Specimens characteristics of MIX0, MIX1 and MIX2 materials.

Specimens	MIX0	MIX1	MIX2
Compaction water content	15%	13%	10%
Wet density (ρ_h $[Mg/m^3]$)	2.21	2.27	2.30
Dry density (ρ_d $[Mg/m^3]$)	1.91	1.98	2.09
Compactness	76%	77%	80%
ρ_d/ρ_{dmax} **Average Ratio**	107%	104%	105%
Compressive strength (MPa)	1.94 $\pm$0.14	2.03 $\pm$0.12	2.13 $\pm$0.11

Pic. 4 : Photos showing the compressive system (photo on the left) and a specimen after it has been compressed (photo on the right).

As these comparisons show, the compressive strength obtained seems to be satisfactory, especially since it meets the requirements of the project owner.

4.4. Stabilization possibilities

As the characteristics of gravel-sand-earth material meets the requirements of the project owner, stabilization using additives (cement, lime or bitumen) is not necessary.
However, if there is an interest in improving these characteristics, the most appropriate stabilizer, in relation to the material plasticity, is cement (according to H. Houben et al., 1995 [2]). Indeed, there are quite few papers dealing with this subject. One of these papers is a paper by S. Kenai et al (2006) that shows the positive effect that cement stabilization can have on dry compressive strength. The paper showed, among other things, an almost linear correlation between cement content and dry compressive strength [30].
Despite these improvements highlighted by this paper among many others, the use of cement as a stabilizer is not advisable due to its negative environmental impact. In a recent paper, H. Van Damme and H. Houben pointed out that the cement stabilization « is in general neither technically nor environmentally advisable as it brings only moderate mechanical improvements at a high environmental cost » [23].
On the other hand, stabilizing the earth studied with plant fibers is quite feasible because as some studies pointed out, such as those of K. Ghavami et al [31], J. Prabakar et al. [32] and M. Bouhicha [33], if the optimum content and the appropriate fiber length are assessed, the use of fibers can improve both thermal and mechanical properties.

4.5. Recommendations for field manufacturing

The field manufacturing process depends on the equipment used for compacting: manual tamper or pneumatic tamper. It also depends on the compaction method applied as revealed an experimental study carried out by R. Bahar et al.[34] and S. Kenai et al. [30]. This study about the effect of the compaction methods on the mechanical properties and durability of earths pointed out that dynamic compaction « seems to enhance the mechanical properties and water resistance of the [earth] as compared to the static or vibro-static compaction ».
As for the present case study, the equipment to be used is a pneumatic tamper. Therefore, it is a dynamic compaction, the recommendations of which are as follows.

- Mixture production

The mixture of the different ingredients should be performed in dry state, or at its natural water contents as long as they are not too wet, according to the formulation corresponding to the MIX2 material.

- Compaction water content

The water content of the mixture must be corrected to the optimum water content of about 10%. Note that the purpose is to produce a material with a density equal to or close to the maximum dry density obtained by the standard Proctor test, which is about 2.10 Mg/m^3. Compliance with the optimum water content is therefore not an objective in itself, but a parameter that must be taken into account since it has an influence on the compaction energy needed to achieve the targeted density. The mixture must be homogenized and stored in a dark place and covered by an impermeable tarpaulin to prevent evaporation.

- Compaction procedures

Compaction procedures have to be defined in such a way that the average dry density of the earth is greater than or equal to 2.10 Mg/m^3.

These procedures must be established in a reproducible way by specifying the thickness of the layers, the distribution of the tamper's blows and, the number of passes per layer. It is therefore required to carry out field tests to validate these procedures.

Dry density can be tested on samples taken by coring. These samples must be representative. Some research studies have been carried out on the representative volume element of rammed earth material. For example, an article from Q. B. Bui, J. C. Morel et al. notes that in each layer, a material density gradient is observed [35]. Indeed, « the upper portion of a layer, directly in contact with the tamper during compaction, is denser, while the lower portion, not affected by the tamper, is less dense ». Therefore, samples made up of two layers are proposed to be used as representative volume element (RVE) of rammed earth.

- Quality control

The results obtained in this case study, and summarized in the table above (tab. 8), indicate a correlation between dry density and compressive strength (fig. 6). Therefore, quality control can be limited to dry density control. The latter can be calculated from the wet density by subtracting the moisture content.

Nevertheless, the compressive strength of the material manufactured can also be measured by testing core specimens. However, particular care must be taken in this procedure as there can be, as discussed by some papers [36], a difference between cast and core specimens results. One of the factors of this difference can be attributed to the use of water and vibration generation during coring which can lead to the separation of the earth layers [35].

In any case, specimens must be made up of at least three layers so that the height is twice the diameter. Also, and taking into account the anisotropy of rammed earth material [37], coring must be carried out in a perpendicular direction to layers.

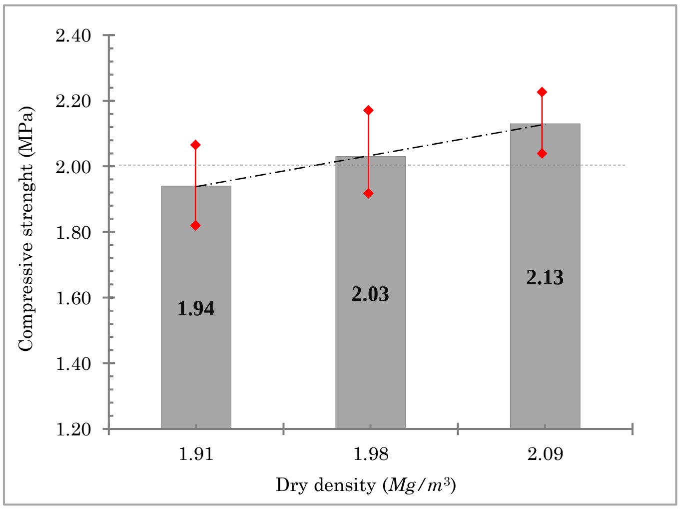


Fig. 6 : Correlation between dry density and compressive strength.

5. CONCLUSIONS AND PERSPECTIVES

The experimental method applied in this study case to make the earth studied suitable for the chosen construction technique, which is the rammed earth method, has been successful as it made it possible, by testing only three formulations, to:

- Decrease clay activity and shrinkage-swelling potential of the raw earth studied;
- Increase dry density by almost 7% for earth-sand material and by more than 12% for earth-sand-gravel material;
- Reduce optimum compaction moisture content, and therefore save water, by 12% for earth-sand material and 36% for earth-sand-gravel material, which is an ecological advantage when applying this stabilization method;
- Manufacture the material in a solid state under its shrinkage limit, and avoid cracks due to shrinkage following drying;
- Improve compactness and compressive strength of the compacted earth.

Comparing the results obtained to the required characteristics, the variant of the earth-sand-gravel (MIX2 material) can be considered satisfactory. As for durability, it is expected that the building façades, especially those exposed to rain, will be covered with lime plaster. Therefore, the unstabilized earthen material formulated can be used without any problem.

Also, the following recommendations can be considered for the construction of a prototype wall on site:

- 10% as compaction water content, this value is for information only and can be increased slightly depending on the compact energy on site;
- 2.1 Mg/m^3 minimum dry density, a value that must be targeted to ensure the required compressive strength;
- Specimens for compressive strength test are to be made according to the on-site compaction procedures in order to control the quality of the prototype wall produced.

Once the conformity of the prototype is confirmed, the building of walls, according to the established on-site conditions, can be started.

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REFERENCES

[1] H. Houben and H. Guillaud, “Convenance des terres,” in *Traité de construction en terre*, 2nd ed., Marseille, France: Editions Parenthèses, 1995, pp. 503–504.

[2] H. Houben and H. Guillaud, *Traité de Construction en Terre*, 2nd ed. Marseille, France: Editions Parenthèses, 1995.

[3] R. A. Silva, D. V. Oliveira, T. Miranda, N. Cristelo, M. C. Escobar, and E. Soares, “Rammed earth construction with granitic residual soils: The case study of northern Portugal,” *Constr. Build. Mater.*, vol. 47, pp. 181–191, 2013.

[4] M. I. Anjum, “Simple Approach for Determination of Optimum Gradation Considering the Combined Index and Angularity Number of Stone Aggregates,” in *Proceedings of The World Congress on Engineering 2011*, 2011, vol. III, pp. 2370–2374.

[5] C. S. Hughes, *Design, Construction and Performance of Heavy Duty Mixes*. Maryland, US: Ntional Asphalt Pavement Association, 2002.

[6] H. Houben and H. Guillaud, “Densification par gradation,” in *Traité de construction en terre*, 2nd ed., Marseille, France: Editions Parenthèses, 1995, pp. 404–405.

[7] AFNOR, *NF P 94-056 - Particle-size analysis - Method by dry sieving after washing*. 1996.
[8] AFNOR, *NF P 94-057 - Particle-size analysis - Sedimentation method*. 1992.
[9] AFNOR, *NF P 94-051 - Determination of Atterberg's limits. Liquid limit test using cassagrande apparatus. Plastic limit test on rolled thread*. 1993.
[10] AFNOR, *XP P 94-060-1 - Shrinkage test. Part 1 : determination of shrinkage characteristic on remoulded soil passing a 400 micrometers test sieve*. 1997.
[11] M. Audiguer, Z. Geremew, S. Laribi, and R. Cojean, "Caractérisation au laboratoire de la sensibilité au retrait- gonflement des sols argileux," *Rev. Française Géotechnique*, no. 120–121, pp. 67–82, 2007.
[12] A. Sridharan and H. B. Nagaraj, "Compressibility behaviour of remoulded , fine- grained soils and correlation with index properties," *Can. Geotech. J.*, vol. 37, pp. 712–722, 2000.
[13] CEN, *EN 13286-2 - Unbound and hydraulically bound mixtures - Part 2 : test methods for laboratory reference density and water content - Proctor compaction*. 2010.
[14] CEN, *EN 12390-1 - Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds*. 2001.
[15] CEN, *EN 12390-7 - Testing hardened concrete - Part 7 : density of hardened concrete*. 2001.
[16] CEN, *EN 12390-4 - Testing hardened concrete - Part 4 : compressive strength - Specification for testing machines*. 2000.
[17] CEN, *EN 12390-3 - Testing hardened concrete - Part 3 : compressive strength of test specimens*. 2003.
[18] H. Houben and H. Guillaud, "Ientification des terres - Plasticité," in *Traité de construction en terre*, 2nd ed., Marseille, France: Editions Parenthèses, 1995, pp. 307–308.
[19] A. J. Lutenegger and A. B. Cerato, "Surface area and engineering properties of fine-grained soils," in *Proceedings of the Fifteenth International Conference on Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey, 27-31 August 2001*, pp. 603–606.
[20] A. Sridharan and K. Prakash, "Shrinkage Limit of Soil Mixtures," *Geotech. Test. J.*, vol. 23, no. March 2000, pp. 3–8, 2000.
[21] ASTM, *D3282 - Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes*. 2004.
[22] ASTM, *D2487 - Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. 2006.
[23] H. Van Damme and H. Houben, "Earth concrete. Stabilization revisited," *Cem. Concr. Res.*, vol. 114, pp. 90–102, 2018.
[24] A. Sridharan and H. B. Nagaraj, "Plastic limit and compaction characteristics of fine-grained soils," *Gr. Improv.*, vol. 9, no. 1, pp. 17–22, 2005.
[25] T. Tsegaye, H. Fikre, and T. Abebe, "Correlation Between Compaction Characteristics and Atterberg Limits of Fine Grained Soil found in Addis Ababa," *Int. J. Sci. Eng. Res.*, vol. 8, no. 6, pp. 357–364, 2017.
[26] Standards Australia, *HB 195 - The Australian earth building handbook*. 2002.
[27] L. Miccoli, U. Müller, and P. Fontana, "Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob," *Constr. Build. Mater.*, vol. 61, pp. 327–339, 2014.
[28] V. Maniatidis and P. Walker, "Structural Capacity of Rammed Earth in Compression," *J. Mater. Civ. Eng.*, vol. 20, no. 3, pp. 230–238, 2008.
[29] L. Miccoli, C. Gerrard, C. Perrone, A. Gardei, and C. Ziegert, "A Collaborative Engineering and Archaeology Project to Investigate Decay in Historic Rammed Earth Structures: The Case of the Medieval Preceptory in Ambel," *Int. J. Archit. Herit.*, vol. 11, no. 5, pp. 636–655, 2017.
[30] S. Kenai, R. Bahar, and M. Benazzoug, "Experimental analysis of the effect of some compaction methods on mechanical properties and durability of cement stabilized soil," *J. Mater. Sci.*, vol. 41, no. 21, pp. 6956–6964, 2006.
[31] K. Ghavami, R. D. Toledo Filho, and N. P. Barbosa, "Behaviour of composite soil reinforced with natural fibres," *Cem. Concr. Compos.*, vol. 21, no. 1, pp. 39–48, 1999.
[32] J. Prabakar and R. S. Sridhar, "Effect of random inclusion of sisal fibre on strength behaviour of soil," *Constr. Build. Mater.*, vol. 16, no. 2, pp. 123–131, 2002.
[33] M. Bouhicha, F. Aouissi, and S. Kenai, "Performance of composite soil reinforced with barley straw," *Cem. Concr. Compos.*, vol. 27, no. 5, pp. 617–621, 2005.
[34] R. Bahar, M. Benazzoug, and S. Kenai, "Performance of compacted cement-stabilised soil," *Cem. Concr. Compos.*, vol. 26, no. 7, pp. 811–820, 2004.
[35] Q. B. Bui, J. C. Morel, S. Hans, and N. Meunier, "Compression behaviour of non-industrial materials in civil engineering by three scale experiments: The case of rammed earth," *Mater. Struct.*, vol. 42, no. 8, pp. 1101–1116, 2009.
[36] R. Gupta, "Characterizing material properties of cement-stabilized rammed earth to construct sustainable insulated walls," *Case Stud. Constr. Mater.*, vol. 1, pp. 60–68, 2014.
[37] Q. B. Bui and J. C. Morel, "Assessing the anisotropy of rammed earth," *Constr. Build. Mater.*, vol. 23, no. 9, pp. 3005–3011, 2009.