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STRUCTURAL INTEGRITY IN EARTHEN ARCHITECTURE WITH NDT METHODS

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Abstract

The resurgence of earthen construction highlights the environmental, economic, and aesthetic benefits of natural materials. Non-Destructive Testing (NDT) methods are important for assessing the integrity and performance of earthen structures without physical damage. This article reviews key NDT techniques, including ultrasonic testing, electrical resistivity tomography, nuclear magnetic resonance, time domain reflectometry, infrared thermography, and acoustic emission testing, emphasizing their role in evaluating moisture content, mechanical properties, and thermal performance. Despite their advantages, challenges such as material variability, lack of standardized protocols, and specialized training persist. Future efforts must focus on standardization, advanced technologies, and improved data interpretation to maximize NDT's potential. By overcoming these obstacles, the construction industry can ensure the structural integrity and sustainability of earthen materials, promote broader acceptance of earthen construction and foster resilient, eco-friendly building solutions.

***Key words**: NDT, Earthen Constructions, Structural Integrity, Structural Health Monitoring.*

INTRODUCTION

Earthen architecture, widely acknowledged as a sustainable and ecologically responsible construction practice, has played a pivotal role in human habitation for millennia, utilizing naturally available soil as a primary building material (Mousourakis et al., 2020). This architectural tradition encompasses a diverse range of construction techniques, including adobe, rammed earth, and compressed stabilized earth blocks (CSEBs), each of which is distinguished by its unique material composition and construction methodology. These techniques have been extensively lauded not only for their minimal environmental impact - characterized by low embodied energy and thermal efficiency - but also for their profound cultural and historical significance in various regions worldwide (Bui & Morel, 2014).

Despite the numerous advantages associated with earthen construction, the long-term structural stability of such buildings remains a significant challenge due to their inherent vulnerability to environmental degradation. Exposure to climatic factors, including fluctuations in moisture levels, temperature variations, and seismic activity, often accelerates material deterioration, compromising the mechanical integrity and durability of these structures over time (Campiani et al., 2019). As a result, the development and implementation of effective assessment methodologies have become imperative to ensure the preservation and continued use of earthen buildings.

Among the various approaches employed to evaluate the condition and mechanical performance of earthen structures, non-destructive testing (NDT) techniques have gained considerable traction due to their ability to provide critical diagnostic insights without inflicting damage on the material. In particular, Ultrasonic Pulse Velocity (UPV) testing has emerged as a highly effective method for assessing key material properties such as density, porosity, and compressive strength, offering valuable data for both conservation specialists and structural engineers engaged in the maintenance and restoration of earthen heritage and contemporary constructions. This approach not only facilitates the preservation of these culturally significant structures but also enhances our understanding of their material properties and performance over time (Charif et al., 2024).

Ultrasonic Pulse Velocity testing involves sending ultrasonic waves through a material and measuring the time it takes for the waves to travel through it. The velocity of these waves is influenced by the material's density, elasticity, and internal structure, making UPV a valuable indicator of the material's quality and strength. In the context of earthen architecture, the relationship between UPV and compressive strength is particularly significant. Numerous studies have established a correlation between the two, indicating that higher ultrasonic velocities typically correspond to greater compressive strength. For example, Kim et al. (2022) demonstrated that ultrasonic pulse velocity can effectively predict the compressive strength of concrete across varying aggregate types, reinforcing the applicability of UPV in assessing earthen materials. Similarly, Hong et al. (2020) provided empirical evidence of the correlation between UPV and compressive strength, proposing a predictive equation based on their findings.

The compressive strength of earthen materials is an important factor in determining their load-bearing capacity and overall durability. Factors such as the composition of the soil, moisture content, and the presence of stabilizers can significantly influence both the compressive strength and the UPV measurements. For instance, the addition of stabilizers like lime or cement can enhance the mechanical properties of earthen materials, leading to improved performance underload (Mohammad, 2011). Ni et al. (2024) highlighted that various factors, including mix proportions and aggregate types, affect both the strength development of concrete and ultrasonic pulse velocity, emphasizing the need for careful consideration of these variables in earthen architecture.

Recent advancements in ultrasonic pulse velocity (UPV) testing methodologies have significantly expanded its applicability within the domain of earthen architecture, offering enhanced capabilities for the non-destructive evaluation of material properties. In particular, the integration of machine learning techniques into UPV data analysis represents a transformative development, as these approaches facilitate more precise predictive modelling of compressive strength by incorporating a broader spectrum of input variables (Boukhelkhal & Guermazi, 2018). Such advancements not only improve the reliability of UPV-based assessments but also contribute to the refinement of diagnostic frameworks for evaluating structural stability in historical and contemporary earthen constructions.

Moreover, the synergistic application of UPV testing with complementary non-destructive testing (NDT) techniques, such as rebound hammer tests, has been increasingly recognized as a robust strategy for achieving a more comprehensive characterization of material properties (Lee et al., 2014). By integrating multiple diagnostic approaches, researchers can mitigate the limitations inherent in individual testing methods, thereby enhancing the accuracy of assessments related to mechanical performance and long-term durability. These methodological innovations underscore the growing potential of UPV testing as an important tool in the preservation, maintenance, and structural analysis of earthen architecture, reinforcing its role in both academic research and practical engineering applications (Lee et al., 2014).

The use of Ultrasonic Pulse Velocity testing represents an important advancement in the assessment of structural integrity in earthen architecture. By establishing a reliable correlation between UPV and compressive strength, this non-destructive method offers a practical solution for monitoring the health of earthen structures. As the demand for sustainable building practices continues to grow, the preservation of earthen architecture through effective assessment techniques will play an essential role in safeguarding this valuable cultural heritage for future generations.

This research paper explores the potential of using Ultrasonic Pulse Velocity (UPV) as a dependable method for evaluating the structural integrity of earthen constructions.

MATERIALS AND METHODS

In this study, a series of experiments were conducted to evaluate the mechanical properties of various earthen mixtures, focusing on the relationship between Ultrasonic Pulse Velocity (UPV) measurements and compressive strength. For this purpose, 44 mixtures were developed (Table 1) with materials that included different soil types, sand, water, and various additives such as lignin, deflocculants, and lime. These components were selected based on their potential to influence the mechanical properties of earthen materials, particularly in enhancing compressive strength and durability. The mixtures were cast into 40 x 40 x 160 mm prisms.

The earthen mixtures were formulated using a systematic approach, where different recipes were created by varying the ratios of soil, sand, and water, along with the incorporation of specific additives. The soil used in the mixtures was sourced from local deposits, ensuring that it was representative of typical earthen materials used in construction. The sand was selected for its grain size distribution, which is known to affect the overall strength of the mixture. The water content was adjusted to achieve optimal workability while maintaining the desired consistency of the mixtures.

Additives were introduced to enhance the properties of the mixtures. Lignin, a natural polymer, was included to improve the binding characteristics of the mixtures, while deflocculants were used to reduce the viscosity of the slurry, facilitating better mixing and compaction. Lime was added as a stabilizer, known for enhancing the compressive strength of earthen materials through pozzolanic reactions.

Table 1. Earth-based materials mix design

	Clay C1	Clay C2	Clay C3	Sand 0-1	Sand 0-2	Sand 0-4	Clay plaster	Water	Lime	Straws	Deflocculant	Lignin
M1	x							x				
M2	x			x				x	x			
M3	x			x	x			x				
M4	x			x	x			x				
M5	x			x	x			x				
M6	x			x	x			x				
M7	x			x				x	x			
M8	x			x				x				
M9			x					x			x	
M10		x						x			x	
M11			x					x			x	
M12		x						x			x	
M13			x					x			x	
M14		x						x			x	
M15		x						x			x	
M16			x					x			x	
M17		x						x			x	
M18			x					x			x	
M19		x						x			x	
M20	x					x		x			x	
M21		x				x		x			x	
M22			x			x		x			x	
M23	x					x		x			x	
M24		x				x		x			x	
M25			x			x		x			x	
M26		x				x		x			x	
M27			x			x		x			x	
M28	x					x		x			x	
M29		x				x		x			x	
M30			x			x		x			x	

	Clay C1	Clay C2	Clay C3	Sand 0-1	Sand 0-2	Sand 0-4	Clay plaster	Water	Lime	Straws	Deflocculant	Lignin
M31	x					x		x	x	x		x
M32	x					x		x	x			x
M33	x						x	x				x
M34	x						x	x				x
M35	x						x	x				x
M36	x						x	x				x
M37	x						x	x				x
M38	x						x	x				x
M39	x						x	x				x
M40	x						x	x				x
M41	x						x	x				x
M42	x						x	x				
M43	x						x	x				
M44	x						x	x				

Ultrasonic pulse velocity (UPV)

The initial phase of the experimental investigation focused on the application of Ultrasonic Pulse Velocity (UPV) testing as a means of evaluating the quality, homogeneity, and structural integrity of the prepared earthen material mixtures. This non-destructive testing procedure was conducted utilizing a portable ultrasonic testing device, which was equipped with transducers operating at a frequency of 150 kHz. These transducers were responsible for generating and transmitting ultrasonic waves through the test specimens, facilitating the assessment of their internal consistency and mechanical performance.

The selection of transducers with a 150 kHz frequency was informed by established technical guidelines, which recommend their use for assessing relatively thin structural elements - specifically those with dimensions of less than 50 mm. This frequency range has been demonstrated to provide an optimal balance between wave penetration depth and resolution, thereby enabling the precise detection of internal inconsistencies, voids, or heterogeneities within the tested materials. By employing UPV testing in this manner, the study aimed to generate a reliable dataset for characterizing the physical and mechanical behaviour of the prepared mixtures, ultimately contributing to a more comprehensive understanding of their suitability for use in earthen construction applications (NP137-2014). The time taken for the waves to traverse the material was recorded, and the velocity was calculated. This measurement provided insights into the density and elastic properties of the mixtures, which are closely related to their compressive strength. For these types of specimens with dimensions of 40x40x160 mm, the UPV testing was conducted at two points on each sample, as shown in Figure 1. In Figure 2 a cross section with the positioning of the transducers can be observed. This positioning of the transducers was chosen due to the fact that the specimens were tested destructively to determine the flexural strength, thus each specimen resulting in 2 samples to be tested for compressive strength. Prior to the destructive testing, each specimen was weighed to determine an air-dry density.

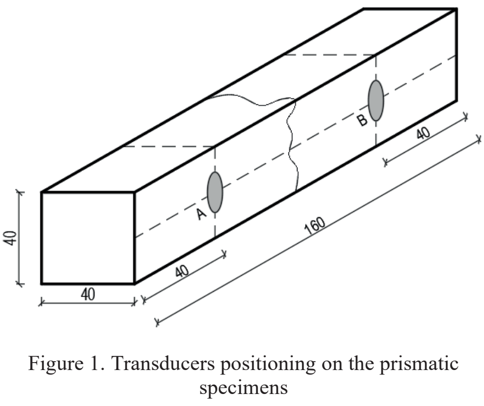

Figure 1. Transducers positioning on the prismatic specimens

Destructive testing for compressive strength

Following the UPV assessments, the same samples were subjected to compressive strength testing to obtain definitive mechanical property data.

The compressive strength tests were performed following standard testing procedures, using a hydraulic press to apply axial loads until failure occurred. The maximum load recorded during the test was used to calculate the compressive strength of each mixture, allowing for a direct comparison with the UPV results.

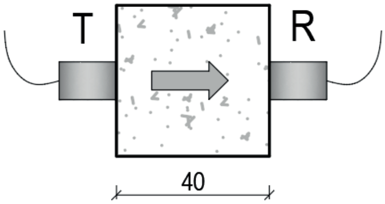

Figure 2. Cross section of the specimens with the positioning of the transducers

RESULTS AND DISCUSSIONS

Correlation between UPV and density

The mean values of the UPV were correlated with the mean values of the air-dry density determined by measuring and weighing each specimen to determine a correlation between them. The UPV values ranged from 0.645 km/s to 1.435 km/s, while density values varied between 1409 kg/m³ and 1782 kg/m³. These measurements indicate a diverse set of materials, with varying degrees of compactness and internal structure. The ultrasonic velocity (UPV) is generally influenced by factors such as elasticity, stiffness, and porosity of the material, while density is determined by the mass per unit volume.

A preliminary dataset analysis suggests a weak correlation between UPV and density, indicating that materials with higher densities tend to exhibit higher ultrasonic velocities. This relationship could be explained by the fact that denser, more compact and cohesive materials offer greater resistance to the propagation of ultrasonic waves. In contrast, lower-density materials, which may contain more voids and less internal cohesion, could allow ultrasonic waves to propagate more easily, resulting in lower UPV values. Figure 3 presents a graphical representation of the correlation between UPV and density. From these values, some trends can be identified:

- Higher UPV values (e.g. 1.252 km/s, 1.383 km/s, 1.435 km/s) are often associated with higher densities (e.g., 1622 kg/m³, 1619 kg/m³, 1603 kg/m³);
- Lower UPV values (e.g., 0.626 km/s, 0.645 km/s, 0.649 km/s) tend to correspond to lower or moderate densities (e.g., 1516 kg/m³, 1591 kg/m³, 1473 kg/m³).

The observed correlation between UPV and density, however, is not linear, as there is some variation in the data. For instance, some samples with relatively high UPV values (e.g., 1.186 km/s) have lower densities (e.g., 1502 kg/m³), which could indicate the presence of other factors influencing the UPV, such as differences in soil composition or structure. Further statistical analysis and experimental studies would be necessary to fully quantify this relationship and account for additional variables.

Correlation between UPV and compressive strength

The ultrasonic velocity values obtained through non-destructive testing (NDT) and the corresponding compressive strength values obtained through destructive testing (DT) were analyzed to identify a correlation between the two (Figure 4). The relationship between ultrasonic pulse velocity (UPV) and compressive strength in the studied soil mixtures reveals significant variations, indicating the influence of material composition and structural characteristics on mechanical performance. The recorded UPV values range from approximately 0.472 km/s to 1.626 km/s, while the compressive strength values exhibit a broader spectrum, from 0.419 MPa to 7.421 MPa.

An initial observation highlights that higher UPV values tend to correspond to increased compressive strength, which aligns with the general principle that denser and more compact materials facilitate faster ultrasonic wave propagation and exhibit greater strength. However, exceptions exist, particularly in cases where relatively low UPV values are associated with remarkably high compressive strengths. For instance, a UPV of 0.759 km/s is linked to a compressive strength of 2.837 MPa, while another instance with a similar UPV of 0.731 km/s reaches 3.970 MPa.

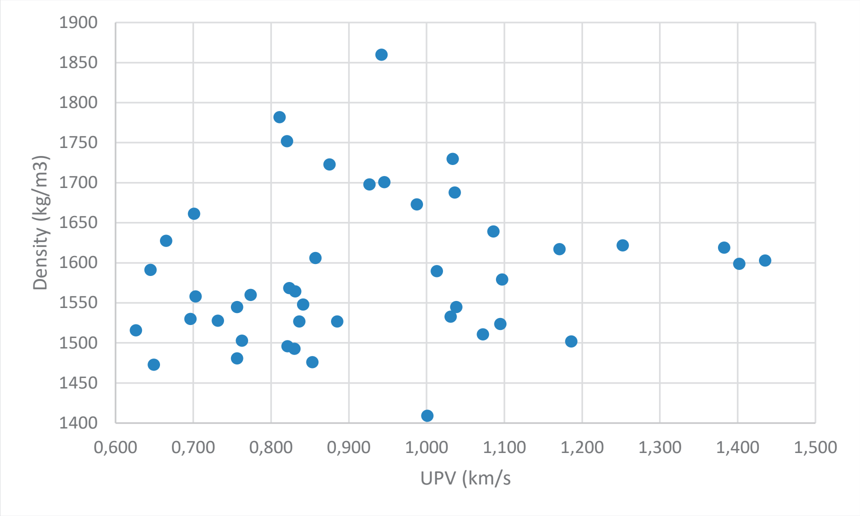

Figure 3. Correlation between UPV and density

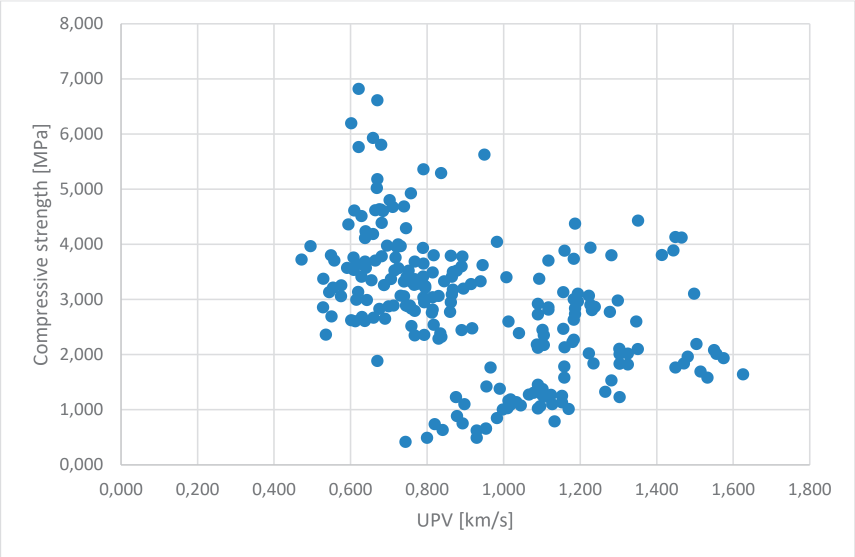

Figure 4. Correlation between UPV and compressive strength

This suggests that factors beyond wave velocity, such as bonding properties and granular arrangement, play an important role in determining compressive strength.

In the lower UPV range (below 0.8 km/s), the compressive strength fluctuates significantly. Some samples exhibit moderate values (e.g., 0.744 km/s corresponding to 0.419 MPa), whereas others demonstrate much higher strengths (e.g., 0.629 km/s associated with 4.513 MPa). These variations imply that certain compositions enable substantial strength development even at relatively low wave velocities, possibly due to optimized particle packing and binder interactions.

Conversely, in the upper UPV range (above 1.2 km/s), compressive strength values remain predominantly higher. For example, a UPV of 1.498 km/s corresponds to a compressive strength of 3.108 MPa, while another instance with 1.303 km/s reaches 2.109 MPa. The consistency in this range suggests that wellcompacted and structurally sound mixtures promote both enhanced wave transmission and mechanical resistance.

Notably, some outliers indicate a deviation from the expected trend. For instance, a UPV of 0.670 km/s corresponds to a remarkably high compressive strength of 6.613 MPa, demonstrating that under specific conditions, even materials with relatively low ultrasonic velocities can exhibit superior values of compressive strength. These anomalies may arise from unique microstructural formations or particular curing processes that enhance cohesion and load-bearing capacity.

Overall, the data suggest a general positive correlation between UPV and compressive strength, albeit with notable exceptions influenced by material-specific properties. The findings highlight the complexity of soil-based materials and underscore the necessity for a comprehensive understanding of both physical and chemical factors when evaluating their mechanical performance.

CONCLUSIONS

The first part of the analysis focused on the relationship between UPV and density. A general trend was observed, where higher UPV values tended to correspond to higher densities. This is consistent with the fundamental principles of material science, as denser materials typically allow sound waves to propagate more quickly due to their compact and homogeneous structure. For example, samples with UPV values above 1.0 km/s often exhibited densities exceeding 1600 kg/m³, while lower UPV values (e.g., 0.626 km/s) were associated with lower densities (e.g., 1409 kg/m³). However, exceptions to this trend were noted, indicating that factors such as soil composition, porosity, and moisture content also play a significant role in influencing UPV independently of density.

The second part of the analysis examined the relationship between UPV and compressive strength. The data revealed a general trend where higher UPV values tend to correspond to higher compressive strengths. This aligns with the fundamental principles of material science, as materials with greater density and compactness typically exhibit faster ultrasonic wave propagation and higher resistance to compressive forces. For instance, samples with UPV values exceeding 1.0 km/s often demonstrated compressive strengths above 1.0 MPa, with some reaching up to 4.136 MPa. This trend supports the hypothesis that UPV can serve as an indirect indicator of compressive strength in soil and similar materials.

Despite the general trend, the dataset exhibited significant variability and several outliers. Some samples with relatively low UPV values (e.g., 0.629 km/s) displayed unexpectedly high compressive strengths (e.g., 4.513 MPa), while others with moderate UPV values (e.g., 0.930 km/s) showed low compressive strengths (e.g., 0.491 MPa). These anomalies highlight the influence of additional factors, such as soil composition, moisture content, curing conditions, and the presence of binding agents, which can significantly alter the mechanical properties of the material independently of UPV.

Combining the insights from both analyses, it is evident that density, UPV, and compressive strength are interrelated but not solely dependent on one another. Higher density generally contributes to both higher UPV and higher compressive strength, but the relationships are not strictly linear or deterministic. For example, some samples with moderate densities exhibited high UPV but low compressive strength, while others with lower densities showed high compressive strength due to factors such as strong internal bonding or optimal moisture content. This highlights the complexity of the interactions between these variables.

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