forum acusticum 2026
8-12 September · Graz, Austria

ACOUSTIC PERFORMANCE OF RAW EARTH CONSTRUCTION SYSTEMS: MEASUREMENT AND PREDICTION

T. Blinet[1], C. Guigou-Carter[2], P. Glé[3], A. Clément[4]

[1] *CSTB, 84 Avenue Jean Jaurès, 77420 Champs Sur Marne, France*
[2] *CSTB, 24 Rue Joseph Fourier, 38400 Saint-Martin-D'Hères, France*
[3] *Cerema, Univ. Gustave Eiffel, UMRAE, 11 Rue Jean Mentelin, 67200 Strasbourg, France*
[4] *LASA, 20 Boulevard Eugène Deruelle, 69003 Lyon, France*

Abstract

The building sector faces the dual challenge of reducing environmental impacts while ensuring occupant comfort. In this context, raw earth materials represent a promising low-carbon solution due to their local availability and favourable thermal properties. However, their acoustic performance remains insufficiently documented, limiting their broader use.
This paper presents experimental and numerical investigations carried out within the CarAc'Terre project. The airborne sound insulation of various earthen wall systems is evaluated through laboratory measurements following standardized procedures and compared with predictions obtained using a Transfer Matrix Method (TMM).
A good overall agreement between measurements and simulations is observed, generally within a few decibels. Heavyweight systems ($\rho > 1000$ kg/m^3) are mainly governed by mass and mechanical properties, whereas lightweight systems are dominated by porous acoustic behaviour. The model successfully captures key phenomena such as critical frequency effects, thickness resonances, and mass–spring–mass behaviour.
These results demonstrate the relevance of TMM-based modelling for predicting the acoustic performance of raw earth walls. However, more complex FEM modelling is under investigation in order to evaluate the effect of the wood frame incorporated in some of the raw earth walls for structural reason, or wall homogeneity.

Corresponding author: thibaut.blinet@cstb.fr.

Keywords: raw *earth constructions, sound insulation, measurement, acoustic modelling*

1. Introduction

Environmental regulations increasingly shape the selection of construction materials by imposing strict requirements in terms of energy performance and greenhouse gas emissions. In this context, raw earth materials constitute a relevant alternative due to their low environmental impact, local availability, and renewability. In addition, they exhibit favourable thermal and hygroscopic properties, particularly in terms of heat storage capacity and relative humidity stabilization, contributing to improved indoor comfort especially in summer and enhanced energy efficiency of buildings.
Despite these advantages, the use of raw earth in modern construction remains limited due to the lack of shared building rules and performances adapted to the contemporary building requirements. One of the major barriers is the lack of reliable and comprehensive data on acoustic performance. Sound insulation is a key parameter for both occupant comfort and regulatory compliance, and insufficient knowledge in this domain prevents stakeholders from confidently integrating earthen materials into building projects.
Previous studies have provided initial insights into the acoustic behaviour of specific earthen systems [1]. However, these investigations remain limited in scope and do not cover the diversity of construction techniques and material formulations. Moreover, predictive approaches allowing extrapolation to various configurations are still underdeveloped.
In this context, the CarAc'Terre project, supported by the French National Earth Project [2], aims to develop a multi-scale framework for the characterization and prediction of acoustic performance of raw earth

constructions, combining laboratory measurements and numerical modelling [3-6]. The effect of soil properties on the acoustic behaviour at the material scale is discussed in a companion presentation [7]. Understanding the contribution of soil characteristics (particle size distribution, clay type and content, etc.) with respect to acoustic behaviour, is major step in order to account for their effects at the wall and building scales.

The present paper focuses on airborne sound insulation of earthen walls. The objective is to evaluate the ability of a Transfer Matrix Method (TMM) model to reproduce experimental results and to identify the key parameters governing acoustic performance.

2. Measurement and modelling methods

2.1 Laboratory measurements

The sound insulation performance of walls is assessed through the sound reduction index R, measured in accordance with EN ISO 10140-2 [8]. Measurements are carried out between 50 Hz and 5000 Hz using a standardized transmission suite.

The sound reduction index is defined as:

$$R = L_E - L_R + 10\log(S/A) \qquad (1)$$

with L_E and L_R, the sound level respectively in the emission and reception room in dB, S, the surface area of the model to be tested in m², A, the equivalent absorption area in the reception room in m² such that

$$A = (0.16 \times V)/T \qquad (2)$$

where V is the volume of the reception room in m³ and T is the reverberation time of the same room in s.

Single-number quantities R_w (C; C_{tr}) are determined according to ISO 717-1 [9].

2.2 Acoustic modelling

2.2.1 Method

The acoustic performance is predicted using a Transfer Matrix Method (TMM) [10] [11] implemented in the AcouSYS software, developed and commercialized by CSTB. The model accounts for multilayer structures composed of solid, fluid, viscoelastic and porous layers (according to the generalized Biot-Allard theory [12]). Moreover, a spatial windowing method is applied to account for finite-size effects when subjected to airborne excitation [13].

2.2.2 Input parameters

The parameters required for modelling, characterized directly or indirectly on material samples, are as follows:

- Physical parameters such as thickness t and density ρ.
- Mechanical and elastic parameters such as:
  - Young's modulus E and damping factor η (mainly evaluated according to the standard NF EN 14146 [14])
  - Poisson's ratio ν
- Acoustic parameters related to the dissipation of the fluid phase by viscous and thermal effects inside a porous material such as:
  - Acoustic porosity ϕ (evaluated as described in [15])
  - Airflow resistivity σ (directly measured with the standard NF EN ISO 9053-1 [16]),
  - Tortuosity α_∞ and characteristic viscous and thermal lengths Λ and Λ' (indirectly determined following the methods in [17], [18]).

Some parameters were adjusted to better match experimental observations, reflecting potential differences between small-scale samples and full-scale wall behaviour, as well as model simplification (absence of wood frame, wall homogeneity for example).

3. Acoustic performance of raw earth constructions

The different systems investigated are described in detail below and the calculation/measurement comparison results obtained for each system studied are presented (focused on the single number quantity R_w+C).

All the walls tested were 2.5 m high and 4.2 m wide. For information, investigations and results on an adobe wall have already been presented in [4].

3.1 Heavyweight earthen walls

3.1.1 Systems description

- Rammed earth walls

Two earthen walls, made from soils of different origins, were tested in the laboratory. In order to facilitate the walls constructions in the acoustic laboratory, it was decided to use prefabricated rammed earth blocks.

The first wall consisted of earth blocks with a thickness of 300 mm and a mass per unit area of 614 kg/m², while the second had a thickness of 400 mm and a mass per unit area of 800 kg/m². No surface finishing was applied (see Fig. 1).

(a) (b)

Figure 1. Two rammed earth walls tested: (a) 300 mm thick, (b) 400 mm thick.

- Cob wall

The mixture for the wall was obtained by mixing together layers of wheat straw and of moistened soil.

The wall was built up layer by layer in formwork and also compacted by trampling.
The tested cob wall was 300 mm thick for a mass per unit area of 536 kg/m². No surface finishing was applied (see Fig. 2).

Figure 2. Two faces of the bare cob wall tested.

- <u>Extruded raw earth brick wall</u>

The tested extruded raw earth brick wall was composed of bricks of 300 mm x 100 mm x 100 mm (L x H x t) with a mass per unit area of 203 kg/m². A 10 mm thick earthen coating (mixture of clay, straw and sand) with a mass per unit area of 20 kg/m² was applied on one side (see Fig. 3).

(a) (b)

Figure 3. Extruded raw earth brick wall tested: (a) bare, (b) coated one side.

3.1.2 Calculation/measurement comparison results

- <u>Rammed earth walls</u>

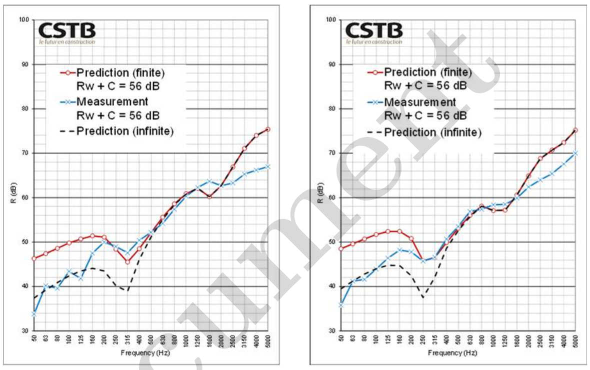
The comparisons between the predicted and measured sound reduction index for the two raw earth walls of thicknesses 300 mm and 400 mm are presented in Fig. 4. The parameters used as input data for the calculation are presented in Table 1.

Table 1. Input data used for calculation (mechanical parameters).

	Rammed earth	
t (mm)	300	400
ρ (kg/m³)	2 046	1 998
E (MPa)	2 067 / 1 900*	1 483 / 1 550*
η (%)	13.7 / 11.0*	18.4 / 8.0*

* Measured value / adjusted value

The simulated performance and behaviour correspond to the measured performance, despite an overestimation of the simulated performance at low frequencies. This difference can be reduced when the calculation does not consider the wall dimensions (indicated as 'prediction (infinite)' in Fig. 4).
The weaknesses observed at the 315 Hz and 2 000 Hz one-third octave bands for the thinner wall (300 mm) are shifted toward lower frequencies, at the 250 Hz and 1 250 Hz one-third octave bands, for the thicker wall (400 mm). These specific frequencies correspond respectively to the critical frequency of walls and to the compression resonance frequency through the wall thickness.
It should also be noted that although the thicknesses of the two walls are significantly different for a relatively similar density, their acoustic performance is of the same order of magnitude. This is probably due to the difference in the earth material (granulometry and clay content) used for prefabricated rammed earth blocks.



(a) (b)

Figure 4. Sound reduction index R for the rammed earth walls: (a) 300 mm and (b) 400mm thick.

- <u>Cob wall</u>

The comparison between the predicted and measured sound reduction index for the bare cob wall is presented in Fig. 5. The parameters used as input data for the calculation are presented in Table 2.
The model reproduces the overall performance, although some differences in behaviour remain. An overestimation of the simulated performance is still observed at low frequencies; this discrepancy can be reduced by neglecting wall dimensions (indicated as 'prediction (infinite)' in Fig. 5).

Table 2. Input data used for calculations (mechanical parameters).

	Cob earth
t (mm)	300
ρ (kg/m³)	1 700
E (MPa)	2 860 / 2 000*
η (%)	3.0

* Measured value / adjusted value

The wall critical frequency, observed in the simulation in the 250 Hz one-third octave band, is not clearly visible on the measured curve. However, the compression resonance frequency observed around the 1 600 Hz one-third octave band shows a slight shift between the calculated and measured values. The inhomogeneity of the wall due to its implementation is probably responsible for the discrepancy between calculated and predicted sound reduction index.

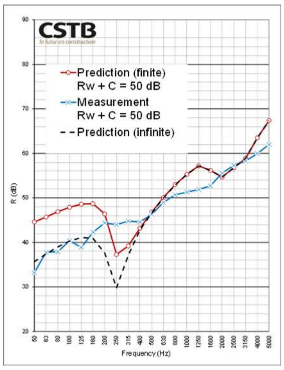


Figure 5. Sound reduction index R for the bare cob wall 300 mm thick.

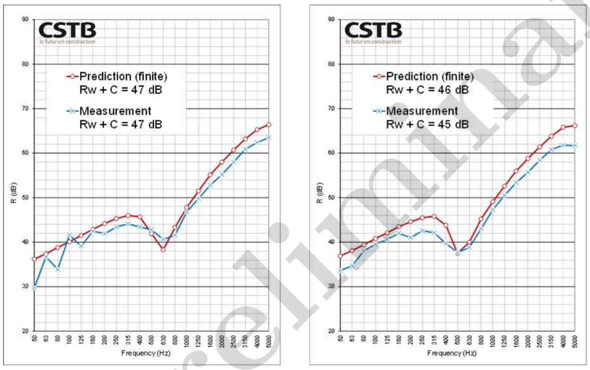
- <u>Extruded raw earth brick wall</u>

The comparisons between the predicted and measured sound reduction index for the extruded raw earth brick wall without and with coating are presented in Fig. 6. The parameters used as input data for the calculation are presented in Table 3.

Table 3. Input data used for calculations (mechanical parameters).

	Extruded brick	Earth coating
t (mm)	100	10
ρ (kg/m³)	1 880	1 605
E (MPa)	4 256 / 3 200*	4 285
η (%)	4.4 / 8.0*	2.9

* Measured value / adjusted value



(a) (b)

Figure 6. Sound reduction index R for the extruded raw earth brick wall: (a) bare and (b) with earth coating on one side.

The simulated performance and behaviour match the measured performance. However, a slight overestimation of performance is observed when the coating is added.

The weakness observed around the 630 Hz one-third octave band corresponds to the critical frequency of the supporting wall.

3.1.3 Discussion

For the heavyweight earthen walls, the acoustic performance is primarily governed by the physical and mechanical parameters. Systems with different thicknesses but similar mass per unit area exhibit comparable insulation performance.

Critical frequency effects associated with bending wave coincidence, as well as thickness resonances related to longitudinal compression modes, are accurately captured by the model. Moreover, a systematic overestimation of acoustic performance is observed at low frequencies. In order to improve prediction in the low frequency range, more complex models should be investigated such as FEM taking into account boundary conditions, inhomogeneities, etc.

3.2 Lightweight earthen walls

3.2.1 System description

- <u>Light earth wall</u>

The tested light earth wall was 180 mm thick for a mass per unit area of 30 kg/m².

It was composed of a raw earth–wheat straw mixture shuttered into a wooden framework (staggered studs spaced every 600 mm and horizontal battens every 300 mm). A layer of earth and straw coating of 30 mm thick and mass per unit area of 43 kg/m² was applied on both sides (see Fig. 7).

(a) (b)

Figure 7. Light earth wall tested: (a) bare, (b) coated both sides.

- <u>Wattle and daub wall</u>

The tested wattle and daub wall was 150 mm thick for a mass per unit area of 113 kg/m².

It was composed of strips of hay and earth twisted around a wooden framework (studs spaced every 800 mm and horizontal battens every 200 mm). The assembly is then covered with a layer of earth and straw coating of 20 mm thick and mass per unit area of 34 kg/m² was applied on both sides (see Fig. 8).

(a) (b)

Figure 8. Wattle and daub wall tested: (a) bare, (b) coated both sides.

3.2.2 Calculation and measurement comparison results

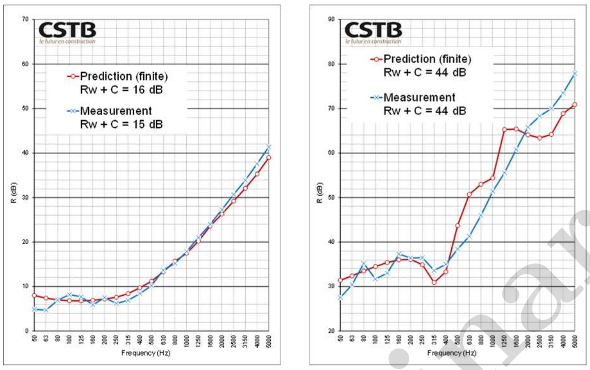
- Light earth wall

The comparisons between the predicted and measured sound reduction index for the light earth wall without and with coating are presented in Fig. 9. The parameters used as input data for the calculation are presented in Table 4.

Table 4. Input data used for calculations (mechanical and acoustical parameters).

	Light earth	Earth coating
t (mm)	180	30
ρ (kg/m³)	215	1 440
E (MPa)	7.1 / 19*	1 254 / 1 500*
η (%)	11.7 / 20.0*	1.4 / 2.0*
ϕ (%)	63 / 72*	
σ (Pa.s/m²)	22 000 / 4 000*	
α∞ (-)	3.00 / 1.40*	/
Λ (µm)	220 / 80*	
Λ' (µm)	450 / 160*	

* Measured value / adjusted value



(a) (b)

Figure 9. Sound reduction index R for the light earth wall: (a) bare and (b) with earth coating on both sides.

A good correlation is observed between calculated and measured performance, although the behaviour in the coated configuration is not fully reproduced by the simulation. The effect of the wood framework could be cause in the observed differences. More complex modelling (FEM) should be investigated.

In this case, the weakness observed at the 315 Hz one-third octave band corresponds to the mass–spring–mass resonance frequency of the system.

Moreover, it is important to note that, in the configuration without finishes, the acoustic performance of the wall is primarily governed by its intrinsic acoustic properties.

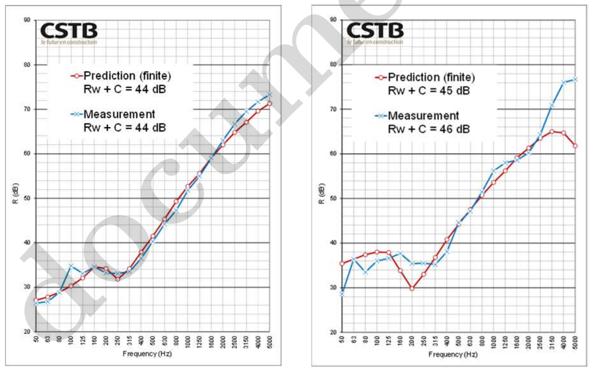
- Wattle and daub wall

The comparisons between the predicted and measured sound reduction index for the wattle and daub wall without and with coating are presented in Fig. 10. The parameters used as input data for the calculation are presented in Table 5.

Table 5. Input data used for calculations (mechanical and acoustical parameters).

	Wattle and daub earth	Earth coating
t (mm)	150	20
ρ (kg/m³)	753	1 605
E (MPa)	600.6 / 3 500*	4 195
η (%)	5.5	4.2 / 6.0*
ϕ (%)	62	
σ (Pa.s/m²)	180 000	
α∞ (-)	5.47	/
Λ (µm)	71	
Λ' (µm)	140	

* Measured value / adjusted value



(a) (b)

Figure 10. Sound reduction index R for the wattle and daub wall: (a) bare and (b) with earth coating on both sides.

A good agreement is noted between the calculated and measured acoustic performance without or with coating.

Once again, the acoustic performance of the bare wall is primarily governed by its acoustic properties.

The weakness observed around the 250 Hz one-third octave band is the critical frequency of the supporting wall.

3.2.3 Discussion

For lightweight systems, acoustic performance is no longer governed by mass but by porous behaviour (visco-inertial and thermal effects). Parameters such as airflow resistivity and porosity play a dominant role in this case.

The good agreement between measurements and predictions confirms the relevance of using a poroelastic modelling framework for these materials.

Finishing layers significantly influence acoustic performance. In multilayer systems, mass–spring–mass resonance appears, particularly at low frequencies, leading to reduced sound insulation.

This effect is clearly observed in coated lightweight walls and must be carefully considered in design.

4. Final comments and conclusion

This study presents a combined experimental and numerical analysis of the acoustic performance of raw earth wall systems. The comparison between measurements and TMM predictions demonstrates that the model is able to reproduce the main physical mechanisms governing sound insulation.

A good overall agreement is observed, typically within a few decibels, although some discrepancies remain at low frequencies. The results highlight general trends based on two distinct behavioural regimes: mass-controlled behaviour for heavyweight systems ($\rho > 1000$ kg/m^3) and porous-controlled behaviour for lightweight systems.

The study also emphasizes the importance of accurate parameter identification and the strong influence of multilayer configurations and finishing systems.

These findings provide a solid basis for the development of predictive laws and design guidelines for earthen construction. Future work will focus on extending the approach to a wider range of configurations, with the aim of supporting the integration of raw earth materials into building practice and regulations.

5. Acknowledgments

This project is supported by the French State as part of France Relance, now integrated into France 2030, and operated by ADEME.

References

[1] T. Blinet, C. Guigou-Carter, P. Glé, A. Héllouin de Ménibus, "Project report on acoustic performances of light earth (clay and hemp shiv mix) walls," (in French), *2025.* https://hal.science/hal-04841720v1.

[2] https://projet-national-terre.univ-gustave-eiffel.fr/

[3] S. Tochon-Danguy, P. Glé, C. Guigou-Carter, L. Leguen, M. Romagné, A. Clément, T. Blinet, M. Ziapkoff et A. Marcom, "Acoustic characterisation of earthen construction systems: parameter analysis and development of a multi-scale experimental framework," in *Proc. of the CFA 2025,* (Paris, France), pp. 667–673, 2025.

[4] C. Guigou-Carter, P. Glé, T. Blinet, M. Ziapkoff, M. Romagné, L. Le Guen, S. Tochon-Danguy, A. Clément, A. Marcom, "Acoustic performance of raw earth construction systems: state of the art and preliminary results," in *Proc. of the Forum Acusticum Euronoise 2025,* (Málaga, Spain), pp. 295–302, 2025.

[5] M. Romagné, P. Glé, C. Guigou-Carter, E. Gourdon, "Acoustic performances of earthen walls, review of modeling approaches and tools," in *Proc. of the Internoise 2024,* (Nantes, France), pp. 4418–4428, 2024.

[6] M. Ziapkoff, P Glé, A. Hellouin de Menibus, T. Blinet, C. Guigou-Carter, "Characterization of the acoustic behavior of raw earth coatings," in *Proc. of the Forum Acusticum Euronoise 2025,* (Málaga, Spain), pp. 2611–2618, 2025.

[7] P Glé, M. Ziapkoff, E. Bourjaillat, R. Dumesnil, T. Blinet, C. Guigou-Carter, "Investigating the effect of soil properties on the acoustic behaviour of earthen constructions," in *Proc. of the Forum Acusticum Euronoise 2026,* (Graz, Austria), 2026.

[8] NF EN ISO 10140-2:2021, Acoustics - Laboratory measurement of sound insulation of building elements - Part 2: measurement of airborne sound insulation.

[9] NF EN ISO 717-1:2020, Acoustics — Rating of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation.

[10] J.F. Allard and N. Attala: *Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials.* John Wiley & Sons, 2009.

[11] M.L. Munjal: "Response of a multi-layered infinite plate to an oblique plane wave by means of transfer matrices," *Journal of Sound and Vibration*, 162, pp. 333-343, 1993.

[12] M.A. Biot: "Theory of elastic waves in a fluid saturated porous solid. I. Low frequency range, II. Higher frequency range," *Journal of the Acoustical Society of America*, 28, 1pp. 68-91, 1956.

[13] M. Villot, C. Guigou-Carter and L. Gagliardini: "Predicting the acoustical radiation of finite size multi-layered structures by applying spatial windowing on infinite structures," J*ournal of Sound and Vibration*, 245 (3), pp. 433-455, 2001.

[14] NF EN 14146: 2004, Natural stone test methods - Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency)

[15] M. Degrave-Lemeurs, P. Glé, A. Hellouin de Menibus, "Acoustical properties of hemp concretes for buildings thermal insulation: Application to clay and lime binders," in *Proc. of the Cons. Build. Mat.* 160, pp. 462-474, 2018

[16] NF EN ISO 9053-1: 2018, Acoustics - Determination of airflow resistance - Part 1: Static airflow method.

[17] X. Olny, R. Panneton, "Acoustical determination of the parameters governing thermal dissipation in porous media," *Journal of the Acoustical Society of America,* 123 (2), pp. 814-824, 2008.

[18] R. Panneton, X. Olny, "Acoustical determination of the parameters governing viscous dissipation in porous media," *Journal of the Acoustical Society of America,* 119 (4), pp. 2027-2040, 2006.