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CORRELATION BETWEEN DENSITY, ULTRASONIC PULSE VELOCITY, AND DRYING SHRINKAGE IN ECO-CLAY POURED-EARTH

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Abstract

This paper presents an experimental investigation on the interrelationship between physically measured density, ultrasonic pulse velocity (UPV), and drying shrinkage of Eco-Clay poured-earth materials. Five representative mixtures, covering optimized mineral compositions and biopolymer-modified formulations, were selected from a larger experimental program. Density was determined by direct physical measurements and estimated using UPV as a non-destructive method. Drying shrinkage was monitored throughout the natural curing period. The results indicate that optimized Eco-Clay mixtures exhibit high and narrowly distributed dry densities, increased UPV responses, and reduced shrinkage, confirming the formation of a dense and homogeneous internal structure. In contrast, biopolymer-modified compositions show higher variability, increased sensitivity to curing conditions, and amplified shrinkage. A strong correlation between density, ultrasonic response, and shrinkage is demonstrated, validating the use of UPV as a reliable early-stage quality control indicator for poured-earth materials, with notable limitations for biopolymer-modified systems.

Key words*: biopolymer stabilization, drying shrinkage, Eco-Clay, poured earth, ultrasonic pulse velocity.*

INTRODUCTION

Earthen construction materials have regained significant international interest in recent decades due to their low environmental impact, reduced embodied energy, local availability, and compatibility with sustainable development principles. Stabilized earth products, including compressed earth blocks (CEB), rammed earth, and poured-earth systems are increasingly investigated as viable alternatives for modern ecological construction (Walter et al., 2024). Nevertheless, the large-scale structural application of such materials remains constrained by the variability of their physical properties, particularly density, drying shrinkage, and internal structural homogeneity.
Bulk density is one of the most influential parameters governing the mechanical behavior, durability, and dimensional stability of earthen materials (Turco et al., 2021). It is strongly affected by particle size distribution, moisture content at casting, degree of compaction, and the presence of stabilizing additives (Bogas et al., 2023; Turco et al., 2024). Drying shrinkage represents a critical vulnerability of earth-based materials, as it can generate tensile stresses, surface cracking, and long-term dimensional instability if not properly controlled (Bogas et al., 2023). Consequently, the coupled evaluation of density and shrinkage is essential for assessing the technological reliability of stabilized earth products (Keita & Perrot, 2024).
In parallel with conventional destructive testing, nondestructive testing (NDT) methods have gained increasing attention for the assessment of earthen materials. Among these, Ultrasonic Pulse Velocity (UPV) testing offers a rapid and non-invasive means of evaluating internal compactness, homogeneity, and defect distribution. Numerous studies have

demonstrated strong correlations between UPV, density, moisture content, and mechanical performance for stabilized soils and compressed earth products (Bolborea et al., 2021; Sathiparan et al., 2024; Chajec et al., 2025). Studies have also confirmed the effectiveness of ultrasonic methods for assessing stabilized soils over long curing periods, with UPV shown to be sensitive to compaction level and binder type (Kasinikota & Tripura, 2022; Kozubal et al., 2023).

The integration of biopolymers as sustainable stabilizers for soils and clay-based materials represents a rapidly expanding research area in sustainable geotechnical and construction engineering. Natural polymers such as xanthan gum and lignin have been shown to enhance interparticle bonding, stiffness, and water retention capacity (Armistead et al., 2020; Abbasi et al., 2025). However, biopolymer modification also introduces microstructural heterogeneities and moisture-sensitive behavior, which can significantly affect ultrasonic wave propagation and shrinkage response (Xu et al., 2010; Zhang et al., 2020; Vieira et al., 2026). Recent ultrasonic investigations on biopolymer-stabilized soils confirmed that ultrasonic pulse velocity remains sensitive to both curing evolution and internal heterogeneity induced by bio-based binders (Armistead et al., 2020; Abbasi et al., 2025).

Ultrasonic characterization of poured-earth systems has been previously explored mainly in relation to thermal, hygrothermal, and mineral fiber stabilization behavior (Walter et al., 2024; Canivell et al., 2025). However, direct experimental correlations between physically measured density, drying shrinkage, and UPV response in eco-modified poured-earth clay systems remain insufficiently documented in the scientific literature.

Despite the growing body of research on stabilized earth, ultrasonic testing, and biopolymer-based stabilization, the coupled influence of density, ultrasonic response, and drying shrinkage on poured-earth materials incorporating eco-modified clay systems has not yet been comprehensively quantified.

The present study addresses this gap by experimentally investigating the interrelationship between physically measured density, ultrasonic pulse velocity (UPV), and drying shrinkage for representative Eco-Clay poured-earth compositions, including both optimized mineral mixtures and biopolymer-modified formulations. By combining direct physical measurements with nondestructive ultrasonic testing, the study aims to assess the reliability of UPV as a quality-control indicator and to define the technological boundaries governing the dimensional stability of Eco-Clay materials.

MATERIALS AND METHODS

Experimental design and investigated compositions

The experimental program was designed to ensure reproducibility, comparability, and scientific validity of the results. A total of 36 Eco-Clay specimens were prepared and tested, grouped into the following composition families:

- D family (C2-D, C3-D, C4-D): optimized mixtures without additional biopolymers;
- DL family (C2-DL, C3-DL, C4-DL): mixtures with controlled lignin addition;
- DLN family (C2-DLN, C3-DLN, C4-DLN): mixtures with lignin and granulometric corrections;
- NM family: experimental limit compositions;
- R-CAM: reference mixtures used for calibration and comparison; invalid specimens (e.g., zero recorded mass) were excluded prior to statistical processing.

For the present article, five representative formulations were selected: C3-D, C4-D, C2-D, C3-DL, and C3-DLN. These formulations cover optimal, intermediate, and unfavorable behaviors.

Specimen preparation and casting procedure

All specimens were produced using the Eco-Clay poured-earth technology, employing two standardized mold geometries: 150 × 150 × 150 mm and 141 × 141 × 141 mm.

The technological process involved the following steps:

- Mechanical homogenization of the Eco-Clay mixture;
- Single-stage casting without stratification;

- Mechanical vibration for 30–90 s to eliminate internal voids;
- Controlled demolding at 24–48 h, depending on early stability;
- Natural drying for 7–50 days, depending on specimen size, initial moisture, and composition.

Measurement methods and instrumentation

Geometrical and mass measurements

Specimen dimensions were measured using a digital caliper (±0.1 mm), and mass was determined using a precision electronic balance (±0.1 g). Initial dimensions at casting (a_0, b_0, and c_0) and final dimensions after drying (a, b, and c) were recorded.

Density determination

Density was determined by two independent methods:

Direct physical method based on mass and final volume.

Ultrasonic Pulse Velocity (UPV) measurements were performed using a PUNDIT PL-200 ultrasonic testing device equipped with two 54 kHz transducers. The testing procedure was based on the principles of ultrasonic evaluation commonly applied for non-destructive estimation of material compactness and mechanical performance, using a Salman-type correlation between wave velocity and density. The acquisition methodology followed an approach conceptually similar to the combined non-destructive assessment procedure described in the Romanian code NP 137-2014 for concrete investigations.

Measurements were performed in direct transmission configuration on opposite specimen faces in order to evaluate internal compactness and structural homogeneity. The following parameters were recorded:

- ultrasonic path length (mm);
- propagation time (μs);
- UPV1 and UPV2 velocities (km/s);
- mean UPV (km/s).

Drying shrinkage evaluation

Drying monitoring was performed through successive mass measurements during the natural curing period. Moisture loss evolution was evaluated based on the stabilization (flattening) of the weight–time curve, which was considered indicative of the completion of the drying process. The specimens were stored under natural laboratory environmental conditions with uncontrolled temperature fluctuations, maintained within the range of approximately 19-23°C throughout the drying period.

Drying shrinkage was determined by comparing the initial specimen dimensions measured immediately after casting with the final dimensions measured after complete drying. Linear and volumetric shrinkage were evaluated using a digital calliper with an accuracy of ±0.1 mm.

The evaluation procedure followed the general principles commonly applied for dimensional stability assessment of earthen and cementitious materials, adapted to the specific characteristics of Eco-Clay poured-earth compositions.

Visual observations were systematically recorded throughout the drying process, focusing on:

- superficial cracking;
- surface texture and homogeneity;
- localized defects and edge curling.

RESULTS AND DISCUSSIONS

Density of Eco-Clay specimens

The bulk density of the selected representative Eco-Clay formulations (C2-D, C3-D, C4-D, C3-DL, and C3-DLN) was determined after the completion of the natural drying process. Density values were calculated using the physical method based on the ratio between the final dry mass and the measured specimen volume.

Across the representative series, the measured dry density ranged between 1892 and 2108 kg/m³, while the majority of values were concentrated in the interval 1950-2080 kg/m³, confirming a generally good material compactness and technological repeatability. The highest average densities were recorded for the C3-D and C4-D formulations, reflecting improved particle packing and optimal moisture content at casting.

Mixtures from the DL and DLN families exhibited slightly increased density dispersion, which can be attributed to the influence of lignin addition and granulometric corrections

on the internal structure and water retention during curing. In particular, some C3-DLN specimens showed lower density values, correlated with increased shrinkage and localized drying defects, indicating structural sensitivity to binder dosage.

From a technological perspective, density proved to be a key indicator of:

- mixture homogeneity;
- degree of compaction;
- sensitivity to segregation and void formation.

Lower density values were systematically associated with unfavourable UPV responses and higher drying shrinkage, outlining a clear physical interdependence between these parameters. Table 1 synthesizes the representative density values corresponding to the five selected Eco-Clay formulations determined by the physical method.

Table 1. The representative density values corresponding to the selected Eco-Clay formulations determined by the physical method

Family	Density mean (kg/m^3)	Number of specimens
C2-D	~2070	3
C3-D	~2095	3
C4-D	~2084	3
C2-DL	~1995	3
C3-DL	~2072	3
C4-DL	~2027	3
DLN	~1967	9
NM	~2037	9
R-CAM	1937 - 2018	multiple

Density estimation based on Ultrasonic Pulse Velocity (UPV)

In parallel with the direct physical measurements, density was also estimated non-destructively using Ultrasonic Pulse Velocity (UPV). The method is based on the correlation between wave propagation velocity and material compactness, as expressed by established empirical relationships (e.g., Salman-type) (Bolborea et al., 2021).

The measured UPV values for the representative mixtures covered the interval between 0.965 km/s and 2.315 km/s, which corresponds to a broad spectrum of internal structural conditions, from highly compact to porous or poorly consolidated zones. The low UPV value of 0.965 km/s is attributed to local porosity, air entrapment, and heterogeneous internal structure in some experimental mixtures. This behaviour was mainly observed in non-optimized or biopolymer-modified compositions, where ultrasonic wave propagation is more sensitive to internal discontinuities and moisture gradients. Based on these values, the estimated ultrasonic densities showed a good overall agreement with the physically measured densities, particularly for the C3-D and C4-D formulations.

For mixtures belonging to the DL and DLN families, larger deviations between physical and UPV-based densities were observed. These deviations are attributed to:

- heterogeneous pore distribution induced by lignin addition;
- increased moisture sensitivity during curing;
- localized microstructural discontinuities affecting wave propagation.

Specimens exhibiting UPV values below 1.2 km/s systematically displayed lower estimated densities and were associated with unfavourable technological behaviour, such as high shrinkage and surface cracking. Figure 1 illustrates the density values associated with the various composition families analyzed in this study.

UPV–density correlation (method validation)

Comparing the physically measured density with the density estimated using UPV (Salman correlation) reveals a strong linear relationship characterized by:

- coefficient of determination $R^2 \approx 0.98$
- estimation accuracy of 96-107%
- the majority of samples falling within 97-100% agreement.

This relationship is illustrated in Figure 2, where the regression line closely follows the ideal reference line.

UPV-density correlation for the complete specimen dataset

The UPV method accurately reflects density variations for the D and DL composition families.

Larger deviations are associated with DLN and NM compositions, where the microstructure is more heterogeneous.

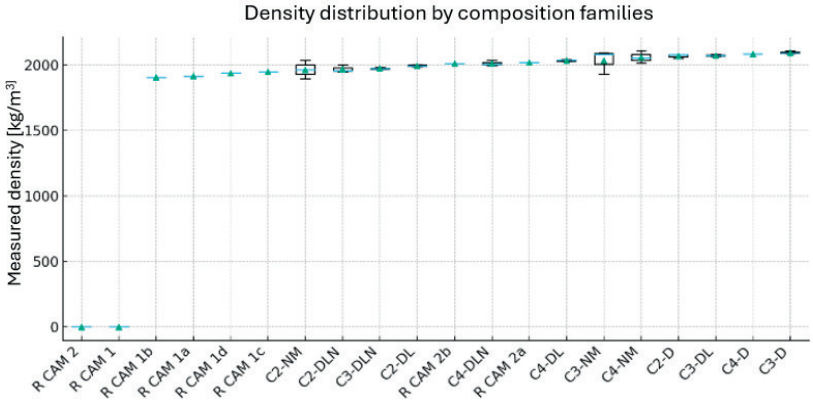


Figure 1. Density distribution by composition families

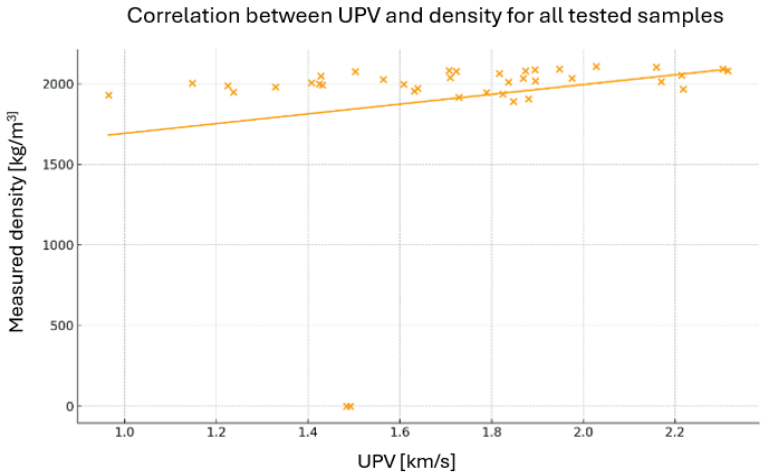


Figure 2. UPV-density correlation by composition families

UPV can, therefore, be used operationally to monitor compaction quality during production stages.

Comparative analysis between physical and UPV-based densities (Figure 2 and Table 2)

The comparative evaluation between physically measured density and UPV-estimated density provides essential insight into the reliability of ultrasonic testing for Eco-Clay materials.

For the optimal mixtures (C3-D and C4-D), the deviation between the two methods remained within a narrow range, confirming that UPV can be reliably used as a non-destructive quality control indicator for compacted poured-earth materials. In contrast, for mixtures with lignin addition (DL and DLN series), the deviation increased, reflecting the sensitivity of ultrasonic wave propagation to microcracking, moisture gradients, and local heterogeneities.

Table 2. Comparison of physical and UPV-estimated density values

Family	Density mean (kg/m^3)	UPV mean (km/s)
C2-D	~2070	~1.65
C3-D	~2095	~2.00
C4-D	~2084	~1.80
C2-DL	~1995	~1.25
C3-DL	~2072	~1.80
C4-DL	~2027	~1.55
DLN	~1967	~1.30
NM	~2037	~1.95
R-CAM	1937 - 2018	1.45 - 1.90

These results emphasize that UPV-based density estimation must be interpreted in conjunction with physical measurements when dealing with biopolymer-modified earth materials.

Drying and shrinkage behavior of Eco-Clay mixtures

Drying and shrinkage were monitored throughout the natural curing period for all representative Eco-Clay compositions by comparing the initial specimen dimensions at the casting stage with the final dimensions after complete drying. Both linear and volumetric shrinkage were evaluated.

The C3-D and C4-D formulations displayed the most stable drying behavior, characterized by uniform dimensional reduction and minimal superficial cracking. The average linear shrinkage for these mixtures remained within a controlled range, indicating a balanced moisture diffusion and internal stress redistribution during drying.

In contrast, mixtures modified with lignin (DL and DLN series) exhibited increased shrinkage variability and a higher sensitivity to curing conditions. Several C3-DLN specimens developed localized surface cracking and edge curling, which correlated well with the following:

- lower physical density;
- reduced UPV values;
- increased internal porosity.

The most unfavorable shrinkage behavior was observed for selected limit compositions (NM family), where rapid moisture loss generated significant tensile stresses and early-age microcracking.

Although these mixtures are not part of the five representative formulations, their behavior is mentioned here to outline the technological boundaries of Eco-Clay materials.

The analysis of volumetric shrinkage across the composition families highlights the following general trend (average values):

- C2 family: higher shrinkage values associated with a solid-liquid ratio more sensitive to drying processes.
- C3 family: moderate shrinkage with relatively low variability between specimens.
- C4 family: intermediate behavior between C2 and C3, with some specimens exhibiting shrinkage values below 1%.
- R family (reference specimens): low shrinkage values consistent with their calibration role.

These results indicate that, within the analyzed dataset, the C3 family exhibits the lowest average volumetric shrinkage with reduced dispersion, suggesting improved dimensional stability compared with C2 and, to some extent, with C4 compositions.

To evaluate the relationship between compaction and dimensional stability, volumetric shrinkage was compared with the physically measured density.

The analysis indicates that:

- specimens with densities above approximately 2050 kg/m³ generally exhibit lower volumetric shrinkage, with average values around 3.5-4%;
- specimens with densities below approximately 1980 kg/m³ show higher shrinkage, with average values around 6-7%;
- the intermediate interval 1980-2050 kg/m³ corresponds to average shrinkage values of approximately 4.9%.

This behavior confirms the general trend in which higher density (i.e., a more compact microstructure) is associated with lower volumetric shrinkage, while lower density corresponds to increased shrinkage and a higher risk of cracking (Zhang et al., 2016; Daneti et al., 2024).

To integrate non-destructive results into the drying behavior analysis, volumetric shrinkage was correlated with ultrasonic pulse velocity values. Figure 3 presents the distribution of specimens in the UPV-volumetric shrinkage plane.

UPV-volumetric shrinkage correlation for Eco-Clay specimens

The results indicate that:

- specimens with high UPV values (> 1.7 km/s) tend to exhibit moderate volumetric shrinkage, with average values around 4-4.5%;
- the interval 1.4-1.7 km/s is associated with slightly higher shrinkage values, averaging approximately 6%;

- specimens with UPV < 1.4 km/s generally show shrinkage between ≈2-5%, but correspond to more sensitive compositions with increased variability.

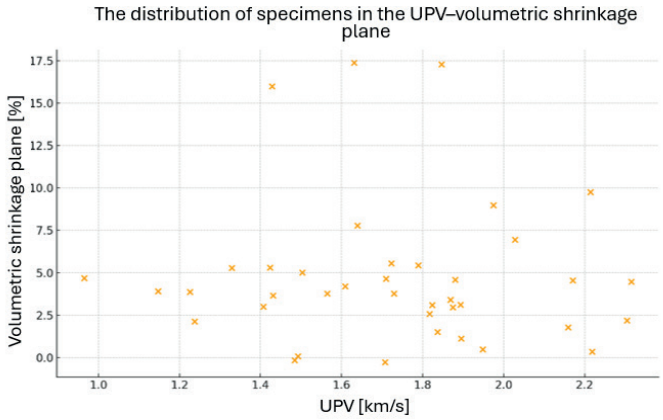


Figure 3. The distribution of specimens in the UPV-volumetric shrinkage plane

Although the UPV-shrinkage relationship is not strictly linear, the results indicate that stable and relatively high UPV values are compatible with reduced to moderate shrinkage levels.

Therefore, UPV can be used as an early indicator for identifying specimens with a more compact microstructure and, consequently, more predictable dimensional behavior during drying (Lim et al., 2018; Chajec et al., 2025).

Overall, the experimental results demonstrate a clear interdependence between density, UPV response, and drying shrinkage, confirming shrinkage as a critical indicator of internal structural integrity and long-term dimensional stability.

Integrated interpretation of density, UPV, and shrinkage

The combined analysis of physically measured density, UPV response, and drying shrinkage highlight a consistent and coherent physical behavior of the Eco-Clay material when optimal granulometry and moisture control are ensured.

For the reference and optimized mixtures (C3-D and C4-D), high dry density values were systematically associated with increased UPV and reduced shrinkage. This triad confirms a dense internal structure, reduced pore connectivity, and improved resistance to drying-induced tensile stresses.

By contrast, the lignin-modified compositions (DL and DLN series) exhibited a more complex behavior. Although certain formulations showed comparable density levels, the presence of biopolymer introduced microstructural heterogeneities that affected ultrasonic wave propagation and amplified shrinkage sensitivity. These effects were particularly visible in the C3-DLN formulation, where lower UPV values coincided with increased dimensional instability.

The limit compositions (NM family), although not central to this article, defined the technological boundaries of Eco-Clay materials. The NM specimens exhibited a more heterogeneous ultrasonic response and increased variability in drying behavior compared with the optimized formulations. Although the mean UPV value of the NM family remained relatively high (approximately 1.95-1.98 km/s), certain individual specimens displayed significantly lower ultrasonic velocities, indicating local heterogeneity, incomplete consolidation, or drying-induced discontinuities. These results suggest that the unfavorable behavior of the NM family is primarily associated with variability and local structural instability rather than with uniformly low UPV values.

From an engineering perspective, the strong interdependence between density, ultrasonic response, and shrinkage validates the use of UPV as a reliable non-destructive indicator for early-stage quality control of poured-earth materials, provided that it is calibrated against

physical density measurements (Kasinikota & Tripura, 2022).

LIMITATIONS OF THE STUDY

The present study has several limitations that should be considered when interpreting the experimental results.

Although the investigated formulations were tested using replicated specimens, the number of samples remained limited for certain composition families, particularly for the experimental and boundary mixtures.

In addition, the drying process was performed under natural laboratory environmental conditions and was not fully climate-controlled. Although the temperature during drying was maintained within an approximate interval of 19-23°C, natural variations in ambient humidity and drying kinetics may have influenced moisture loss evolution and shrinkage variability.

Furthermore, the UPV method presents intrinsic limitations when applied to heterogeneous biopolymer-modified materials. Local discontinuities, pore distribution, moisture gradients, and microstructural heterogeneity may affect ultrasonic wave propagation and generate localized deviations between UPV-estimated and physically measured properties.

Future research should therefore include larger experimental datasets, climate-controlled curing conditions, and extended ultrasonic calibration for highly heterogeneous Eco-Clay systems.

CONCLUSIONS

This study investigated the interrelationship between physically measured density, ultrasonic pulse velocity (UPV), and drying shrinkage for representative Eco-Clay poured-earth compositions, with the objective of supporting early-stage quality control and technological optimization.

The optimal formulations (C3-D and C4-D) exhibited the most stable and consistent behavior, characterized by high and narrowly distributed dry density values ranging approximately between 2070 kg/m^3 and 2095 kg/m^3, increased UPV responses, and reduced linear and volumetric shrinkage. These results confirm the formation of a dense internal structure with limited pore connectivity and improved resistance to drying-induced tensile stresses.

Lignin-modified mixtures (DL and DLN series) displayed a more complex response. Although competitive density levels were achieved in certain cases, the presence of biopolymer introduced microstructural heterogeneities, leading to increased dispersion of UPV values, higher sensitivity to curing conditions, and amplified shrinkage and localized cracking.

The comparative analysis between physically measured and UPV-estimated densities demonstrated that UPV can be reliably employed as a nondestructive indicator for Eco-Clay quality assessment, provided that it is calibrated against direct density measurements and interpreted with caution for biopolymer-modified compositions.

Therefore, for biopolymer-modified materials, it is recommended to combine UPV evaluation with direct physical measurements of density and shrinkage in order to improve the reliability of quality assessment.

From an engineering standpoint, the combined use of density, UPV, and shrinkage offers an efficient and complementary diagnostic framework for optimizing poured-earth Eco-Clay materials. Future research will focus on extending the ultrasonic calibration range for densities below approximately 1800 kg/m^3 and for highly heterogeneous biopolymer-modified systems, refining biopolymer dosage, and correlating nondestructive parameters with mechanical strength for full structural validation.

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