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# ACOUSTIC PERFORMANCE OF RAW EARTH CONSTRUCTION SYSTEMS: STATE OF THE ART AND PRELIMINARY RESULTS

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## ABSTRACT

The main objective of the CarAc'Terre project is to remove regulatory and normative obstacles to raw earth construction techniques relative to acoustics. A multi-scale methodology for characterizing the acoustic performance of raw earth construction systems is proposed using both a performance-based and a perceptual approach. A state-of-the-art review on earth-based walls and floors has been conducted as a means of proposing a large experimental design in response to the identified gaps. Measurements are planned at the material, wall as well as building scale, such that contributions from materials formulation, walls composition, system type, and the construction implementation can be investigated.
This paper describes the general outline of the CarAc'Terre project and discusses the preliminary sound insulation results obtained on different types of walls. Measurements to determine material characteristics are described; these material characteristics are subsequently used as input data to numerical models. Comparison between predicted and measured acoustic performance, in terms of sound insulation, is also examined.

**Keywords:** *acoustic performance, raw earth, building acoustics, measurement, prediction.*

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## 1. INTRODUCTION

### 1.1 The CarAc'Terre project

The main objectives of the CarAc'Terre project are to characterize the acoustic performance of raw earth constructions from a physical and sensory perspective, distinguishing the contributions from material formulation, wall composition, and their implementation.
The project, running for 3 years (2024-2027), is carried out with the support of the French Earth National Project [1] which aims to enable a new, large-scale deployment of raw earth constructions by removing cultural, socio-economic, technical, insurance, and regulatory barriers, particularly by involving craftsmen in the earth industry.

### 1.2 Raw earth in buildings

Environmental regulations strongly influence material choices by imposing strict standards on energy performance and carbon emissions. Raw earth, as a low-carbon material, is a response to these requirements, promoting sustainable construction that respects natural resources. Such a strategic material, naturally abundant and renewable, also offers interesting thermal properties to improve summer comfort, thus impacting the energy efficiency and comfort of buildings.
However, the critical lack of acoustic data on raw earth is a major obstacle to its widespread specification and use. Without this information, architects, acousticians, designers, and construction professionals in general are still hesitant to adopt this material, despite its numerous environmental benefits.

### 1.3 Acoustic issues and challenges of raw earth

Mastering the acoustic properties of raw earth-based materials and construction systems in buildings necessarily requires a better understanding of the physical phenomena governing acoustic properties at the material, wall, and in situ scales.
This work has been initiated for certain materials for which results are already available. This is the case, for example, of lightweight earth mixtures [2]. These initial studies have raised numerous questions, such as the effect of the earth and plant fillers used, the elastic characteristics of various materials, and the assumptions of isotropy or multi-scale porosity. Beyond understanding performance levels, it is important to be able to model acoustic behavior and extrapolate them to various formulations or implementation configurations. An initial benchmark of available acoustic modeling tools was carried out on various raw earth systems (earth brick walls, lightweight earth walls, partitions with earth plates) [3].

## 2. PROJECT METHODOLOGY

The main objective of the project is to remove regulatory and normative barriers for all raw earth construction techniques regarding acoustics. The proposed approach is based on the following tasks:

- State of the art and fabrication
- Laboratory measurements
- In situ measurements and surveys
- Modeling at element and building scales
- Knowledge dissemination

The first task aimed to gather all existing data on the subject through a state-of-the-art review in order to define the most appropriate experimental investigation (earth and construction systems choice).
The experimental approach is implemented in two ways: the laboratory level at the material and wall scales under controlled conditions, and the in situ level, with the aim of completing the characterizations while collecting user feedback on their perceptions of the acoustic comfort associated with the raw earth material.
The modeling task will allow the measurement results to be extended to various configurations (formulations, thicknesses, frame types, junctions, etc.) or construction systems.
Finally, the dissemination task intends to communicate the main results in an understandable manner to the raw earth stakeholders in the construction sector. Databases, charts, test reports and standard construction solutions will be widely shared and usable to promote raw earth for different types of buildings, including collective housing.

## 3. MATERIAL SCALE

### 3.1 Material types

Raw earth is implemented using numerous and very different techniques. Furthermore, the raw earth material itself can be very diverse, partly due to the nature of the earth in question and partly due to the elements associated with it (plant fillers, wooden frames, etc.).
The following materials are mainly distinguished [4]:

- Lightweight earth: obtained by combining a large proportion of fibers (hemp, straw, flax, etc.) to earth, with a density around 150 to 1000 kg/m$^3$, implemented through shuttering or projecting, or precast bricks;
- Cob: mixture of clay earth and fibers (usually straw) around secondary frames, with a density from 600 to 1800 kg/m$^3$;
- Bauge: earth-fiber mixture with density from 1400 to 1800 kg/m$^3$, applied in a plastic state by lifting directly onto a wall, with or without formwork;
- Rammed earth: earth and gravel (no fibers) mounted by compaction with formwork, with density from 1700 to 2200 kg/m$^3$;
- Adobes: earth bricks eventually including fibers shaped manually using molds, with density from 1200 to 1800 kg/m$^3$;
- Earth bricks: generally obtained without fibers through compression or extrusion, with density from 1400 to 2200 kg/m$^3$;
- Raw earth boards: fiber-reinforced earth boards (similar use as plaster boards) with density ranges from 700 to 2000 kg/m$^3$;
- Coatings: earth renderings (with or without fibers) are used in addition to all the previously listed materials as a finishing layer to homogenize the appearance of a wall and to protect it, with density from 1500 to 1800 kg/m$^3$;
- Loose earth for floor: adding weight to wood-based floor systems.

It is desired to be able to use all kind of earths regardless of their origin (quarries, spoil, reuse-deconstruction, etc.). Therefore, the tested samples will be representative of a very wide variability of origins, allowing to generalize the obtained acoustic performance results as much as possible.

### 3.2 Approach implemented

The material-scale approach is based on measuring the acoustic performance (absorption coefficient, transmission loss) in a Kundt tube on the different selected materials, and simultaneously characterizing the porous (porosity, airflow resistance, tortuosity, etc.) and elastic (Young's modulus, structural damping) parameters.
Once these properties and characteristics have been determined, an initial modeling step is carried out at this scale to identify the most appropriate material model for each case. In this context, acoustic models account for three modes of dissipation: viscous and thermal dissipations linked to the porous nature of the material, but also mechanical dissipations linked to the elastic skeleton [5]. The parameters required for these models can be relatively numerous depending on the complexity of the material, but a satisfactory description is generally possible by retaining only the most significant ones. MATELYS's AlphaCell© software based on the transfer matrix method (TMM) will be used primarily to predict the acoustic performance at the material scale.
In addition to these parameters, there are mechanical parameters, whose effect at the wall/component level can be very significant. The longitudinal dynamic modulus of elasticity is determined according to standard EN 14146. This measurement is primarily used to characterize the elastic properties of "solid" materials such as concrete (standard, lightweight, polymer, etc.), terracotta, various renders, etc. The method is based on measuring the fundamental resonant frequency of a "bar" or "cylinder" specimen subjected to longitudinal vibration (compression mode). The damping factor is obtained based on the width of the resonance peak. The flexural elastic modulus of the boards (plaster based or earth based) is also determined using the standard ISO 16940 (sample sizes being in the order of 600 mm long and 60 mm wide).

## 4. BUILDING ELEMENT SCALE

Building elements are made from the materials previously studied to form the construction systems for walls, floors, and their coatings. The acoustic challenges for these components and raw earth construction systems are numerous. One of them is to understand their acoustic properties in terms of direct transmission, lateral transmission, and absorption under controlled laboratory conditions, and to successfully maintain these performances once they are installed in situ.
Others are to include the complexity of ensuring peripheral sealing of walls due to shrinkage and settlement as the material dries, the management of wall junctions, the behavior of the systems, and the inhomogeneities of the material that can cause localized weaknesses.
The acoustic and mechanical properties of diffuse-field systems presented below are measured according to building acoustic standards in the CSTB laboratories.

### 4.1 Mechanical properties

The structural reverberation time Ts (in s) is evaluated according to the EN ISO 10848-1 standard on each supporting wall without finish. The total loss factor, including internal losses, coupling losses, and radiation losses, can then be deduced and used in simulations.
The mechanical mobility $Y_{ij}$ (in m/(Ns)) is the ratio of the velocity response at point i to an excitation force applied at point j, according to the ISO 7626-1 standard. An impact hammer (instrumented for evaluating the injected force) is used to excite the wall (transient excitation), and several measurement points on the wall are considered, along with several excitation positions.

### 4.2 Acoustic properties

The acoustic behavior of a system (wall, floor, etc.) is characterized in a laboratory from a direct sound insulation perspective by measuring the sound reduction index R, evaluated according to standard NF EN ISO 10140-2 and from a lateral transmission perspective by measuring the standardized lateral sound insulation $D_{n,f}$, according to standard NF EN ISO 10848-1. Sound absorption behavior represents the ability of a material or system to absorb the energy of sound waves, thus reducing sound reflection and limiting phenomena such as acoustic reverberation. It is characterized by the sound absorption coefficient $\alpha_s$, measured according to the NF EN ISO 354 standard.

### 4.3 Radiation homogeneity

For non-homogeneous structures of certain raw earth construction systems, such as cob or rammed earth, transmission through the walls has been analyzed using supplementary sound intensity measurements. Areas of greater radiation can be observed locally within the studied walls due to certain cracks, clusters of fibers or aggregates (see Figure 1).

### 4.4 Boundaries treatment

The shrinkage and settling of the earth during drying can create voids around the edges of the walls, ranging from one to several centimeters (see Figure 2), which must be filled to obtain satisfactory acoustic measurement.

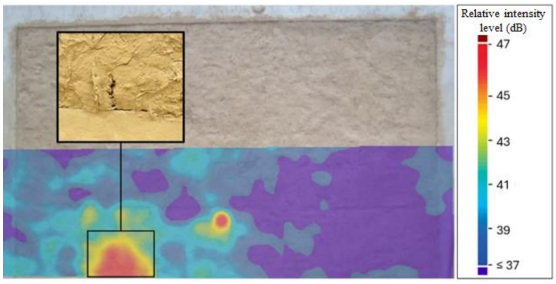


**Figure 1**. Intensity measurement on the cob wall showing effect of local crack (400 Hz).

**Figure 2**. Peripheral shrinkage of an earth wall due to drying.

### 4.5 Modelling

CSTB's AcouSYS software will be used primarily to predict the acoustic performance of multi-layer systems. Calculations are based on the transfer matrix method (TMM) combined with spatial windowing to account for the finite dimensions of the systems. Materials are available: isotropic or orthotropic solid, fluid, porous, perforated, and viscoelastic. Partition assemblies use a frame transmission model with a SEA (Statistical Energy Analysis) approach integrating the distance between studs, the screw pitch, and point contact stiffnesses for frames.
All physical parameters of the materials must be defined.

## 5. BUILDING SCALE

The difficulty in transposing and maintaining performance at the building scale lies in controlling the direct and flanking transmissions.

### 5.1 Junctions

Junction characterizations are planned to be conducted on a prototype built from earth bricks and a timber frame specifically, as well as in situ when the configurations encountered allow it. Measurements will be based on the EN ISO 10848 series of standards for the frequency range covering one-third octave frequencies from 50 to 5000 Hz.

### 5.2 In situ acoustic measurements

Sites containing raw earth construction systems are being identified to conduct in situ acoustic measurements in order to link building elements acoustic performances to the building acoustic performance. The adequacy of the in situ acoustic performance with respect to regulatory criteria and comfort will be verified.

### 5.3 Perceptive survey

A significant built heritage of raw earth is present in France and around the world [6-7]. Despite a Ph.D thesis on the perception of raw earth including the acoustic aspect [8], the absence of quantitative and qualitative data on projects built with raw earth (heritage or recent projects) is quite notable [9]. Therefore, as part of the CarAc'Terre project, it is intended to collect users perception of acoustic comfort and, more broadly, interior comfort based on a survey methodology to be established. The subjective data collected will be compared with acoustic measurements at the building scale in order to observe the influences and relationships between material-related parameters, implementation parameters and user-related parameters (physical, physiological and psychosocial).

## 6. PRELIMINARY RESULTS

### 6.1 Material scale

*6.1.1 Acoustic based characterization*

For each material, an experimental campaign is first carried out to obtain as many mechanical and acoustic parameters as possible, which are essential for subsequent modelling.
An example of material-scale modelling is proposed for the coating on adobe wall. The material behavior can be considered as purely elastic, porous-rigid, or poro-elastic. In the case of a purely elastic material, considered here as isotropic, only the mechanical contributions come into play. These are described in terms of density ρ, Young's modulus E, Poisson's ratio ν, and damping factor η. The porous-rigid hypothesis, which considers only the porous phase of the material, is based on acoustic dissipation resulting solely from visco-inertial and thermal effects. Finally, poro-elastic behavior combines the three dissipative effects. The porous character modeling proposed here is based on the Boutin-Geindreau granular model [10], requiring only two parameters Φ, the porosity, and $R_p$, the radius of earth aggregate considered to be spherical, from which all the other acoustic parameters are deduced.
Five cylindrical samples of coating, with an average

thickness of 41 mm and an average diameter of 96 mm, were tested. Considering the elastic parameters given in Table 1, a Poisson's ratio ν = 0.2 [11], and the acoustic parameters obtained, i.e. Φ=40% and $R_p$=2.1 $10^{-5}$ mm, the absorption coefficient α (-) and the transmission loss TL (dB) of the coating are calculated and compared to the average experimental response measured in a Kundt's tube as shown in Figure 3. Results analysis reveals that the hypothesis of purely porous behavior fails to predict TL, while the one of purely elastic behavior fails to predict α. The poro-elastic behavior hypothesis therefore seems to be the most interesting approaches for TL and α prediction; however, the approach could be refined to improve accuracy.

(a)

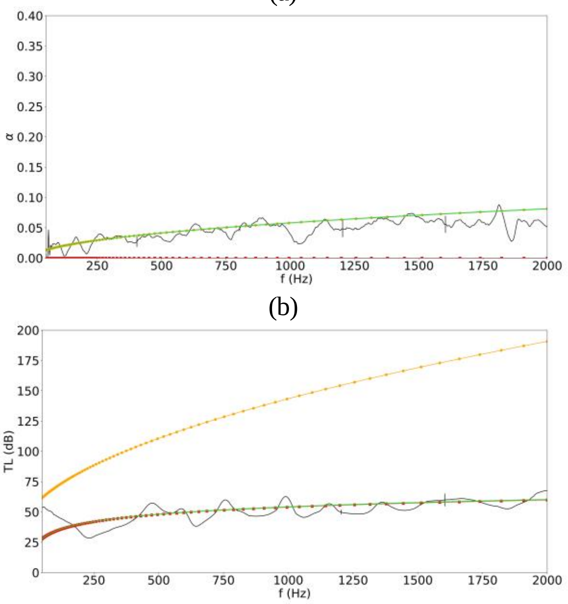


**Figure 3**. Coating material scale behavior for (a) absorption coefficient α (-) and (b) transmission loss TL (dB); experimental measurement (–), simulation of elastic (■), porous-rigid (●), and poro-elastic (–) approaches.

Concerning the acoustic measurement at the material scale for the adobe samples, difficulties were encountered. On the one hand, it was impossible to machine the adobe bricks with the various tools available (hole saw, diamond core bit) to the desired dimensions. The porosity was however measured on brick fragments and found to be around 36%. On the other hand, the materials proved to be too resistive to characterize directly the resistivity. The order of magnitude for this parameter is $10^7$ N.m$^{-4}$s, and this value allowed to determine the absorption behavior and the correct orders of magnitude for transmission performance during modeling at the material scale. Evaluation of other parameters (tortuosity and characteristic lengths) were also not possible due to this impermeable nature.

Therefore, these different materials will be modelled as elastic materials at the building component scale when transmission loss is concerned.

*6.1.2 Structure based characterization*

Samples in the form of bars of 210 mm in length and a square cross section of 50 mm x 50 mm, were produced using the same mix as the adobe bricks. They are used to determine the first compressional mode for longitudinal vibration propagation. Similar measurements were carried out for the coating applied to adobe wall as well as the coating on the earth-based boards mounted on the lining. The elastic modulus of the boards (plaster based or earth based) was determined on beam samples. Table 1 presents the determined characteristics.

**Table 1.** Characteristics determined for the different configurations of the adobe wall.

| Material | ρ (kg/m$^3$) | E (MPa) | η (%) |
|---|---|---|---|
| Adobe | 1835 | 3270 | 2.3 |
| Coating on adobe | 1605 | 4195 | 4.2 |
| Plaster board | 725 | 2200 | 2.0 |
| Earth based board | 1480 | 664 | 3.9 |
| Coating on earth based board | 1738 | 4360 | 2.3 |

## 6.2 Building component scale

Following the state-of-the-art phase, a first group of laboratory measurements has been conducted on different wall systems. Sound reduction index R was obtained for

- Bauge wall
- Two rammed earth walls: 30 and 40 cm in thickness
- Adobe wall considering the effect of a layer of earth slip, earth coating, and plasterboard or raw earth-based board linings

Absorption coefficient α was obtained for several coatings made of clay and earth-hemp mix. Sound reduction index R and airborne flanking transmission $D_{n,f}$ was obtained for a partition wall made of raw earth boards mounted on a metallic frame. Figure 4 illustrates some of the laboratory tested systems.

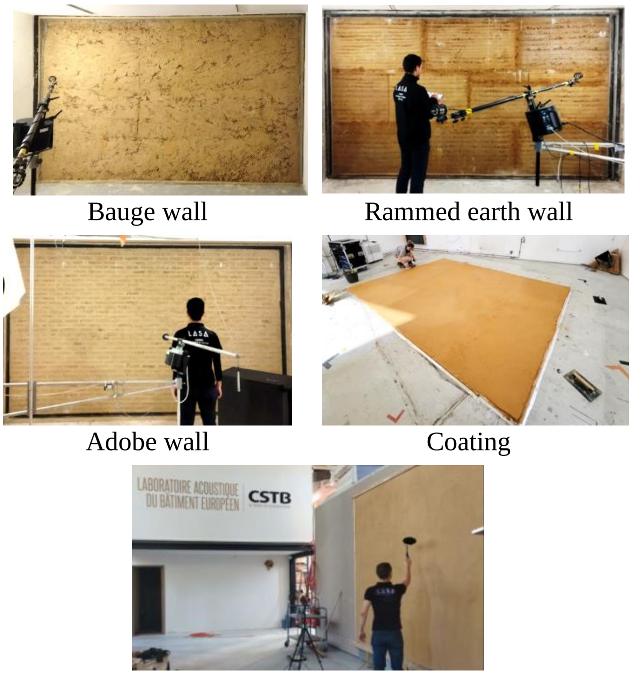


**Figure 4**. Illustration of the systems tested in laboratory.

These measurement results along preliminary prediction results are presented below in details for the adode wall.

*6.2.1 Adobe wall – Laboratory acoustic measurements*

The masonry type adobe wall is 110 mm thick, and made of 110 mm x 50 mm x 220 mm bricks composed of clay, with a mass per unit area of 184 kg/m². The adobe wall is 2.5 m in height and 4.2 m in width and the first measurements were performed 56 days after manufacturing. Then, on the emission side, a thin layer (≈2 mm) of earth slip was first put on the wall, and afterwards a complementary layer of earth coating of 22 mm in thickness was applied.
On the receiving side, two types of lining on standard metallic frame independent from the adobe wall, are considered: the first one is a standard plasterboards lining (45 mm of mineral wool and a double layer of 12.5 mm thick plasterboards); the second one uses earth based boards (earth with coco fibers) 22 mm in thickness instead of the plaster boards, and a earth based coating 10 mm in thickness. The first lining corresponds to a surface mass of about 18 kg/m² while the second one to about 49.5 kg/m².
Figure 5 presents the sound reduction index measurement results for the different configurations considered.

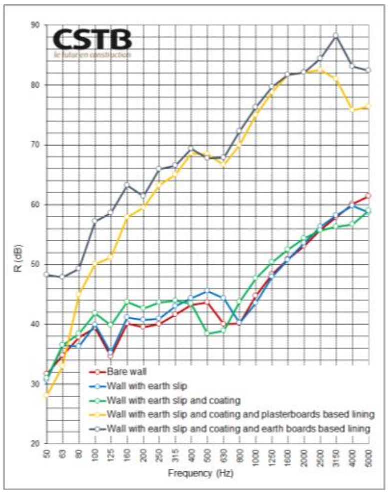


**Figure 5**. Sound reduction index R for the different configurations of the adobe wall.

It can be observed that the application of the earth slip layer has limited influence of the sound reduction index, meaning that the wall has a low porosity. Adding the earth coating layer increases the mass per unit area of the wall thus modifying the apparent critical frequency and improving the sound reduction index below this critical frequency.
Applying a lining on the other side of the wall greatly improves the acoustic performance. The lining using earth based boards with an earth coating finish being heavier than the standard plaster boards is associated to the better performance especially in the low frequency range. In the high frequency range, a flanking pass (probably related to the concrete frame used to mount the wall system) limits the acoustic performance of the linings.

*6.2.2 Adobe wall – Mechanical measurements*

Mobility depends on frequency and has peaks corresponding to the resonance frequencies of the structure considered in the low frequency range. In the high frequency limit, the input mobility $Y_{ii}$ is essentially real and determined by the mass per unit area and the bending stiffness. Figure 6 presents the measured input mobility of the bare adobe wall obtained at 5 different positions on the wall, along with the one predicted using AcouSYS software with an elastic modulus of 2.2 GPa and 3.3 GPa. Since the wall is not a thin plate, the predicted input mobility is not independent of frequency.

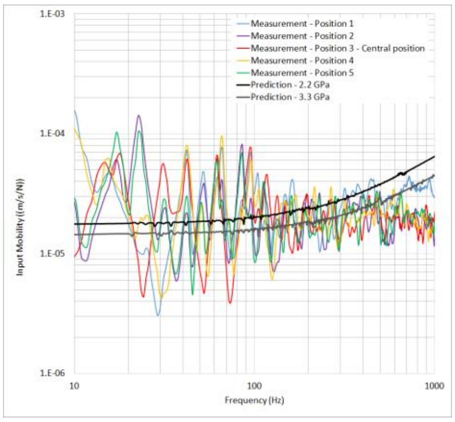


**Figure 6**. Input mobility for the adobe wall (bare configuration).

*6.2.3 Adobe wall – Comparison between measurement and prediction*

The comparison between the measured and predicted sound reduction index for the different configurations of the adobe wall is presented in Figures 7 to 10. The corresponding single number quantities are given in Table 2.

It can be observed that the predicted performances are in line with those measured except for the lower frequency range in the case of the bare wall and the wall with coating on one side (Figures 7 and 8). The elastic modulus of the adobe wall is taken to be 2.2 GPa in order to match the critical frequency between measurement and prediction.

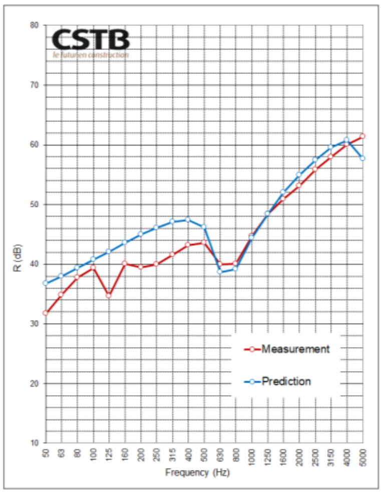


**Figure 7**. Sound reduction index for the bare adobe wall.

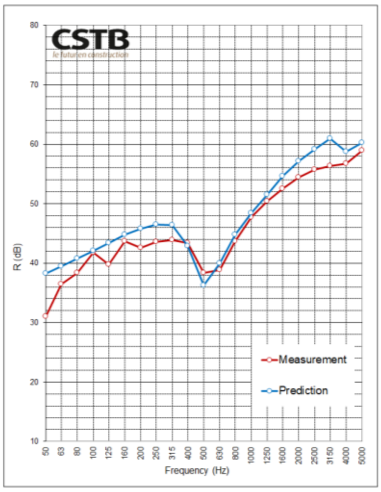


**Figure 8**. Sound reduction index for the adobe wall with earth coating on one side.

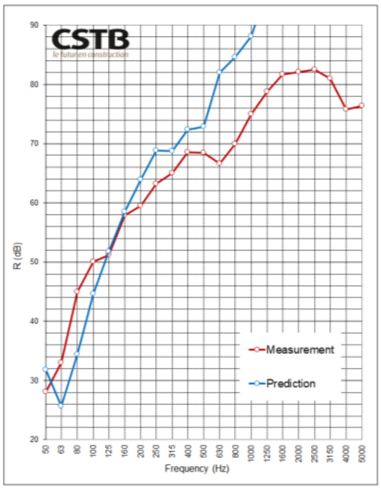


**Figure 9**. Sound reduction index for the adobe wall with earth coating on one side and with standard plaster board lining on the other side.

The presence of a lining improves greatly the acoustic performance; however, the prediction overestimates the acoustic performance (Figures 9 and 10). This is probably due to a flanking transmission associated to the concrete frame holding the wall and the lining. This is under investigation and will be taken into account in the future prediction. However, the SNQ in the case of the standard lining obtained from the measurement and the prediction is close; this is not the case for the other type of lining tested.

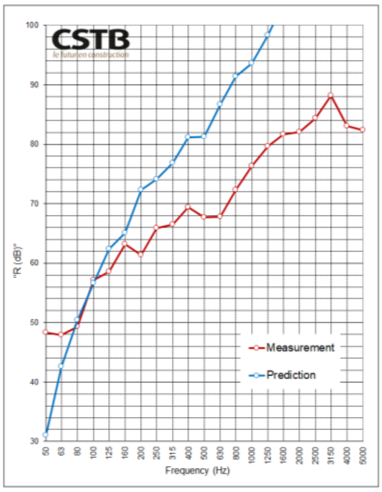


**Figure 10**. Sound reduction index for the adobe wall with earth coating on one side and with earth based board lining on the other side.

**Table 2.** SNQ for the different configurations of the adobe wall – Measurement and prediction.

| Configuration | $R_w$+C (dB) Measured / Predicted |
|---|---|
| Bare wall | 45 / 45 |
| Wall with earth slip and coating | 46 / 46 |
| Wall with earth slip and coating and plasterboards based lining | 70 / 71 |
| Wall with earth slip and coating and earth boards based lining | 73 / 81 |

## 7. CONCLUSIONS

This paper describes the general outline of the CarAc'Terre project and discusses the preliminary sound insulation results obtained on different types of walls. Measurements to determine material characteristics are described; these material characteristics are subsequently used as input data to numerical models.

Preliminary comparison between predicted and measured acoustic performance, in terms of sound insulation, has been examined for the adobe wall. Similar methodology is applied to the other walls already tested.

More measurements both in laboratory and in situ are planned in 2025, as well as the first occupants survey.

## 8. ACKNOWLEDGMENTS

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