Sustainable Bio-Based Composites from Termite Mound Soil and Agro-Waste for Lightweight and Acoustic Applications

Nawarat Seetapong[1,4], Natnaree Chorphakar[2], Nuthita Saenkuea[2], Sarawut Chulok[1,4], Polphat Ruamcharoen[3,4] and Purintorn Chanlert[1,4,*]

[1]Program of Physics, Faculty of Science and Technology, Songkhla Rajabhat University, Songkhla 90000, Thailand
[2]Program of General Science, Faculty of Education, Songkhla Rajabhat University, Mueang, Songkhla 90000, Thailand
[3]Program of Rubber and Polymer Technology, Faculty of Science and Technology, Songkhla Rajabhat University, Songkhla 90000, Thailand
[4]Research Unit in Applied Physics and Advanced Materials, Faculty of Science and Technology, Songkhla Rajabhat University, Songkhla 90000, Thailand

(*Corresponding author's e-mail: purintorn.ch@skru.ac.th)

Abstract

This study explores the use of termite mound soil (TMS) as a partial cement replacement in lightweight composites, with emphasis on physical and acoustic performance. Four formulations were prepared: CT (cement + TMS), CTR (cement + TMS + rice husk), CTE (cement + TMS + eggshell) and CTRE (cement + TMS + rice husk + eggshell), cured in water for 7, 14 and 28 days. Bulk density, compressive strength and noise reduction coefficient (NRC) were evaluated. CT composites showed the highest density and strength but did not significantly differ in NRC from the modified formulations. The incorporation of rice husk and eggshell increased water absorption while reducing mechanical performance. ANOVA confirmed significant effects of formulation and curing duration on density and mechanical strength, while NRC remained largely unaffected. TMS-based composites show strong potential as eco-friendly, non-load-bearing construction materials, although the incorporation of agricultural by-products requires further study to clarify their effects.

Keywords: Termite mound soil, Rice husk, Eggshell, Bio-based materials, Acoustic properties

Introduction

The construction sector significantly depends on traditional building materials such as cement and concrete, which present major environmental issues due to their high carbon emissions [1] and extensive resource consumption [2]. As the industry seeks more sustainable practices, environmentally friendly alternatives like clay composites [3-7] are becoming more popular. Unlike concrete blocks, clay composites have a lower environmental impact [3,8-10] due to their energy-efficient manufacturing process and natural raw material components. Moreover, their porous structure improves thermal insulation [11,12], reducing energy usage in buildings and making them a more eco-friendly construction option.

Recent studies have highlighted the importance of developing green construction materials to replace conventional ones [11,13-15]. Geopolymers have emerged as a viable alternative to concrete blocks [16,17], offering similar mechanical strength while emitting fewer greenho use gases during production [18]. Additionally, bio-based materials such as hemp composites [19,20] and mycelium composites [21] are gaining attention for their renewable and biodegradable properties. These alternatives demonstrate the potential of natural and sustainable materials in the construction

industry, paving the way for a more environmentally friendly future.

A particularly promising bio-based material is Termite Mound Soil (TMS) [22,23], a unique resource found in termite mounds. TMS differs from regular clay due to its fine grain size, enhanced stability, and naturally high mineral content [24,25]. The clay's resilience results from termites mixing organic matter, creating a highly compact and durable structure [26]. This makes TMS ideal for producing strong, eco-friendly composites with excellent insulation properties. Additionally, its availability and renewability make it an attractive and sustainable building material that is garnering increasing interest from scientists [23,27].

To further enhance the sustainability and performance of bio-based composites, rice husk and eggshell were incorporated as supplementary materials. Rice husk, an abundant agricultural byproduct, provides advantages in mechanical properties, cost-effectiveness, and sustainability when used in construction [28]. When processed into rice husk ash (RHA), its high silica content enables pozzolanic reactions, which improve compressive strength, durability, and permeability in cementitious composites [29]. Additionally, raw rice husk increases porosity, reducing density and enhancing sound absorption and thermal insulation in lightweight composites, though it can lower compressive strength if overused [30,31]. Meanwhile, eggshell powder, primarily composed of calcium carbonate ($CaCO_3$), serves as a partial cement replacement, lowering cement consumption and reducing carbon emissions in construction [32]. At optimal replacement levels (typically up to 7%), eggshell powder has minimal negative impact on mechanical strength, while enhancing workability and hydration due to its fine particle size and filler effect [32,33]. Moreover, the interaction between RHA's silica and eggshell's calcium can contribute to the formation of additional cementitious binding phases, further improving material properties [29]. Both materials also support waste management and circular economy principles, converting agro-industrial waste into sustainable, cost-effective building materials [28]. Their integration into termite mound soil-based composites presents an opportunity to develop lightweight, sound-absorbing, and thermally insulating alternatives to conventional

building materials, fostering sustainable and resource-efficient construction [31].

In this study, TMS was combined with cement to create a cement–TMS composite (CT). To enhance performance, rice husk and ground eggshell—locally available agro-waste fillers—were added individually (CTR, CTE) and in combination (CTRE) as illustrated in the schematic diagram in **Figure 1**. The composites were evaluated for water absorption, sound absorption and mechanical properties to assess their suitability as sustainable alternatives. Unlike prior studies, this work explores the synergy between TMS and bio-fillers, offering new insights into how naturally occurring soil-based materials can balance mechanical and acoustic performance in low-impact material applications.

Materials and methods

Sample preparation

The lightweight brick samples were crafted using Termite Mound Soil (TMS) mixed with natural materials, following the ratios of TMS, cement, water, rice husk and eggshell outlined in **Table 1**. To mold the lightweight brick samples, cylindrical PVC pipes measuring 28.6 mm in diameter and 40 mm in height were prepared, each lined with a clear plastic sheet to stabilize the samples upon removal. The specified quantities of TMS, cement, water, rice husk and eggshell were weighed and finely ground. These ingredients were then thoroughly mixed to ensure uniform adhesion between the components. Once mixed, the composite was carefully placed in the prepared PVC molds. The surface of the samples was smoothed to maintain the desired shape, while care was taken to eliminate air bubbles in the liquid mixture. The samples remained in the PVC molds to dry at room temperature for a minimum of two consecutive days. After this period, the composites were removed from the molds and left to sun-dry for one day. The composites were then submerged in water for 7, 14 and 28 days to test the effect of water curing. After that, the samples were placed inside an air-circulating oven at 110°C for 24 h to remove water. Finally, the composites were stored in a desiccator for at least 48 h to ensure complete drying before being further processed for measurement.

Microscopic examinations of the samples were conducted to investigate their surface morphology. The samples, which exhibited cracking, were examined in

the areas inside the cracked regions. The surface morphology of the samples was analyzed using a field-emission scanning electron microscope (FEG-SEM, Phenom Pharos G2, Thermo Fisher Scientific, UK). The surfaces of the CT, CTR, CTE and CTRE samples are demonstrated in **Figure 4**.

Table 1 Ratios of ingredient (proportion by weight).

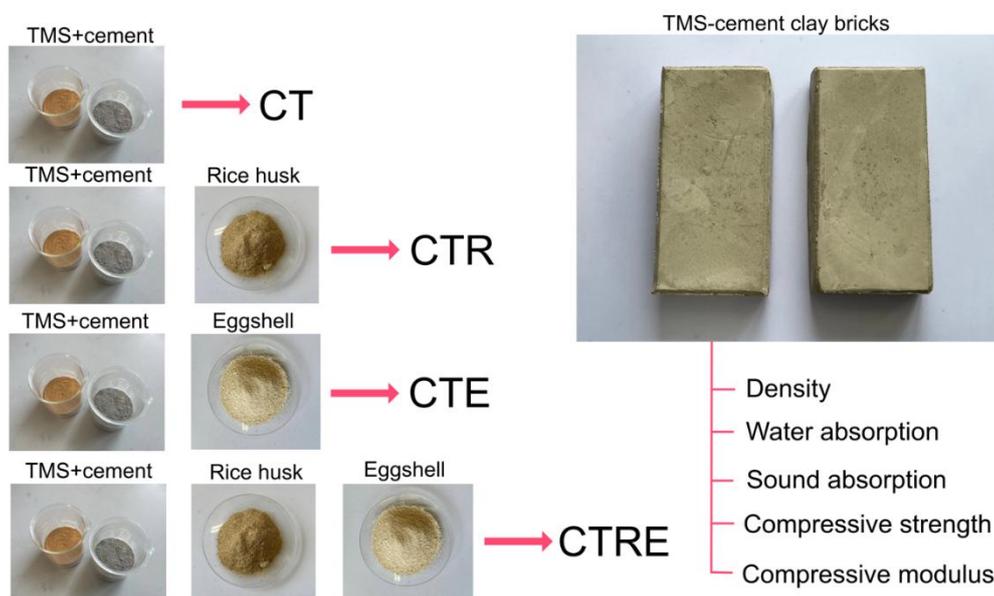| Sample	Cement	TMS	Rice husk	Eggshell	Water
CT	100	100	-	-	110
CTR	50	100	50	-	110
CTE	50	100	-	50	110
CTRE	50	100	25	25	110

Figure 1 Sample preparation procedure.

Sound absorption measurement

To evaluate the sound absorption coefficient (SAC) spectra, an in-house cylindrical two-microphone impedance tube was employed. Constructed from stainless steel with a 28.6 mm diameter to minimize noise interference, the tube adhered to ASTM E1050 [34] and ISO 10534 [35] standards and used the transfer function method. Two laboratory-graded microphones (GRAS 46BD-FV, GRAS Sound & Vibration, Denmark) were hermetically placed and sealed within the tube to accurately measure the SAC, while a broadband noise source from a full-range speaker generated the necessary sound waves directed at the sample. The samples were mounted within a holder backed by a rigid plate to ensure stability and consistent measurement. Sound signals were handled by a data acquisition device (NI-9230, National Instrument, TX, USA), which gathered readings from both microphones to calculate the SAC in Python. **Figure 2** provides a schematic diagram of the two-microphone impedance tube setup.

The transfer function method was used to compute the SAC by analyzing the relationship between incident and reflected sound waves within the tube. This setup enabled a detailed evaluation of the samples' sound absorption properties across a wide range of frequencies, offering valuable insights into their

performance as acoustic insulation materials. SAC can be calculated using the transfer function as follows [36]

$$SAC = 1 - \left| \frac{H_{12} - e^{-ik_0 s}}{e^{ik_0 s} - H_{12}} e^{2ik_0 x_1} \right|^2 \qquad (1)$$

where H_{12} is the transfer function, k_0 is the complex wave number of the sound wave in the air, and s and x_1 are the distances between mic-1 and mic-2, and between the sample surface and mic1, respectively. The SAC spectra in the range of 210 - 5000 Hz are shown in **Figure 6**.
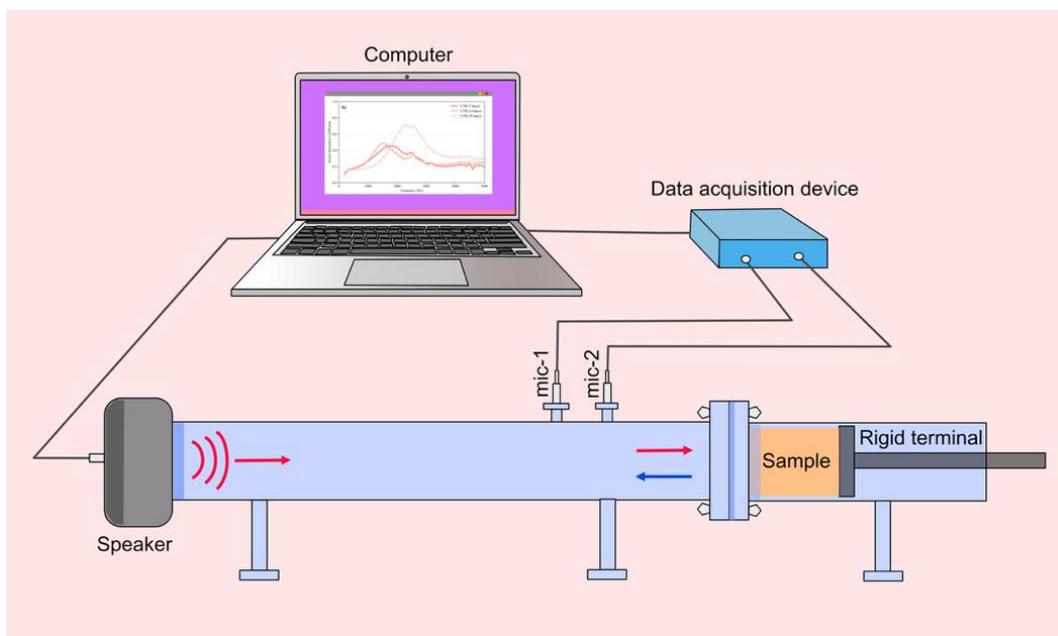

Figure 2 Schematic diagram of normal-incident sound absorption measurement using two-microphone impedance tube.

Water absorption test

Prior to conducting the absorption test, each sample was put air-circulating oven at 110 °C for 24 h to remove traped moisture and then weighed to establish a baseline weight. The samples were then fully submerged in water for 24 h. After the immersion period, they were carefully removed from the water and the surfaces were gently wiped to remove excess water one the surface without affecting the internal absorbed moisture. Each sample was then weighed again to obtain its post-immersion weight. The percentage of water absorption (%WA) was calculated by comparing the initial (m_i) and final (m_f) weights, using the following equation:

$$\%WA = \frac{m_i - m_f}{m_i} \times 100 \qquad (2)$$

Compression test

To assess mechanical properties including compressive strength and compressive moduli, a universal testing machine (NRI-TS500-30B, Narin Instrument, Thailand) was utilized. The testing machine was set to a crosshead speed of 3 mm/min, ensuring consistent application of compressive force to each sample. The standardized crosshead speed allowed for accurate assessment of the mechanical properties of each sample, aligning with established testing protocols. Three specimens were taken for each type of cylindrical sample (CT, CTR, CTE and CTRE) and subjected to compression testing. The average values obtained from the three replicates were used to provide a more reliable representation of the compressive strength and compressive modulus for each sample type. The results, graphically represented in **Figure 8**, highlight the differences in mechanical performance among the various sample formulations and different water curing time. These data will inform the development and optimization of construction materials using Termite Mound Soil, rice husk, and eggshell as bio-based additives.

Results and discussion

Sample characteristics

In this study, termite mound soil (TMS) was collected from Satun province, Thailand. The elemental composition was analyzed using X-ray fluorescence spectrometry (XRF, Zetium, PANalytical, Netherlands), revealing that TMS consists primarily of silicon (Si, 60%), aluminum (Al, 24.2%) and other elements (15.8%) as shown in **Figure 3(a)**. The X-ray diffraction (XRD) analysis (Empyrean, PANalytical, Netherlands) indicated that TMS is composed of quartz (SiO_2), kaolinite ($Al_2SiO_5(OH)_4$) and vermiculite ($Mg_3(Si_4O_{10})(OH)_2$) as the main components. According to **Figure 3(b)**, the presence of SiO_2 is particularly significant, as it is well-known as the main component involved in the pozzolanic reaction, which contributes to the strength of the concrete. Kaolinite, which is generally rich in clay materials, was reported to have positive effect in pozzolanic reaction especially in its calcinated form as metakaolin [37,38]. Vermiculite can be used as a lightweight aggregate in concrete. Its inclusion reduces the overall density of the concrete, making it lighter [39] and improve thermal insulation and fire resistance [40]. Rice husk was reported to contain 15 - 20% silica, which contributes to the pozzolanic reaction in concrete [41]. Similarly, eggshells were reported to consist of approximately 94% calcium carbonate ($CaCO_3$) [32], which can serve as a substitute for limestone in cement production.
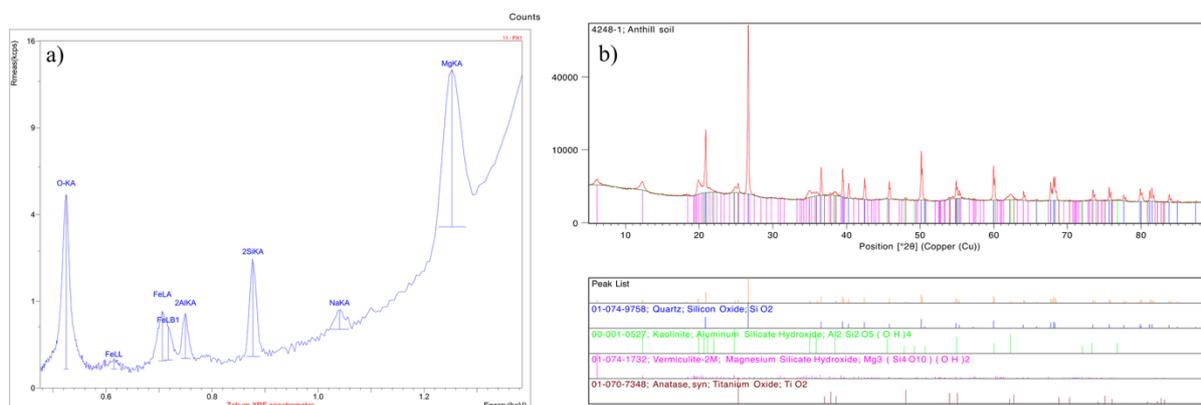

Figure 3 a) X-ray fluorescense spectrum b) powder X-ray diffraction pattern of termite mould soil (TMS).

Figure 4 demonstrates the microstructure of TMS composites observed using a field-emission scanning electron microscopy (FEG-SEM, Phenom Pharos G2, Thermo Fisher Scientific, UK). Small fibers with diameters approximately below 1 μm are visible in the CTR and CTRE samples, which are likely derived from rice husk, as these fibers are rarely observed in other samples, such as CT and CTE. Additionally, pores or voids are prominent in the treated samples (CTR, CTE and CTRE), whereas the CT samples exhibit fewer pores. This difference in porosity could influence physical properties such as density, water absorption and sound absorption, as these variables are closely related to the porosity of the samples. Moreover, porosity may also impact mechanical properties, such as compressive strength and compressive modulus, to some extent [42].
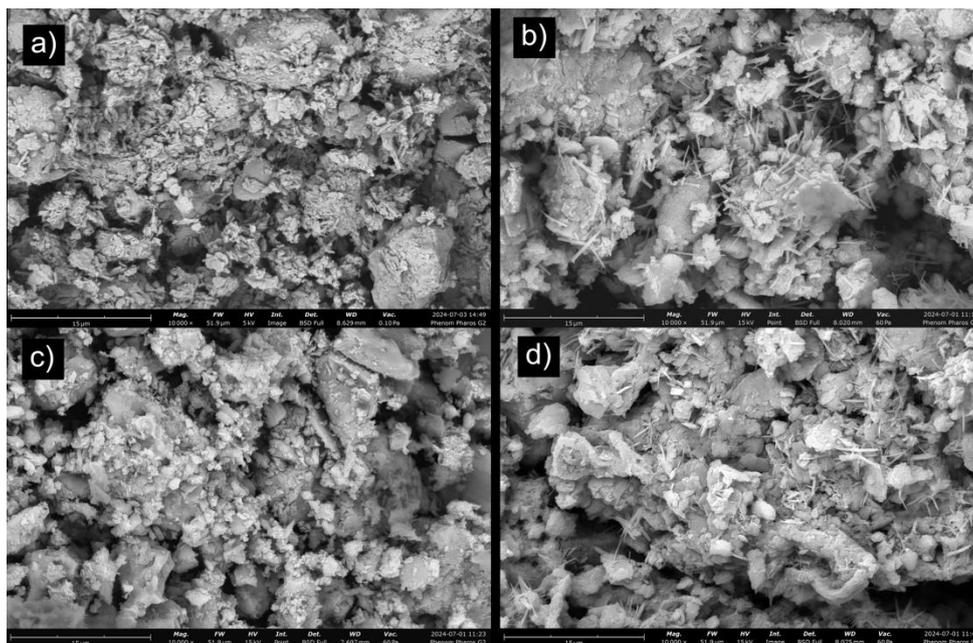
Figure 4 SEM images of the porous structue of a) CT, b) CTR, c) CTE and d) CTRE samples.

The density of all samples is demonstrated in **Figure 7(a)**, with most samples falling within the range of 700 - 800 kg/m³, classifying them as lightweight composites. The control group (CT) exhibits a higher density compared to the other treatment groups, consistent with previous studies reporting that cement-stabilized TMS composites achieve densities between 1,100 - 1,550 kg/m³, depending on cement content [43]. In contrast, the incorporation of lightweight additives, such as agro-waste (rice husk, eggshell powder, etc.), has been shown to further reduce density, aligning with reported termite soil–rice husk composites that range from 1,535 to 1,748 kg/m³ [44]. The observed density reduction in this study suggests that the addition of bio-based fillers increased porosity, a trend similarly observed in termite soil-modified mortars where high replacement levels (> 10%) significantly lowered density [45].

To statistically validate the density differences between treatment groups, a t-test was conducted to compare each treatment with the control (CT). The t-test results confirm that all treatment groups exhibit significantly lower density than the control, with a *p-value* < 0.01, indicating statistical significance at the 99% confidence level. This result aligns with findings by Tebabal *et al*. [45], where termite soil integration caused a measurable and statistically significant density

shift in cementitious materials. The consistent trend of reduced density across multiple studies confirms the effectiveness of agro-waste incorporation in producing lighter, more sustainable bio-based composites for construction applications.

Raman spectroscopy
In Raman spectroscopy analysis, cement, eggshell, rice husk and TMS demonstrate distinct spectral characteristics linked to their compositions and structural properties. According to **Figure 5**, cement exhibits prominent peaks at 277.1, 712.3 and 1,085.3 cm⁻¹, which correspond to the vibrational modes of calcium carbonate (calcite), a common carbonation product in cement. These well-defined peaks indicate the presence of crystalline calcite phases within the cement matrix. Eggshell displays characteristic calcite peaks at 280.1, 630.6, 1059.1, 1,085.3 and 1,414.8 cm⁻¹, along with additional peaks that arise from its organic matrix, resulting in a higher background and a complex spectrum with both mineral and organic contributions. In contrast, rice husk and TMS show no prominent Raman peaks, which can be attributed to their largely amorphous silica content and complex organic and inorganic matrix, leading to weak or absent Raman activity. XRF and XRD analyses reveal that TMS is primarily composed of silicon (60%) and aluminum

(24.2%), with quartz (SiO_2), kaolinite ($Al_2Si_2O_5(OH)_4$), and vermiculite ($Mg_3(Si_4O_{10})(OH)_2$) as the main crystalline phases. Quartz, the dominant component in TMS, is typically weakly Raman-active, especially in its highly crystalline form, resulting in minimal Raman response. Likewise, clay minerals like kaolinite and vermiculite contribute little to the Raman spectrum due to their layered structures and low scattering efficiency.

The Raman spectra of the composite samples (CT, CTR, CTE and CTRE) reveal distinct peaks grouped by position, reflecting contributions from calcite, silicates, and organic components. A consistent calcite peak appears at 1,085.3 cm⁻¹ across all samples, corresponding to carbonate ion vibrations, though its intensity diminishes as cement content decreases, especially in CTR and CTRE. Peaks in the 280 - 320 cm⁻¹ range, slightly varied in position, are observed in all samples and likely stem from lattice or bending modes within calcite and silicate phases, reflecting the interaction between these components. In the silicate-associated range (630 - 664 cm⁻¹), notable peaks appear in CTR (639.1 cm⁻¹) and CT (664.5 cm⁻¹), with CTR showing a prominent peak due to its higher rice husk content, indicating contributions from Si-O stretching in silicate phases of TMS and rice husk.

At higher wavenumbers (1,300 - 1,750 cm⁻¹), broad humps rather than sharp peaks emerge across CTR, CTE and CTRE, linked to mixed-phase interactions and organic residues. Specifically, humps around 1,300 cm⁻¹ and 1,750 cm⁻¹ suggest C-H or C-O vibrations from trace organics in rice husk and eggshell. Summarily, CT displays clear calcite and silicate peaks; CTR features strong silicate-related peaks and broad organic humps; CTE primarily shows calcite peaks with organic humps from eggshell and CTRE exhibits both calcite and silicate peaks with mixed organic contributions. This grouping by peak position and prominence demonstrates the dilution effects and complex interactions among cement, TMS, rice husk and eggshell components in the composite samples.
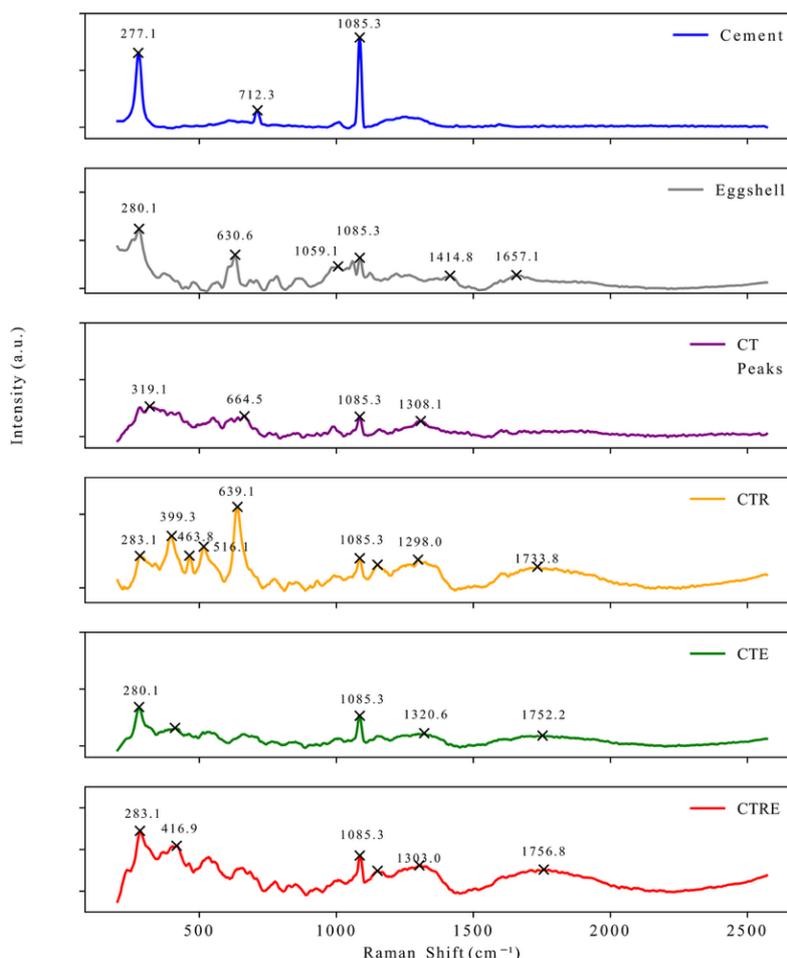

Figure 5 Raman spectra of a) cement, b) eggshell, c) CT, d) CTR, e) CTE, and f) CTRE samples.

Water absorption analysis

The water absorption results (%) for all samples are presented in **Figure 7(b)**. Most samples exhibit water absorption values above 40%, with the exception of the control group (CT), where the percentages are notably lower. Based on the bar graph in **Figure 7(b)**, a t-test was performed to evaluate the significant differences between each treatment and the control group (CT). The t-test results reveal that the water absorption values of all treatment groups differ significantly from the control group, with a p-value of less than 0.01, indicating statistical significance at the 99% confidence level.

In evaluating the water absorption characteristics of the different brick compositions, the CT samples exhibited an average water absorption of 38.43%, indicating a relatively moderate level of porosity. This absorption rate aligns with the expected performance of cement-based composites, with TMS contributing to improved cohesiveness and durability while maintaining the ability to absorb moisture [26]. The CTR samples, which include fine-grain rice husk as an additional filler, displayed a higher average water absorption rate of 48.74%. This increase can be attributed to the porous nature of rice husk [5,46], which introduces micro-cavities within the brick matrix. These cavities might facilitate moisture penetration, enhancing the overall porosity of the composite structure. The CTE samples, which incorporate ground eggshells as a secondary filler, recorded an average water absorption rate of 43.67%. This is significantly higher than the results reported by Lokesh *et al*. [47] where concrete containing 15% eggshells (without TMS) exhibited a maximum water absorption rate of approximately 6%. This suggests that TMS may play a crucial role in determining water absorption, as clay brick tends to absorb water more effectively than cement-based brick. Due to the structural differences between eggshells and rice husk, the limited water absorption capacity of eggshells [48] resulted in a more moderate increase in porosity than cement and TMS (CT) samples but less than those incorporating rice husk (CTR). The

combination of both fillers in the CTRE samples resulted in an average water absorption of 46.25%. This absorption rate falls between that of the CTR and CTE samples. This indicates that while rice husk notably increases porosity [5], the presence of eggshells reduces this effect to some extent.

Sound absorption properties

The Sound Absorption Coefficient (SAC) measures how efficiently a material absorbs sound at various frequencies. It ranges from 0 to 1, where a coefficient of 0 indicates total reflection (no absorption) and 1 signifies complete absorption (no reflection). Thus, higher SAC values indicate better acoustic insulation properties. According to **Figure 6**, across all tested samples, the SAC spectra consistently started low at 210 Hz and gradually increased, reaching approximately 0.2 - 0.3 around 400 - 500 Hz. This initial rise demonstrates each material's increasing ability to absorb sound as frequency rises. After reaching 0.2, the rate of increase slowed before picking up again to reach a peak maximum and then drop to be around 0.2 again. The SAC showing peak in similar way as one observed in other construction materials such as plasters produced with perlite aggregate [49] and concrete embedding crumb rubber waste [50].

The SAC at the peak maximum varied among the samples at different stages of curing. Samples cured for 28 days tended to show higher SAC values at their peak maximum compared to those cured for 7 and 14 days, illustrating that prolonged curing generally enhances sound absorption properties. The SAC values at peak maximum for the 28-day samples ranged from approximately 0.6 to 0.7, indicating efficient sound absorption across most samples. While the frequency at which the peak maximum occurred varied randomly across samples, most peaks fell within the 1,500 - 3,500 Hz range. This overlapped with the peak maximum for crumb rubber waste, which fell within the 600 - 2200 Hz range [50], and for concrete with basalt aggregate (2.36 - 13.2 mm aggregate size), which fell within the 400 - 1200 Hz range [51].
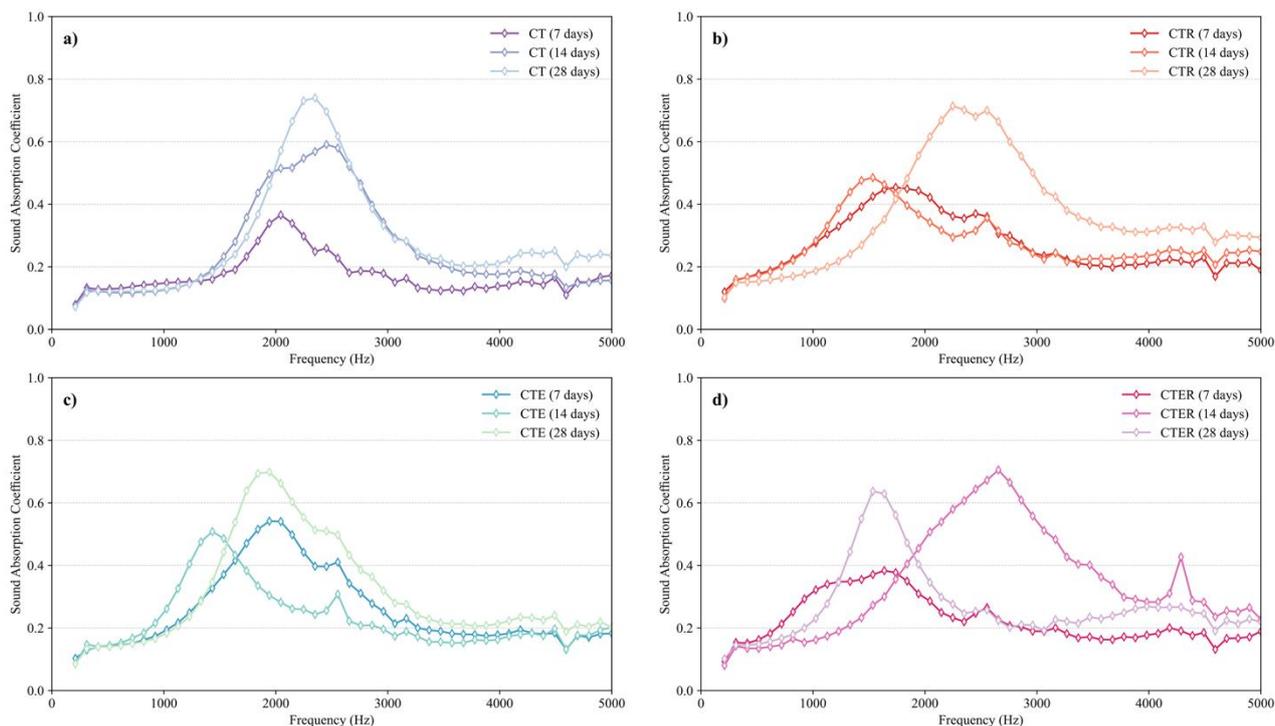
Figure 6 Sound absorption coefficient spectra of all samples at 7, 14 and 28 days of a) CT, b) CTR, c) CTE and d) CTRE.

The Noise Reduction Coefficient (NRC) is a measure of how effectively a material can absorb sound across a set of standard frequencies (250, 500, 1000 and 2000 Hz) as described in ASTM-C423 [52]. Although in this study NRC was calculated from the normal incidence sound absorption coefficient, it provides a useful index for evaluating the suitability of materials for acoustic absorption in buildings. The NRC values for all samples are shown in **Figure 7(c)**. Most samples demonstrated values around or above 0.20, with the control group (CT) showing slightly lower averages. Based on the bar graph in **Figure 7(c)**, a t-test was conducted to examine the differences between each treatment group and the control group (CT). The t-test results indicate that none of the treatments (CTR, CTE and CTRE) differed significantly from CT, with p-values of 0.058, 0.161 and 0.554, respectively. These results confirm that NRC was not significantly affected by the inclusion of rice husk and/or eggshell fillers. However, CTR did not differ significantly from CT (t-test *p-value* = 0.058), suggesting that some structural characteristics may influence NRC, but the effect was not strong enough to be considered statistically meaningful.

Among the CT samples, NRC values increased slightly with curing time, from 0.195 at 7 days to 0.220

at 14 days and 0.228 at 28 days. Despite this improvement, CT remained comparable to the other formulations, suggesting that the compact and homogeneous structure of cement and TMS limits the extent of acoustic absorption. Sound waves are more likely to be reflected or transmitted through the dense matrix rather than dissipated. In contrast, the CTR samples showed relatively consistent NRC values of 0.260 at 7 days and 0.242 at 14 days, increasing slightly to 0.271 at 28 days. The inclusion of rice husk may contribute to the porous nature of the composites, generating micro-cavities that trap sound waves and improve absorption, although the difference compared with CT was only marginal. The CTE samples exhibited NRC values of 0.257 at 7 days, decreasing slightly to 0.207 at 14 days before rising to 0.286 at 28 days. The eggshells, while not as effective as rice husk at increasing NRC, still introduce porosity that aids absorption. The CTRE samples, which combined rice husk and eggshells, had NRC values of 0.233 at 7 days, 0.229 at 14 days, and 0.221 at 28 days. This indicates that combining the two bio-based fillers does not necessarily produce additive effects in terms of NRC but maintains comparable absorption performance to the individual modifications. The NRC results in this study can be compared to the NRC measured using random-

incident sound absorption of foam concrete containing aggregates such as zeolite, silica sand, river sand, or coarse aggregate, which were approximately 0.2 - 0.3 for majority of samples [53].

Overall, the marginally lower NRC of the CT samples can be attributed to the compact matrix formed by cement and TMS, which lacks the porous structure necessary for enhanced acoustic absorption. According to previous studies [14,54,55], porosity is one of the main factors contributing to the sound absorption ability of porous samples, as higher porosity results in higher overall sound absorption coefficient. The other formulations incorporating bio-based fillers such as rice husk and eggshells may introduce additional internal cavities [47,48] and surface irregularities that help trap and dissipate sound waves. However, according to the ANOVA results in **Table 2**, their effect on NRC was not statistically significant compared with CT.
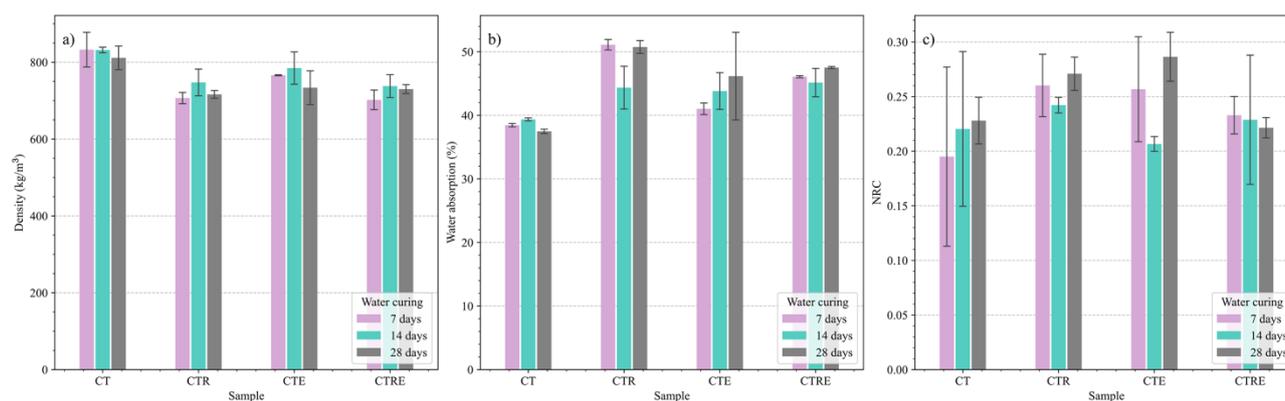

Figure 7 Sample characteristics including a) sample density and b) water absorption percentage and c) noise reduction coefficient (NRC).

Mechanical properties

A compressive test was performed, and a representative stress-strain curve is shown in **Figure 8(a)**. The compressive strength was measured at the maximum stress (f_c), indicated by the peak of the curve. After reaching this peak, the sample cracked and the stress began to decrease. The results are presented in MPa. The initial modulus was measured in the first linear region of the stress-strain curve. The tangent modulus was measured at the point corresponding to half of the compressive strength, with the tangent line comprising 10% of the total points around 0.5 f_c. The secant modulus was measured by connecting the initial point to the point at 0.5 f_c. The values of the compressive strength and the two moduli are presented using bar plots in **Figures 8(b)** - **8(d)**, respectively. Different curing times (7 days, 14 days, and 28 days) are indicated with blue, orange and grey bars, respectively.

From **Figure 8(b)**, the compressive strength tests revealed that the CT samples exhibited significantly higher compressive strengths compared to the other formulations. The CT samples had an average compressive strength of 4.72 MPa at 7 days, 6.30 MPa at 14 days and 6.53 MPa at 28 days. These results indicate consistent improvement in compressive strength over time, which is attributable to the ongoing hydration reaction of cement that strengthens the material as it cures. Additionally, TMS likely contributed to this improvement through its pozzolanic properties, further enhancing the mechanical integrity of the composites. The CTR samples, incorporating rice husk as a filler, showed markedly lower compressive strengths than the CT samples, averaging 1.04 MPa at 7 days, 1.36 MPa at 14 days and 1.42 MPa at 28 days. While the compressive strength did increase over time due to hydration, the improvement was less pronounced than in the CT samples. The porous nature of rice husk likely introduced structural weaknesses that limited the ability of the cement matrix to provide mechanical reinforcement. In contrast, the CTE samples, which included eggshells as a filler, displayed the lowest compressive strength among all the formulations, with an average of 0.48 MPa at 7 days, 0.77 MPa at 14 days, and 0.52 MPa at 28 days. The decline in strength after 14 days suggests that eggshells may not be a suitable filler for cement and TMS. Their chemical composition

might include components that degrade or weaken under prolonged exposure to water, potentially outweighing the positive effects of cement hydration. The CTRE samples, which combined rice husk and eggshells as fillers as shown in **Table 1**, had compressive strengths averaging 0.57 MPa at 7 days, 1.11 MPa at 14 days and 0.96 MPa at 28 days, falling between those of the CTR and CTE samples. Similar to the CTE samples, these

composites also exhibited a reduction in strength after the peak at 14 days. The combination of eggshells and rice husk appears to introduce both structural porosity and potential chemical interactions that undermine the benefits of cement hydration, resulting in reduced compressive strength over time.
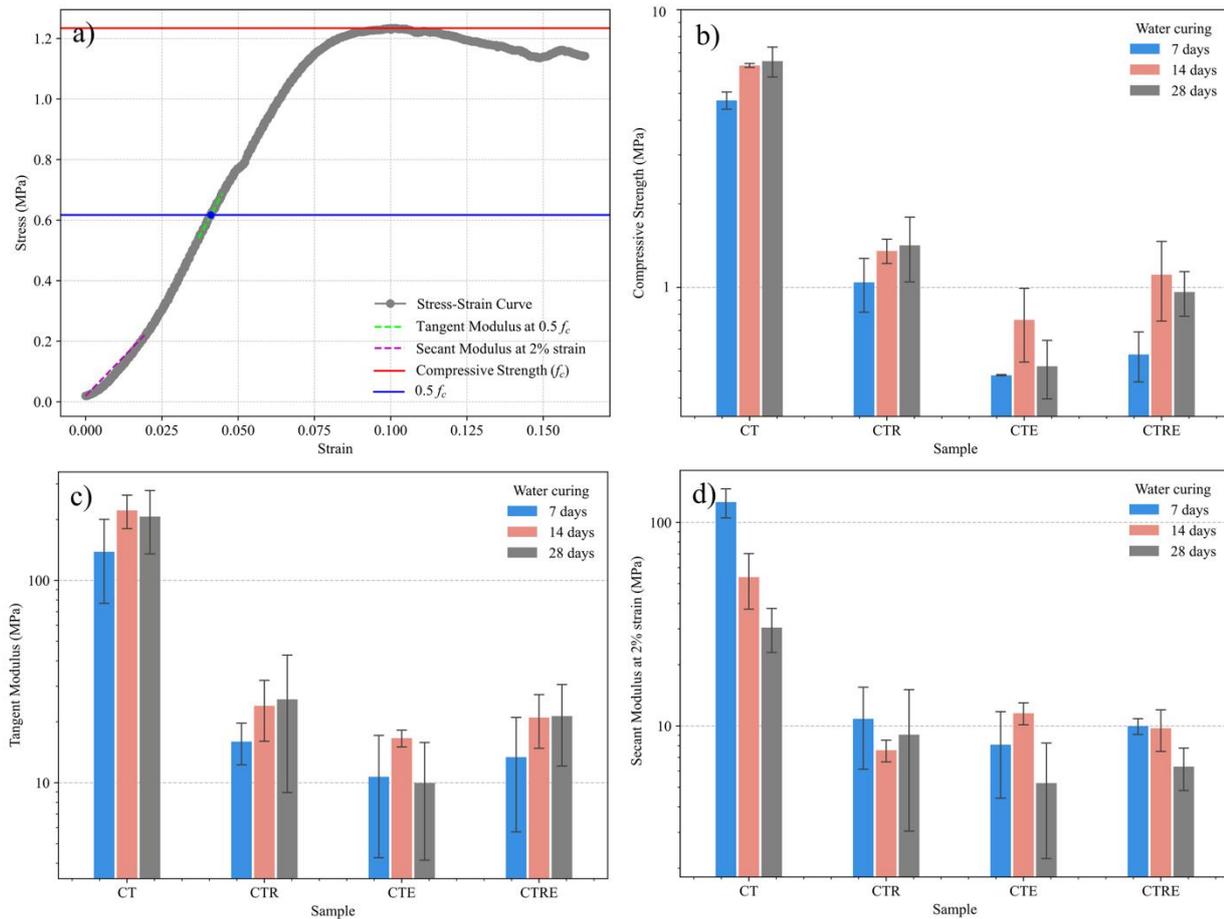

Figure 8 Mechanical properties of lightweight brick a) stress-strain curve of compressive test and the bar graphs for b) compressive strength c) tangent modulus at 0.5 f_c and d) secant modulus at 2% strain.

For the compressive modulus, tangent modulus (at 0.5 fc) and secant modulus at 2% strain were investigated and displayed in **Figures 8(c)** - **8(d)**. Although the tangent modulus of each sample tended to be higher than the secant modulus, the trends were similar for both. The tangent and secant moduli of the CT samples, for all three water curing durations, were approximately 150 MPa and 90 MPa, respectively. In contrast, the CTR, CTE and CTRE samples exhibited similar tangent and secant moduli, around 15 MPa and 10 MPa, respectively. This indicates that the tangent and

secant moduli of the CT samples are approximately ten times higher than those of the other samples, suggesting that controlled samples (CT) are notably more resistant to deformation compared to CTR, CTE, and CTRE samples. From **Figures 8(c)** - **8(d)**, it is evident that the water curing time (indicated by different colors) does not notably affect the moduli. However, statistical analysis like ANOVA is necessary to determine the effects of independent variables on the dependent variables.

The inclusion of bio-based materials like rice husk and eggshells in brick formulations seems to negatively impact mechanical performance. This may be attributed to the inherently porous nature of these fillers, which creates structural cavities within the composite, reducing its overall integrity. Moreover, the chemical composition of eggshells might contribute to degradation when soaked in water, possibly interfering with the hydration reaction of cement. To address these issues, strategic improvements such as pre-treatment of agricultural by-products can be considered, since factors like hydrophobicity and polarity of the fillers play an important role in composite behavior. Further research is therefore needed to evaluate how such pre-treatments influence the interactions between cement, TMS and bio-based fillers, with the aim of improving strength while maintaining the sustainability of these brick formulations.

Statistical analysis

In this study, ANOVA was used to test the effects of independent variables, specifically the sample formula (F) including CT, CTR, CTE and CTRE and the number of days (D) for curing including 7, 14 and 28 days, on several dependent variables: density, noise reduction coefficient (NRC), compressive strength, tangent modulus at $0.5f_c$, and secant modulus at 2% strain. The Python library *statsmodels* was utilized to perform the ANOVA. Normality of the residuals for each variable was assessed using the Shapiro–Wilk test. For most variables, the residuals satisfied the assumption of normality (*p-value* > 0.05), supporting the reliability of these results. In cases where residuals were non-normally distributed, such as compressive strength, tangent modulus, and secant modulus, a square root transformation ($\sqrt{A+1}$) was applied to satisfy the assumptions of ANOVA. NRC showed only marginal compliance with the normality assumption (Shapiro–Wilk p = 0.035), whereas the water absorption percentage did not meet the normality assumption, even after log and square root transformations (Shapiro–Wilk *p-value* < 0.001).

Table 2 presents the results of a two-way ANOVA (with sample size of three (n = 3) for each measurement) performed to investigate the effects of treatment formula (F) and curing duration (D) on the properties of TMS composites. This approach provides insight into how each factor, as well as their interaction, contributes to the observed variations in the TMS brick properties after treatment and soaking.

Table 2 p-values from the ANOVA test of the physical properties of CT, CTR, CTE and CTRE samples

Factor	Density	%WA	NRC	Compressive strength (sqrt)	Tangent modulus (sqrt)	Secant modulus (sqrt)
Formula (F)	< 0.001**	< 0.001**	0.122	< 0.001**	< 0.001**	< 0.001**
Day (D)	0.057	0.096	0.281	< 0.001**	0.050*	< 0.001**
F · D	0.522	0.029*	0.542	0.060	0.638	< 0.001**
CV%	3.79%	5.64%	17.2%	4.91%	22.16%	14.82%
Adj. R-Square	0.685	0.732	0.084	0.978	0.891	0.920
Shapiro-Wilk p (resid, z)	0.610	< 0.001	0.035	0.196	0.117	0.320

*, ** Significant factor at *p-value* ≤ 0.05 and *p-value* ≤ 0.01, respectively.

Shapiro–Wilk *p-value* ≥ 0.05 indicates residuals are normally distributed (ANOVA assumption met).

ANOVA results indicated that formula had a significant effect on density, compressive strength, tangent modulus, and secant modulus (*p-value* < 0.001 for all), whereas its effect on NRC was not significant (*p-value* = 0.122). Curing day also significantly influenced compressive strength (*p-value* < 0.001), tangent modulus (*p-value* = 0.050) and secant modulus (*p-value* < 0.001), while effects on density (*p-value* = 0.057) and NRC (*p-value* = 0.281) were not significant. For NRC, normality was borderline (Shapiro–Wilk p

just below 0.05), suggesting cautious interpretation but consistent with the overall nonsignificant findings. In contrast, water absorption showed clear deviations from normality (*p-value* $\ll$ 0.05) and its ANOVA outcomes should therefore be treated with caution despite a relatively high adjusted R². Interaction effects were generally nonsignificant, except for secant modulus, where a strong interaction between formula and curing day was observed (*p-value* < 0.001). Overall, formula and curing time had pronounced effects on most mechanical properties whereas, for an acoustical property, NRC was largely unaffected.

Further post-hoc comparisons using Tukey's HSD test (*p-value* $\leq$ 0.05) confirmed that the control formula (CT) was significantly different from all other treatments (CTR, CTE and CTRE) across density, compressive strength, tangent modulus, and secant modulus. For the mechanical properties, Tukey's test was performed on the square-root–transformed data, and the differences may still be interpreted in relation to the original scale. Specifically, CT exhibited the highest density and mechanical stiffness (compressive strength, tangent modulus and secant modulus), but NRC did not show significant differences among the formulas, indicating that acoustic performance was relatively unaffected by filler type. These statistical outcomes are consistent with the trends visually observed in **Figures 7** and **8**, where the separation between CT and the modified groups is clearly evident for mechanical parameters. In contrast, no significant differences were found among the three modified formulas for most properties, suggesting that the incorporation of rice husk and eggshell—either individually or in combination—led to similar material behavior. These results reinforce the central role of the filler type in governing the functional characteristics of the composites and validate the statistical significance of the observed trends.

Comparative studies on mechanical properties

In comparing the compressive strength of clay-based composites from this study with those reported in the literature, several notable observations emerge. The CT formulation (unfired clay brick containing 50% TMS and 50% cement) achieved a compressive strength of 6.5 MPa, which is comparable to the clay composites with 12% Doum fibers [11], who reported a strength of 6.6 MPa. This performance level highlights that unfired clay composites can approach the strength of fiber-reinforced clay composites without the need for extensive natural fiber additions, simplifying the production process. When compared to fired clay composites, such as those reported by Legese *et al*. [56] and Johari *et al*. [57], with compressive strengths of 11.0 MPa and 10.0 MPa at firing temperatures of 500 °C and 800 °C, respectively, the unfired CT composites in this study demonstrate the potential of sustainable, energy-saving alternatives, albeit with slightly lower strength.

Table 3 Comparative studies of compressive strength of various types of construction material.

Materials	Compressive Strength (MPa)	Reference
CT (unfired 50% TMS + 50 % cement)	6.5	This work
CTR (unfired 25% TMS + 50 % cement + 25% rice husk)	1.4	This work
CTE (unfired 25% TMS + 50 % cement + 25% eggshell)	0.5	This work
CTRE (unfired 25% TMS + 50 % cement + 12.5% rice husk + 12.5 % eggshell)	1.0	This work
Unfired clay composites (20% TMS + 80% cement)	3.0	Mahamat *et al*. [23]
Unfired clay composites (70% TMS + 30% cement)	16.0	Akinyemi *et al*. [58]
Unfired clay brick (70% TMS + 30% calcium carbide)	9.0	Akinyemi *et al*. [58]
Unfired clay brick (TMS with Si/Al = 1.57, 0.03 alkali activation)	2.7	Mahamat *et al*. [59]

Materials	Compressive Strength (MPa)	Reference
TMS brick fired at 500 °C	11.0	Legese *et al*. [56]
TMS brick fired at 800 °C	10.0	Johari *et al*. [57]
Clay composites with 12% Doum fibers	6.6	El-yahyaoui *et al*. [60]
Clay composites with 10% Diss fibers	3.0	El-Yahyaoui *et al*. [61]
Bioformulated mortars (E.coli + Fe)	0.4	Parracha *et al*. [42]

The CTR (25% TMS, 50% cement and 25% rice husk) and CTRE (25% TMS, 50% cement, 12.5% rice husk and 12.5% eggshell) formulations exhibit lower compressive strengths of 1.4 MPa and 1.0 MPa, respectively. These formulations, however, incorporate bio-based additives that may offer advantages beyond compressive strength, such as improved thermal properties and environmental benefits. In comparison to bioformulated mortars (E. coli + Fe) studied by Parracha *et al.* [42], which demonstrated a compressive strength of only 0.4 MPa, the materials developed in this study show improved mechanical performance. This suggests that integrating cement and clay-based materials like TMS can offer a compromise between sustainability and structural integrity. The use of TMS not only enhances the eco-friendliness of the composites through local sourcing and reduced processing energy, but also provides a platform for developing niche, low-impact construction applications. Future optimization efforts should focus on enhancing mechanical performance — possibly through hybrid reinforcement strategies — to expand the applicability of these composites while maintaining their environmental benefits.

Conclusions

This study investigated the properties of lightweight composites made with cement and TMS or Termite Mound Soil (CT), TMS and rice husk (CTR), TMS and ground eggshells (CTE) and a combination of all three integredients (CTRE).

The CT composites showed the highest bulk density, while the addition of rice husk and eggshells resulted in lower densities. However, CT composites exhibited the lowest water absorption compared to other samples.

In terms of sound absorption, CT composites had the marginally lower noise reduction coefficient (NRC) than other formulations, likely due to their higher density, which results in lower porosity, a key factor in determining sound absorption performance.

Additionally, CT composites displayed the highest compressive strength, which decreased drastically with the inclusion of rice husk and eggshells. Furthermore, the tangent and secant moduli of CT samples were significantly higher than those of CTR and CTE samples, indicating greater resistance to deformation. The comparative studies suggest that some formulations have potential for use in non-load-bearing, sustainable applications such as acoustic panels or thermal insulators.

The ANOVA results confirmed that sample formula significantly affected most measured properties except NRC, while curing day had a statistically significant effect on compressive strength, tangent modulus, and secant modulus, but not on density and NRC. A strong interaction effect (Formula - Day) was observed only in the secant modulus (*p-value* < 0.001).

Future studies should aim to optimize the interaction between cement, TMS and bio-based fillers through strategies such as filler pre-treatment, with the goal of enhancing mechanical and acoustic performance. In addition, a comprehensive environmental assessment, including life-cycle analysis, would be valuable to quantify the sustainability benefits of incorporating bio-based fillers in brick production.

CRediT Author Statement

Nawarat Seetapong: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Natnaree Chorphakar: Data curation, Formal analysis, Investigation, Writing – review & editing. **Nuthita Saenkuea**: Data curation, Formal analysis, Investigation, Writing – review & editing. **Sarawut Chulok**: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Polphat Ruamcharoen**: Formal analysis, Investigation, Supervision, Writing – review & editing. **Purintorn Chanlert**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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