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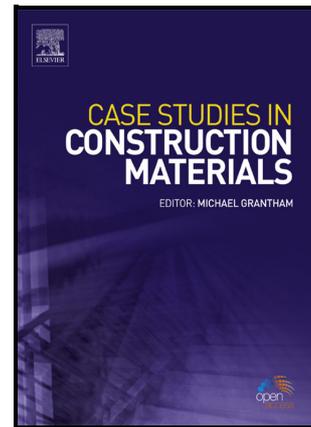
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A similitude relation to assessing the compressive strength of rammed earth from scale-down samples

Author 1 (corresponding author)

Antoine Pelé-Peltier, M.D., PhD candidate

LTDS, UMR 5513 CNRS, ENTPE, 2 rue Maurice Audin, 69100 Vaulx-en-Velin, France

Faculty of Engineering, Environment & Computing, Coventry University, 3 Gulson Rd, Coventry CV12JH, UK

Orcid: 0000-0003-3345-8168

Tel. (+33) (0)663491079 – antoine.peltier@entpe.fr

Author 2

Antonin Fabbri, PhD

LTDS, UMR 5513 CNRS, ENTPE, 2 rue Maurice Audin, 69100 Vaulx-en-Velin, France

Orcid: 0000-0002-2234-2461

Author 3

Jean-Claude Morel, PhD

LTDS, UMR 5513 CNRS, ENTPE, 2 rue Maurice Audin, 69100 Vaulx-en-Velin, France

Orcid: 0000-0002-2583-2490

Author 4

Erwan Hamard, PhD

MAST-GPEM, Univ Gustave Eiffel, F-44344 Bouguenais, France Orcid: 0000-0003-2160-3022

Author 5

Maxime Lhenry, M.D. LTDS, UMR 5513 CNRS, ENTPE, 2 rue Maurice Audin, 69100 Vaulx-en-Velin, France

Highlights:

- Compression tests on 66 rammed earth (RE) samples with the same clay-matrix but different gravel sizes.
- The grain size influence on the compressive strength of RE is examined.
- A similitude relation links the grain size, water content during the test and compressive strength.
- Applying the similitude relation allows using smaller samples with scale-down grain size.

Abstract: Rammed earth (RE) as a construction material fits perfectly into the circular economy concept as the soil is usually taken from excavation works (a waste) and is upcycled to build earthen architecture without adding any other components (unstabilised RE). RE is therefore recoverable at the building end-of-life. For non-common buildings, it is crucial to measure the compressive strength by lab testing on representative samples. While it is necessary to remove the biggest grains to manufacture standard size samples to achieve a homogeneous material, there is no research on how such samples are representative of the in situ RE. This paper develops a similitude relation to take into account the scale effect of the reduction of the size of the biggest grains of scale-down RE samples.

The similitude relation is designed for the dry density, the manufacturing water content, and the grain size of the RE. Those parameters were first determined from the construction field of a case study, to define the equivalent parameters to manufacture the scale-down samples with three different grain sizes, capped at 12, 20, 30mm for the earth; 50mm being the maximum grain size of

the earth used on-site. Compression tests were performed on 66 samples with samples of three different sizes, two geometries and four manufacturing water contents.

The compressive strength using the scale-down granulometry samples designed with the similitude relation is similar to the strength of full-scale granulometry whatever samples size or geometry. For a given earth, the method using the similitude relation allows reducing the size of samples without hampering the representativeness of the results. This will help to reduce projects' costs.

Keywords: Earthen architecture, rammed earth, Circular economy, Compressive Strength, Scale effect

1. Introduction

In the context of climate change, it is necessary to reduce the impact of the construction industry, which is one of the most polluting industries with, in 2009, 30% of the global carbon emissions and more than 40% of global energy use [1]. The objective in the UK of 80% reduction of carbon emissions by 2050 in the construction sector necessitates the decrease of building embodied energy [2]. One solution is the use of low-embodied carbon construction materials, such as timber, straw-bale, hemp, bamboo or earth [2], as alternatives to cement and steel which participate together in 44% of industrial carbon emissions [3].

Earth materials used in construction are clayey soils, with different implementation techniques according to the type of soil and socio-economic context of construction [4]. Some authors have recently developed a system to categorize the techniques according to the type of soil, based on the passing at 80 μm and clay activity [5]. To avoid any confusion, the word "soil" will not be used anymore in this article while the word "earth" will be preferred. Earth for construction can be found locally on the five continents [6] and, when unstabilised, it is completely recoverable. The construction sector generates half of the waste in Europe, among which excavation earth represents on average 75% (2005) [7]. Upcycling this waste, to make a construction material from it, would help to implement a circular economy (CE) in the built environment. That is why this paper is considering the approach of using local and unstabilised earth material as it looks optimized in terms of CE and carbon emissions, compared with an approach based on mixing materials from quarries, which is not compliant with a CE approach because consuming primary resources. Moreover, using materials from quarries would increase transportation, and therefore, carbon emissions [8].

There is a variety of techniques to build with earth such as cob, wattle and daub, adobe or compressed earth block, among others. However, this article focuses on unstabilised Rammed Earth, simply labelled RE. RE is a process to obtain monolithic walls by the compaction of successive layers of earth in a rigid formwork. The use of local earth, a non-standard material, would imply to change the regulation paradigm (as construction materials composition are usually standardized e.g. concrete) towards the regulation of the process instead of the material composition. To achieve this, a performance regulation (i.e. "thinking and working in terms of ends rather than means" [9]) could be developed through a set of testing of the local material, including compression tests. The current RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures; the acronym RILEM comes from the name in French) technical committee "274-TCE: Testing and characterization of earth-based building materials and elements" is responding to the

need for new standardized test procedures, as for compression tests. Indeed, there are still no standardized test procedures for compression tests of RE in Europe and this acts as a barrier to the development of earth construction [10].

For the design of any building project, compressive strength (CS) is a major parameter. This is particularly true for non-standardized and natural materials as earth. Indeed, some authors [11–13], as well as regulations (e.g. [14]), recommend the application of compression tests before the execution of RE buildings or during the execution for quality control [15].

This leads to different issues. Firstly, as earth is a natural and non-industrial material, a statistical characterization of the CS is required, for which at least three or four samples should be tested (see for example the appendix D “design assisted by testing” of Eurocode 0 [16]). Then, as it has been shown by different authors [17,18], RE compressive strength is highly dependent on the water content, through the suction, which evolved considerably between the execution of the walls and the utilization of the building. A relation between suction and CS, to predict the latter through Mohr-Coulomb criterium, have been investigated [19].

Therefore, to design a building made with RE, it is useful to estimate its CS for different water content to assess the drying kinetic and the potential variation of the indoor air relative humidity of the building. To characterize an earth for the design of a building, it is then required to test a large number of samples.

Other parameters influencing the CS already have been investigated. The dry density of the material, linked to the energy of compaction and the manufacturing water content, is an important parameter as it has been shown that the higher it is, the higher is the CS [20]. The effect of friction, according to the aspect ratio, have been studied [21], where an aspect ratio of 2 is recommended. The RE compressive strength is also very sensitive to the clay content of the mix (quantity and type of clay).

RE is a heterogeneous material. Firstly because of the natural earth used, which is heterogeneous in itself and, for RE, generally composed of big grains (sometimes with a grain size higher than 50mm) [6]. Secondly, the process of manufacturing by compacted layers of earth make the material heterogeneous with, in particular, higher density on top of the layers than on the bottom [22,23]. This highlights the practical issue of the minimum size of samples to obtain homogeneous and representative results. Indeed, it would be too costly and time-consuming to perform laboratory tests on wallets or real-size samples, which are representative of the site construction. Thus, the possibility to test smaller samples while still being representative to the on-site must be investigated.

Few authors have studied the scale effect: Some, by testing various RE sample sizes of the same material, have highlighted a difference in the results obtained between the different sizes [24], This can be explained easily through the size effect mainly dictated by confined friction at the specimen ends at the time of the test. While others, by testing two sizes of extruded earth bricks, have shown the possibility to obtain similar results between small and large scale bricks [25]. Then, the impacts of the scale effect and the representativeness of laboratory tests according to the size of the samples require further investigation for RE.

Therefore, this study, based on more than 66 compression tests on an earth used in a real project, explores the scale effect, by proposing a similitude relation of the CS considering the key parameters that drive the representativeness of the results (water content, dry density and the granulometry).

2. Presentation of the case study

The earth investigated for this study was used for an office building (Figure 1a). Following the classification of the ISO 14688-1 standard, that earth was composed of 8% of Clay (<2 μm), 11% of Silt (between 2 μm and 50 μm), 26% of sand (between 50 μm and 2mm) and 55% of gravel (between 2mm and 50mm), Figure 2.

The 3-storey building façade is made with load-bearing RE that is why assessing the CS of RE was essential. RE usually necessitates thick walls (500mm in general). For this particular building, the pillars were 800mm thick on their basis to support loads of the structure. These thick RE walls allow the use of earth with big grains such as small stones. In fact, due to the high variability of earth and the willingness to use local earth to decrease the environmental impact of the building, a performance approach has been adopted for this project. It means that structural designers based their calculations on a characterization of small-scale building elements.

In this context, the assessment of the CS was crucial for two reasons: the selection of earth, where two types of earth, previously pre-selected by skilled contractors, were tested to select the one that offered the highest results; And for the design of the building to adjust the size of the pillars. The development of the CS during the drying process of the walls was considered in the design. Such an approach could be time-consuming and expensive if it was required to test real scale samples to obtain representative results.

This justifies the relevance to investigate representativeness of CS obtained through testing small samples, where those latter are easier to manufacture and test and then are cost-effective. To manufacture such small

samples, it is necessary to limit the size of the biggest grain by sieving the earth used in situ. About 500 tons of earth sourced from excavation work at 30km from the construction site were used for this project limiting the environmental impact of material transportation. That 500 t would have ended in a landfill. Blocks of RE were pre-manufactured on-site (Figure 1b) by a semi-industrial process following the principle of a “flying factory”, i.e. a small and movable machine unit [26]. It has different advantages: good quality control by the contractor during the manufacturing process (e.g. adjustments of the manufacturing water content) and high repeatability and consistency in the manufacturing process. The blocks were then assembled with a mortar composed of the fine part of the earth.



Figure 1 : The case study building with unstabilised rammed earth (RE) with a load bearing façade, in Lyon (France) (a) view from the South-East (b) Picture of the premanufactured RE blocks, contractor: Meunier le pisé, structural engineers: Batiserf, architects C. Vergely Agency (©: Fabrice Fouillet for (a) and Pelé-Peltier for (b))

On-site, the contractor sieved the earth at 50mm. They built a testing wall to assess the dry density and manufacturing water content of the RE implemented. This testing wall had a section of about 1000mmx500mm on 1000mm high and was mechanically compacted. Samples of batches and the wall had been withdrawn and carried into the laboratory, the first to estimate the manufacturing water content by an oven-drying process, the second to obtain the dry density of the wall by hydrostatic weighing. The site-construction parameters obtained in the lab were a mean dry density of 1.90 g/cm^3 with a standard deviation of 0.07 g/cm^3 and a mean manufacturing water content of 8% with a standard deviation of 1.1%. Those parameters are key parameters as it is known that the dry density has a high impact on the CS of earth materials [20] and the manufacturing water content influences the compactness of the material [27].

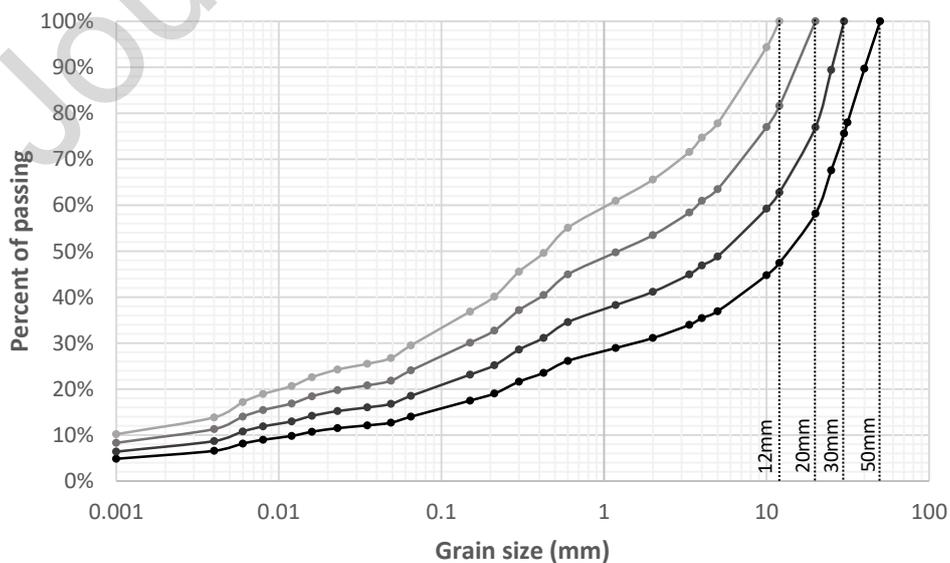


Figure 2: Grain size distribution. The same initial earth has been used but sieved at different maximum grain sizes (12, 20, 30 and 50mm). The darkest grey is the biggest the maximum grain size is considered, from light grey (12mm maximum grain size) to black (50mm maximum grain size).

3. Set up of the experimental campaign

3.1. Samples preparation

To design the similitude relation, nine full-scale prisms 300mmx300mmx600mm, called full-scale (FS) prisms (FS₂₀ and FS₅₀), made by the contractor, were used as a reference. The FS prisms labelled FS₅₀ were manufactured with the same earth (same granulometry) as the earth used in situ for the building, while the earth was sieved at 20mm for the FS₂₀ prisms. Small samples were then prepared, some by the contractor, and some in the laboratory. Two different geometries were studied: cylinders Ø160mmx320mm and prisms 160mmx160mm of section and 320mm of height. The samples, made by the contractor, were manufactured with a pneumatic rammer, while those made in the laboratory were made with manual rammers with a circular section for the cylinders and a square section for the prisms. For the cylinders, metallic moulds were used while for the small-scale prisms wood formworks were employed.

The aspect ratio was constantly equal to 2, as recommended by Venkatarama Reddy et al. [21], who have shown for cement-stabilized RE that aspect ratios from 2 to 5 doesn't affect the results, while aspect ratios less than 2 tend to overestimate the results, because of friction between the samples and the machine platen.

To estimate the homogeneity of those samples, the French standard on the testing procedure in compression for rock samples [28] was taken as a reference. Although RE could be considered as soft rock, we used only the principle of homogeneity of the sample that is linked to the continuum mechanics assumption and would not deeply vary with different geomaterials. The norm notifies that the biggest grain size of the geomaterial used to make the samples should not exceed 1/10 times the smallest length of the sample (i.e. $d_{max}/\varnothing = 1/10$, where \varnothing is the diameter of the sample and d_{max} the biggest grain size of the material). Following this size ratio is supposed to ensure the homogeneity of the sample. For the small samples, the size of the biggest grain should then not exceed 16mm (The diameters of cylinders are equal to 160mm while the smallest length of the prisms is 160mm) while for the big samples it should not exceed 30mm. For earth, it has been shown by Seif El Dine [29] that size ratios of 1/5 to 1/6 can be taken for triaxial compression testing. Therefore, to investigate the influence of the grain size fraction and the size ratio on the results, the earth was sieved at different maximum grain sizes: 12mm, 20mm, 30mm and 50mm. Table 1 summarizes the samples manufactured for the study.

The small samples (C₅₀) made with the same earth grading as on the building site (50mm-sieved earth) were manufactured with a targeted dry density of 1.90 g/cm³ and a manufacturing water content of 8% (corresponding to the on-site key parameters). The results obtained for those samples were used as a matter of comparison with the ones for which the similitude relation was applied.

Table 1: Samples manufactured, P prisms, C cylinders, FS Full-scale prisms, D Dimension, GSF Grain Size Fraction, M made by the contractor and L made in the laboratory, MPS Mass Proportion Sieved compared with the reference grading 0/50mm or percentage of mass withdrawn.

Geometry	Prisms		Cylinders			Full-scale prisms	
D (mmxmmxmm)	160x160x320		Ø160x320			300x300x600	
Code	P ₁₂	C ₁₂	C ₂₀	C ₃₀	C ₅₀	FS ₂₀	FS ₅₀
GSF (mm)	0/12	0/12	0/20	0/30	0/50	0/20	0/50
MPS (%)	25%	25%	15%	5%	0%	15%	0%
Size ratio d_{max}/\varnothing	1/13	1/13	1/8	1/5	1/3	1/15	1/6
M or L	L	L	M	M	M	M	M

3.2. Similitude relation principle

For sieved earth, two options are possible. One is to use the same manufacturing water content and dry density as the earth implemented on-site with a grain size up to 50mm. This option was chosen for the samples sieved at 20mm (C₂₀). However, in practice, this option leads to a too dry material that is quite complicated to compact at the targeted density. Indeed, the water is mainly contained in the fine portion of the earth that is the clay-silt-sand-matrix, simply called here the clay-matrix. So, while removing big grains by sieving, with the same manufacturing water content, there will be less water in the clay-matrix, in proportion, than in un-sieved earth.

Therefore, under the premise that the cohesion of the material is mainly due to the clay-matrix, one other option, which is chosen here, is to ensure the same manufacturing water content and dry density of the clay-

matrix of the samples, whatever its grain size proportion. In other terms, it is necessary to calculate the manufacturing water content and the dry density that should have the samples' clay-matrix at X (where X=12mm, 20mm or 30mm here) to reach the same clay-matrix dry density and manufacturing water content as the 0/50mm reference earth (Figure 3).

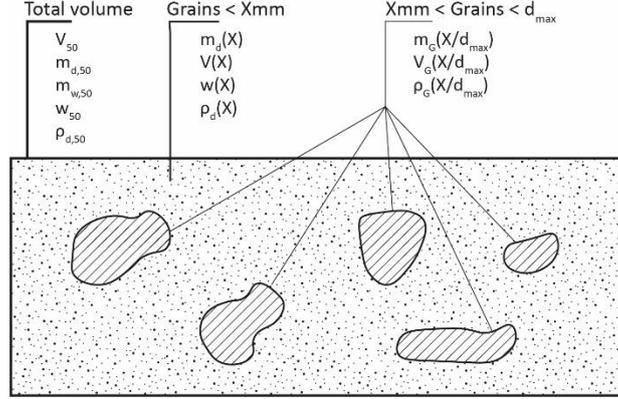


Figure 3 : Schematic illustration of an earth

By definition, the mass proportion of material with grain size lower than X within a volume of 0/50mm earth, denoted by $P(X)$, is equal to:

$$P(X) = \frac{m_d(X)}{m_{d,50}} \quad (1)$$

Where $m_{d,50}$ is the dry mass of the 0/50mm material and $m_d(X)$ is the dry mass of the grains of size lower than X. The dry density of these grains within the volume V_{50} of 0/50mm material is equal to:

$$\rho_d(X) = \frac{m_d(X)}{V(X)} \quad (2)$$

Where $V(X)$ is the volume of grains of size lower than X within the volume V_{50} of 0/50mm earth. $V(X)$ cannot be directly measured.

Similarly, the dry density of the grains of size higher than X within the volume V_{50} , which is denoted by $\rho_G(X/d_{max})$, writes in the form:

$$\rho_G(X/d_{max}) = \frac{m_G(X/d_{max})}{V_G(X/d_{max})} \quad (3)$$

Where

$$m_G(X/d_{max}) = m_{d,50} - m_d(X) \text{ and } V_G(X/d_{max}) = V_{50} - V(X) \quad (4)$$

Again, $V_G(X/d_{max})$, which is the volume of grains higher than X contained in the volume V_{50} , cannot be measured. $\rho_G(X/d_{max})$ was measured through hydrostatic weighing of grains of different grain size higher than 12mm, then the mean value was obtained and $\rho_G(X/d_{max})$ was taken constant equal to 2.35 g/cm^3 .

Then,

$$\rho_d(X) = \frac{m_d(X)}{V(X)} = \frac{P(X).m_{d,50}}{V(X)} = \frac{P(X).m_{d,50}}{V_{50} - V_G(X/d_{max})} = \frac{P(X)}{\frac{V_{50}}{m_{d,50}} - \frac{V_G(X/d_{max})}{m_{d,50}}} = \frac{P(X)}{\frac{1}{\rho_{d,50}} - \frac{V_G(X/d_{max})}{m_{d,50}}} \quad (5)$$

Whereas from (1) and (4):

$$m_{d,50} = \frac{m_G(X/d_{max})}{1 - P(X)} \quad (6)$$

Finally, from (5) and (6), the calculation of the dry density of the 0/X proportion contained in the 0/50mm reference earth, denoted by $\rho_d(X)$, can be made through the relation:

$$\rho_d(X) = \frac{P(X)}{\frac{1}{\rho_{d,50}} - \frac{V_G(X/d_{max})}{\rho_G(X/d_{max})}} \quad (7)$$

where $P(X)$ is the mass proportion of material with grain size lower than X within a volume of 50mm earth; $\rho_{d,50}$ is the dry density of the unsieved material (equal to 1.90 g/cm^3) and $\rho_G(X/d_{max})$ is the dry density of the grains higher than X within the volume V_{50} . This latter was measured through hydrostatic weighing for X=12mm and 30mm. The obtained value was found to be constant and equal to 2.35 g/cm^3 .

Similarly, for the same volume V, the water content of the 50mm sieved material is given by:

$$w_{50} = \frac{m_{w,50}}{m_{d,50}} \quad (8)$$

Where $m_{w,50}$ is the mass of water (kg) inside the volume V. It is assumed that this mass is equal to the mass of

water inside the fine part as grains of size higher than X are non-porous, i.e. $m_{w,50} = m_w(X)$ for $X = \{12, 20, 30\}$, where $m_w(X)$ is the mass of water contained in a volume of $0/X$ mm earth (which was checked for $X=12$ mm through an immersion test).

Then, with equations (1) and (8), we obtain the water content within the $0/X$ proportion of the unsieved material, which is denoted by $w(X)$:

$$w(X) = \frac{w_{50}}{P(X)} \quad (9)$$

where w_{50} is the water content of the unsieved material taken as a reference (equal to 8%). Results of $\rho_d(X)$ and $w(X)$ obtained for $X= 30$ mm, 20mm and 12mm are reported in Table 2.

Dry density and water content effectively used for the manufacture of samples made with the earth of maximum grain size equal to X are, on their side, denoted by $\rho_{d,X}$ and w_X . The manufacturing water contents (w_X) were measured by oven-drying and weighing sample of batches while fabricating the samples. The specimens were weighed before drying and then put in the oven at 105°C and regularly weighed until a constant mass. The dry densities ($\rho_{d,X}$) were calculated by knowing the water content, the volume, and the mass of samples.

For all the samples, the condition $w_X = w(X)$ has been satisfied to within 0.2% so that the manufacturing water content for the clay proportion of all the samples can be considered to be the same. However, as it is shown in Table 2 and underlined at the beginning of this section, the condition $\rho_{d,X} = \rho_d(X)$ (to within 0.01 g/cm³) is satisfied for $X= 30$ mm and 12mm, while for the samples made with the $0/20$ mm earth the condition $\rho_{d,20} = \rho_{d,50}$ (to within 0.01 g/cm³) was applied.

Table 2: Corresponding $P(X)$ for different grading for the earth studied, their targeted manufacture parameters $\rho(X)$ and $w(X)$ calculated through equations (7) and (9), except for $X=20$ mm, for which $\rho(X)$ is targeted equal to ρ_{d50} , and $\rho_{d,X}$ and w_X , respectively the dry density and the manufacturing water content actually measured after manufacturing.

X	50mm	30mm	20mm	12mm
$P(X)$ [%]	100	94	87	77
$\rho_d(X)$ [g/cm ³]	1.90	1.88	1.85	1.80
$\rho_{d,X}$ [g/cm ³]	1.91	1.88	1.91	1.79
$w(X) = w_X$ [%]	8	8.5	9	10.5

The principle of the process to manufacture samples following the similitude relation described above is presented in Figure 4.

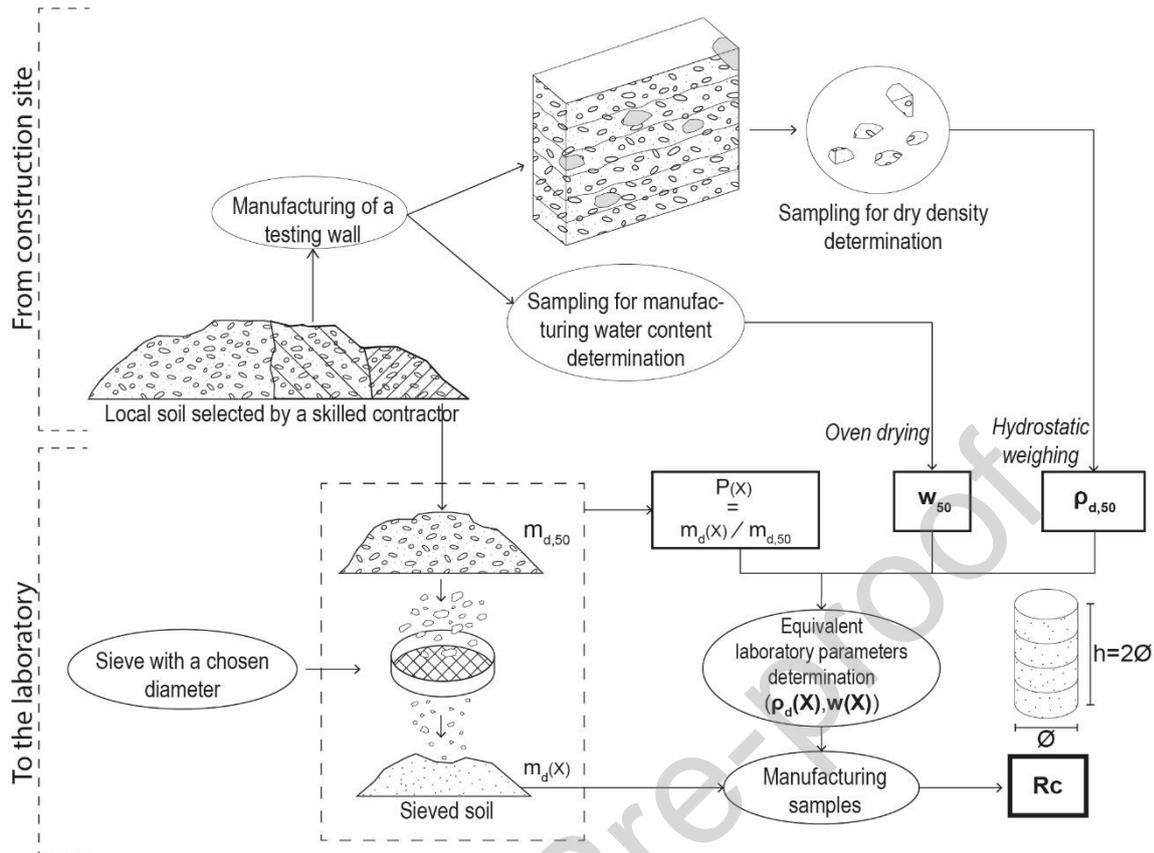


Figure 4: Scheme of the process to manufacture samples with equivalent parameters, where $(\rho_{d,50}, w_{50})$ are the site construction key parameters, respectively dry density and manufacturing water content; $P(X)$ is the percentage of passing obtained from the total dry mass of un-sieved earth $m_{d,50}$ and the dry mass of earth after sieving $m_{d,x}$; $(\rho_d(X), w(X))$ are the equivalent parameters obtained through the similitude relations, respectively dry density and manufacturing water content of sieved earth, ϕ is the diameter of the sample and h its height. (Source: authors)

3.3. Sample conditioning

For each type and geometry of samples, different curing conditions were performed to obtain different testing water content and thus the evolution of the CS against the testing water content. Three states of samples were considered to be tested: dry (about 1%), intermediate water content (between 2 and 8%) and wet (8 to 10%). Those states have been defined from the construction project. Indeed, the manufacturing water content on-site was around 8 % and during the life of the building, the water content inside the walls will not climb above this value except in exceptional cases (pathology), which are not considered here. The dry state of the water content of 1% corresponds to the service phase of the building, at the end of the drying process of the wall. This value has been obtained from a hygrothermal model in another study. And finally, the intermediate state is related to the drying process of the walls, which is thus contained between 8 and 1%.

The samples tested at a dry state were dried either in the oven at 50°C (to accelerate the drying process) or in the atmosphere of the laboratory until obtaining a steady mass through regular weighing. Whatever the drying process, before testing, samples were hygrothermally stabilized in the atmosphere of the laboratory (temperature of 23°C +/- 3°C and relative humidity of 50% +/- 10%) for a few days until the mass has stabilised, for small scale samples, (160mmx160mmx320mm prisms and ϕ 160mmx320mm cylinders) and several weeks until the mass has stabilised, for FS prisms (300mmx300mmx600mm).

The ones tested at intermediate water content were either dried in the oven at 50°C or dried in the atmosphere of the laboratory. By knowing the manufacturing water content and the initial mass of those samples, it was possible to estimate the mass corresponding to targeted water contents. The samples were regularly weighted and, when the targeted mass was reached, they were wrapped in an airtight plastic film until performing the compression tests. The water content homogeneity was assumed and verified after testing through measuring the water content selected from different places of the tested samples. Samples tested at a wet state were wrapped in an airtight plastic film directly after being manufactured and until being tested in

compression. Whatever the curing condition, samples top surfaces were coated with a thin layer of about 3mm of clay-sand plaster which was applied at least 2 days before testing (only top surfaces because the ramming process led to perfectly flat bottom ones).

3.4. Experimental set-up

For the small-scale samples (P_{12} , C_{12} , C_{20} , C_{30} , C_{50}), a hydraulic press was used with a force sensor of a capacity of 100 kN. For the FS prisms, (FS_{20} and FS_{50}) a hydraulic press was used with a force sensor of a capacity of 250kN. All the tests were controlled in displacement with a rate of 1.2 mm/min until the failure to obtain a rupture between 1 and 5 minutes as notified in the XP P13901 norm.

Before each test, samples were weighted and their size was measured. Latex layers were placed at the bottom and top of the small samples to homogenise the stress transfer from the press to the samples. After the failure, specimen were collected from the tested sample to determine the water content by an oven-drying process at 105°C. Finally, by measuring the different sizes and calculating the volume, mass and water content of the samples, their dry densities were calculated.

4. Results and Discussion

4.1. Raw results

The results obtained (Figure 5) are consistent with previous literature. An increase of the CS while the water content decrease is noted [30,31]. For wet samples (around 7 to 12% of water content), the CS is between 0.05 and 0.25 MPa, while for dry samples (around 0.5 to 2%), the CS is between 0.65 and 2 MPa. This is relevant with results generally obtained for RE in previous studies [32].

Exponential regressions have been chosen to describe all the curves as simple models which offered a good correlation, although other models could fit better.

At first sight, these data do not show good consistency between the different types of samples. However, a deeper analysis can be pursued considering different parameters that could influence the CS: the geometry, the grain size fraction, the density, the size effect, and the different correction that could be applied.

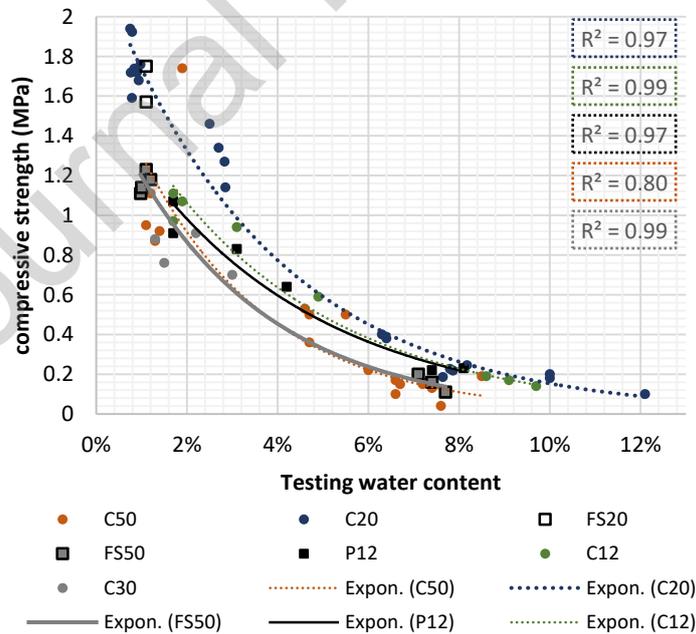


Figure 5 : Compressive strength of all the samples tested, against their testing water content

4.2. Influence of the geometry

The influence of the geometry of the samples on the compressive strength has been studied for the ones manufactured with 0/12mm earth. For those latter, the size of the biggest grain is more than ten times lower than the samples size either if they are cylindrical or prismatic (Table 1). Those samples can thus be assumed homogeneous [28,29].

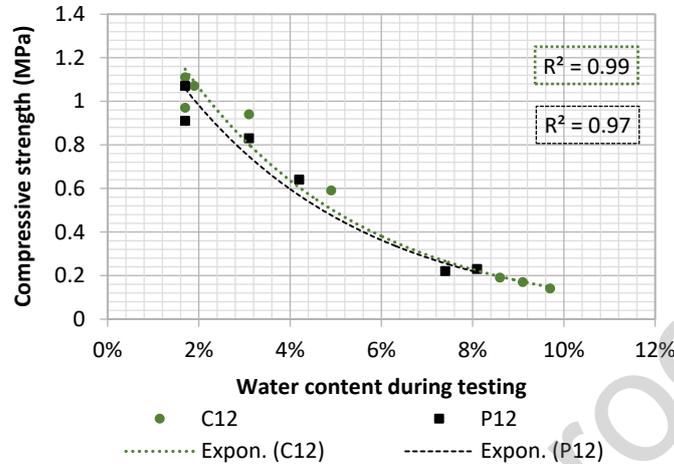


Figure 6: Compressive Strength against water content during testing for cylindrical (C_{12}) and prismatic (P_{12}) samples

The results obtained seem to indicate that the influence of the geometry is negligible (Figure 6), confirming what Venkatarama Reddy et al. [21] have obtained for cement stabilized RE. However, we can observe slightly lower results for the P_{12} compared with the C_{12} at dry states (between 1 and 2% of water content). This might be explained by the manufacturing process. Indeed, it was identified during the study that cylinders were easier to manufacture. The corners of the prisms were particularly brittle due to the stress concentration and then tended to partially break, particularly when moving the samples at a wet state, which could lead to untestable samples. Moreover, there might be an edge effect that could induce a lower local dry density on the corners and thus, a lower compressive strength. Both geometries of samples could then be used to determine the CS for further studies. However, as cylinders are easier to manipulate, this geometry is recommended.

4.3 Influence of the grain size fraction and validity of the method of equivalent parameters

The influence of the grain size fraction was first estimated by comparison between the CS results obtained with the samples of 0/12, 0/30 and 0/50mm earth at several water contents. Results are presented in Figure 7a. In the case of 0/12mm, to ease the reading of data and according to Figure 6, both cylinder and prism samples, are captioned under the same label.

Results appear quite different from one type of sample to another. The two curves are distinct due to the difference in earth grading between the samples.

At first, for 0/30 and 0/50mm earth, the size ratio of 1 to 10 between the smallest length of the sample and the maximum grains size is not fulfilled. That may explain why the results of these samples appear to be more scattered ($R^2=0.8$ for 0/50mm samples versus $R^2=0.98$ for 0/12mm samples). The heterogeneity induced by the presence of big grains could also lead to singular points. Indeed, as observed in figure 7a, one sample made with 0/50mm earth reached a CS of 1.74 MPa for a testing water content of 1.9%. However, a higher dry density could also partially explain this result (dry density of 2.03 g/cm^3 compared with a mean dry density of 1.91 g/cm^3 for the other samples of the same category). The number of big grains in small samples has a high impact on the dry density (as grains have a mean dry density of 2.35 g/cm^3 in our case) and on the water content. Thus, the greater is the size fraction the more chances are to have heterogeneity. There are two types of possible heterogeneity, one inside the samples themselves and one between the samples (variability of dry density or water content and thus variability of the results). Both can be induced by the presence of big grains in the earth used.

Secondly, as it is mentioned previously, the cohesion of the material is mainly provided by the clays and adsorbed water. Therefore, the dependency of CS on the water content should be linked to the amount of water within the clay fraction of the material. To avoid this problem, instead of directly using the sample's water content (which is the mass of water per unit of sample's dry mass), we rather use an equivalent one,

which takes into account the fact that the clay proportion within the earth increases when it is sieved. Following the same approach as the one presented in section 3.2, this equivalent water content can be written in the form:

$$w_{cor} = P(X) \cdot w \quad (10)$$

Where $P(X)$ is the mass proportion of material with grain size lower than X within a volume of 0/50mm earth, and w is the measured testing water content of the sample. w_{cor} can be considered as the equivalent water content that should have a sample made with 0/50mm earth to reach the same water content of its clay proportion as the tested sample at a water content equal to w and made with a 0/ X mm earth.

CS results obtained with the cylinders of 0/12, 0/30 and 0/50mm earth in the function of the equivalent water content are presented in Figure 7b. This graph underlines that considering the equivalent water content tends to significantly reduce the discrepancies between the samples made with earth of several grain size fractions.

Finally, sieving the earth and using the method of equivalent parameters allow fulfilling the ratio of 1 to 10 between the biggest grain and the smallest length of the sample. By doing so, greater repeatability can be observed for 0/12mm earth samples compared with 0/50 earth samples (Figure 7a and b).

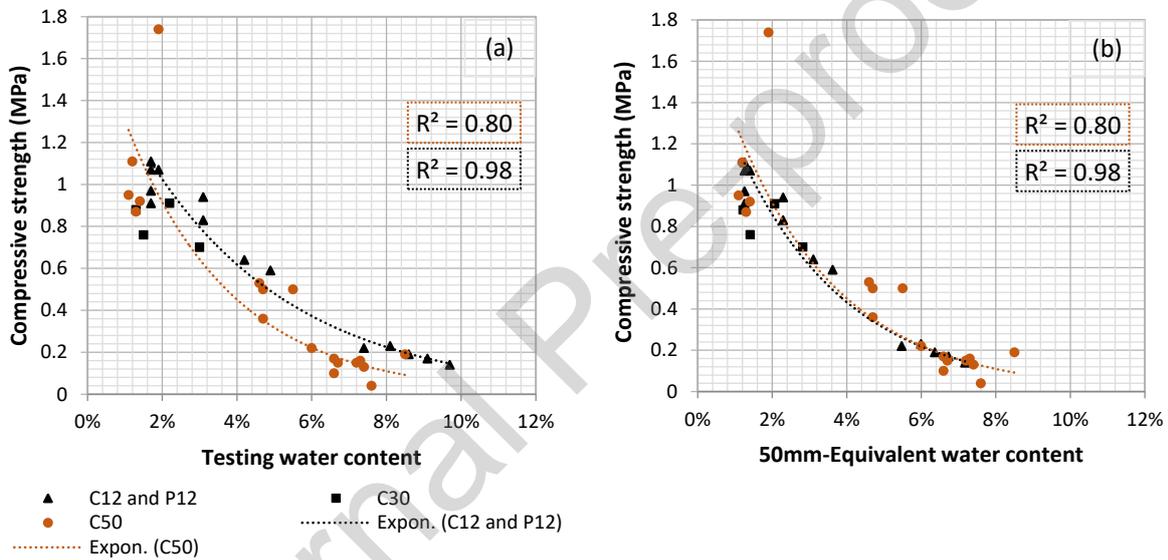


Figure 7: a, CS against testing water content for C_{12} , P_{12} , C_{30} and C_{50} ; b, CS against 50mm-equivalent water content for C_{12} , P_{12} , C_{30} and C_{50} .

Let us underline that the 0/20mm samples have been dismissed from Figure 7 as their equivalent dry density is much higher (mean equivalent dry density of 1.97 against 1.90 for the other samples). The next section 4.4 will then discuss the effect of density.

4.4 Effect of density

As noticed in table 2, different dry densities were considered to investigate the effect of the density. Figure 8 shows the results of 0/20mm earth and 0/50mm earth. Those samples were manufactured under the same conditions: similar mean dry density (1.91 g/cm³ with a standard deviation of 0.05 g/cm³ for C_{50} and 1.92 g/cm³ with a standard deviation of 0.04 g/cm³ for C_{20}), similar manufacturing water content (8% for C_{50} and 9% for C_{20}) and both manufactured by the contractor. Thus, Figure 8 shows directly the influence of the grading on the CS. Discrepancies can be observed with significantly higher results for the 0/20mm earth samples. The two curves get closer when the corrected water content is considered (Figure 8b), however, the results still present a high variability between the two types of samples. This illustrates the importance to consider an equivalent dry density as well. Indeed, a mean dry density of 1.92 g/cm³ for the 0/20mm earth samples corresponds to a dry density of 1.97 g/cm³ brought back to 0/50mm earth, which can explain the gap between the two curves. Thus, targeting a similar dry density as the walls on-site and using sieved earth for manufacturing samples might lead to overestimating the real CS.

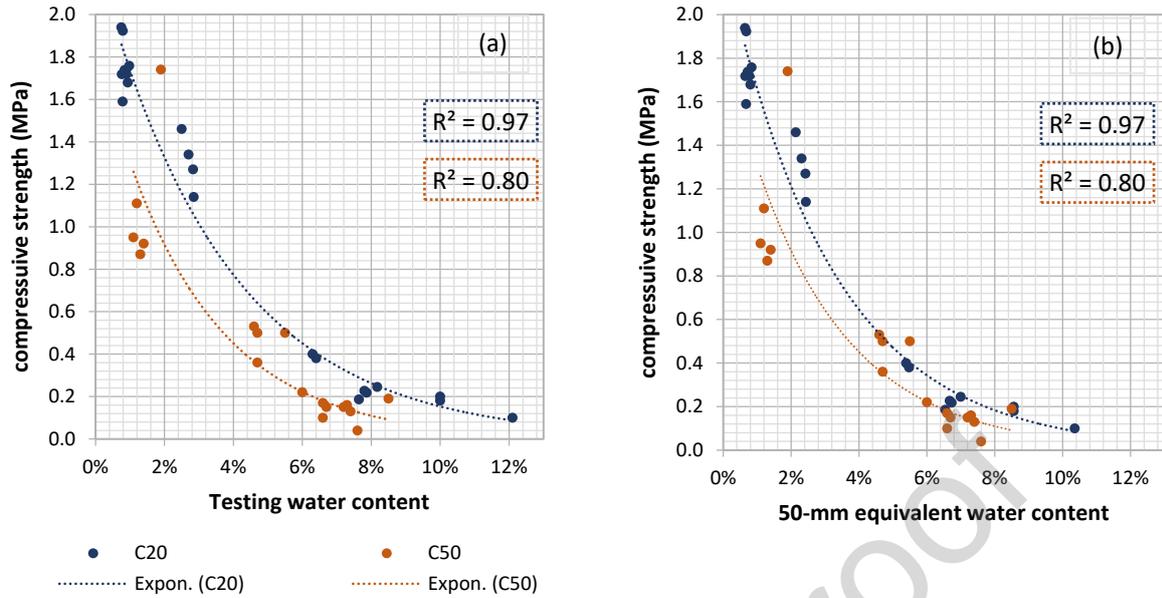


Figure 8: CS against testing water content (a) and 50mm equivalent water content (b) of C_{20} and C_{50}

To investigate the effect of density and apply a correction, the dry density of C_{20} samples (considering here only those tested at a dry state) and the ones of FS_{20} were measured. The CS for those two types of samples shows similar results (Figure 9). Indeed, for the mean water content of 0.8% (standard deviation of 0.1%) and a mean dry density of 1.93 (standard deviation of 0.10), we obtained for C_{20} , tested at a dry state, a mean CS of 1.76 MPa with a standard deviation of 0.10 MPa, while the mean CS obtained for FS_{20} is 1.66 MPa for a mean testing water content of 1.1% and a mean dry density of 1.91. The C_{20} results are included in the margin of error of the W_{20} results. Moreover, the lower dry density, and the slightly higher water content of FS_{20} , compared with C_{20} , could explain the slight difference between these two results.

The size ratio for the samples made with 20mm earth is equal to 1/8, which is too high to follow the criteria of the norm on rocks [28]. However, after testing, the earth of the samples was sieved at 15mm (corresponding to a size ratio of 1/10), and the grains above 15mm length represented only 5% of the samples. Thus, those grains can be assumed negligible. Thus, following the norm, the samples C_{20} were considered homogeneous.

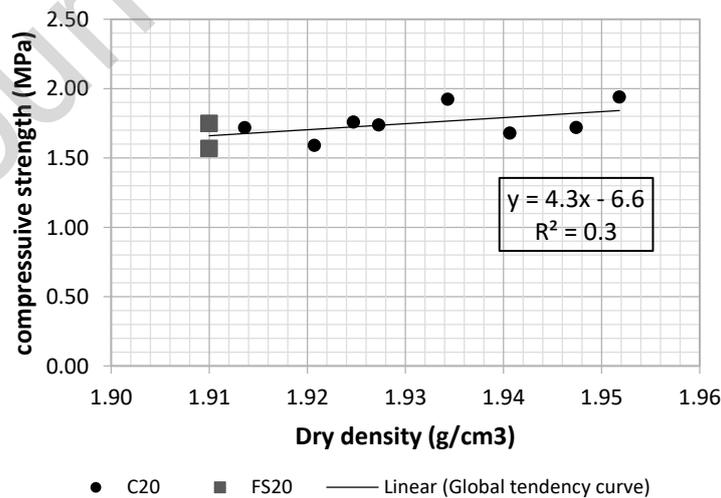


Figure 9: CS against the dry density of C_{20} and FS_{20} samples with a mean testing water content of, respectively, 0.8% (standard deviation of 0.1%) and 1.1%.

The results show that, under homogeneous conditions, it is possible to obtain representative results through testing small samples.

While this output is limited because only two full-scale samples were tested, it is promising for further

consideration of scale effect on RE samples. It shows that with a ratio between the biggest grain and the smallest size of the samples of 1/8 (for C_{20} , 20mm/160mm), we can obtain representative results compared with full-scale samples (ratio of 20mm/300mm=1/15 for W_{20}).

To compare the results obtained on 0/20mm earth samples and those on C_{12} , P_{12} , C_{30} and C_{50} , a correction on the density is then required. Figure 9 shows the strength increases with an increase in dry density with a linear relationship. Because such a correlation already has been proved by different authors [20], we use this linear regression to estimate an equivalent CS for the C_{20} and FS_{20} samples tested at a dry state. The C_{20} samples have a mean dry density of 1.97 g/cm^3 , thus, by targeting the dry density of the site construction 1.90 g/cm^3 , this corresponds to a decrease of 0.07 g/cm^3 and thus a decrease of 0.30 MPa applied to the eight samples C_{20} tested at a dry state and the FS_{20} .

Figure 10 presents the results with this correction applied on the samples tested at dry state (around 1% of water content). Fewer discrepancies are observed than on figure 8b. This tends to validate our hypothesis of using equivalent parameters and particularly equivalent dry densities.

4.5 Comparison with full-scale samples: scale effect

Finally, by applying all the corrections discussed in the previous sections 4.3 and 4.4, we obtain better-correlated results with a much lower variability (Figure 10). In particular, less discrepancies, than in Figure 5, can be observed between Full-scale prisms, representative of on-site construction, and small samples. Slightly higher results are obtained for the dry samples FS_{50} (300x300x600mm) compared with the small samples (C_{12} , P_{12} , C_{30} and C_{50}). This could be due to a residual scale effect after the corrections. Then testing small samples would tend to underestimate slightly the compressive strength, which goes into the direction of safety for building design. Other studies will be required, with other types of earth to investigate this.

In any case, the comparison of figures 5 and 10 show the relevance to use equivalent parameters and the possibility to test small samples instead of Full-scale samples and still obtain representative results. This is an important outcome for further studies, as smaller samples are much easier to manufacture and much cheaper to test in laboratories. This work will also help designers of RE buildings.

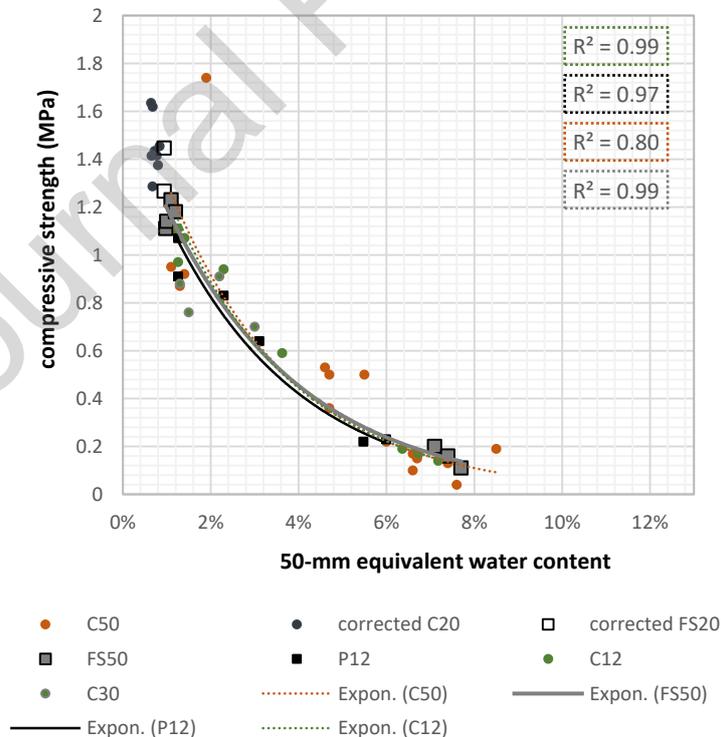


Figure 10: Results obtained of CS against equivalent testing water content after all corrections applied

5. Conclusion

While designing a structural material for a building, one of the most important parameters is the compressive strength of that material. In particular, compressive strength should be obtained through lab testing

representative of the real site materials. Compared with other materials, such as Compressed Earth Blocks, where the earth is sieved, or concrete, where the grading is well known and standardized, rammed earth (RE) walls are generally made with local earth, which can contain big grains. Thus, to ease the manufacturing process in a laboratory and obtain a lower variability in results, those big grains need to be removed and sometimes the material needs to be sieved before making samples. However, by sieving the earth, the granularity of the material is modified and those samples cannot be representative of the earth used on-site. A specific testing procedure had to be designed to tackle this issue.

Through the tests of 66 samples of different geometries of one earth used on a real project, this paper designed a similitude relation and analysed the influence of different parameters on the compressive strength, such as the use of equivalent manufacturing parameters (dry density and manufacturing water content), the geometry, and the influence of the grading compared to the size of samples.

Key parameters (dry density and manufacturing water content) were first determined on-site and then the similitude relation was defined from those key parameters according to the sieving used for the different samples. The samples were then manufactured following the similitude relation.

The principal outcomes of this study are:

- The geometry of samples (cylinders or prisms) does not affect the compressive strength. This means that it is possible to obtain representative results of on-site walls by testing cylinders in the laboratory. We recommend manufacturing cylinders instead of prisms because they have generally less default than prisms (stress concentration due to sharp edges). In any case, an aspect ratio of 2 should be chosen for the geometry of the samples.
- For the same grain size fraction (0/20mm), similar results can be obtained for two different sizes of samples.
- The sieving of the earth for the preparation of samples is useful for different reasons: to test smaller samples (easier and cheaper), to obtain homogeneous samples and then better results with fewer variations. Further studies could establish more precisely what ratio should be considered.
- The similitude relation is established with three equations to define equivalent parameters allowing us to reach similar results, whatever the sieving have been applied to the earth to make the samples, between small-scale samples and full-scale samples.

Finally, since this experimental study was done for one earth only and considering the high variability of earth for different sites, further studies could assess the validity of the similitude relation by investigating other earths. To do so, appendix A can be followed.

Moreover, the similitude relation proposed in that paper worked with an earth with a well-distributed grading. For example, with an earth with 5% of clay (similar to the earth studied), but with no grains between 0 and 12mm, samples made with a fraction of 0/12mm would have only been composed with clay which would probably have changed the compressive strength properties of the material.

CRedit:

Antoine Pelé-Peltier, Conceptualization, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization

Antonin Fabbri, Conceptualization, Writing – Original Draft, Validation

Jean-Claude Morel, Conceptualization, Supervision, Review & Editing

Erwan Hamard, Validation

Maxime Lhenry, Investigation

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Appendix A: Reproducibility of the approach

To reproduce the approach of similitude used in this paper, the below indicative tick points can be followed:

- For a given earth used in situ, called reference earth
- Determine: the grain-size curve (to obtain the per cent of passing $P(X)$, where X is the chosen sieving diameter for the study), the porosity of the grains of size higher than X (immersion test) and the density of the grains $\rho_G(X/d_{\max})$ (through hydrostatic weighing), where d_{\max} is the diameter of the biggest grain contained for in the reference earth.
- Determine the reference parameters (manufacturing dry density ρ_{ref} and the manufacturing water content w_{ref}). Those parameters can be obtained from the on-site for the case of a real construction project, or in laboratory through proctor tests for example.
- Calculate the equivalent parameters (manufacturing dry density $\rho_d(X)$ and manufacturing water content $w(X)$) using the two following equations.

$$\rho_d(X) = \frac{P(X)}{\frac{1}{\rho_{ref}} - \frac{1-P(X)}{\rho_G(X/d_{\max})}} \quad (1)$$

where $P(X)$ is the mass proportion of material with grain size lower than X within a volume of the reference earth; $\rho_G(X/d_{\max})$ is the dry density of the grains higher than X within the volume V_{ref} , the latter corresponding to the volume of reference earth.

$$w(X) = \frac{w_{ref}}{P(X)} \quad (2)$$

- Manufacture the samples: preferably cylinders, with an aspect ratio of 2. In order to assess the similitude relationships, the same size should be chosen for the different samples. Ideally, the two set of samples (samples made with sieved earth C_x and samples made with reference earth C_{ref}) should be manufactured under the same conditions.
- To draw the results for the sieved earth, the following correction concerning the water content should be applied:

$$w_{cor} = P(X) \cdot w \quad (3)$$

Where w is the measured water content of the sample.

- Finally, compare the results between the sieved earth samples and the reference.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Graphical abstract

