

Characterization of Composite Panels Based on Thick Clay, Limestone and Typha Australis for the Thermal Insulation of Buildings

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Abstract

This study focuses on the characterization of composite panels made from Thick clay, Bandia limestone, and Typha australis, intended for thermal insulation of buildings. A geotechnical characterization of the raw materials was carried out, including particle size analysis, Atterberg limits, and determination of natural water content. The Thick clay has a composition of 41% clay, 49% silt, and 10% sand, while the limestone consists of 5% clay, 17% silt, and 78% sand. The natural water contents are 4.71% for the clay, 13.12% for the Typha, and 5.93% for the limestone. Three panel formulations, P1, P2, and P3, were studied. The clay and limestone content was kept constant at 22% and 17%, respectively, while the Typha content varied from 7% to 9% and the water content from 54% to 52%. The average compressive strengths obtained were 1.985, 2.135, and 2.432 MPa, respectively. The thermal conductivities were 0.255, 0.221, and 0.186 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, with thermal effusivities of 580, 520, and 450 $\text{W}\cdot\text{s}^{-1/2}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for P1, P2, and P3. The results show a change in mechanical and thermal properties between the three formulations. However, given the simultaneous variation in Typha content and water quantity, the observed differences are interpreted as a result of the overall change in formulation and not as an isolated effect of Typha.

Keywords

Clay, Typha, Thermal Conductivity, Compressive Strength

1. Introduction

The scale of the climate crisis, marked by phenomena such as rising sea levels, is driving research towards environmentally friendly solutions. By prioritizing ecological materials and environmental considerations, this approach offers numer-

ous advantages: improved indoor air quality, optimized thermal insulation, and a reduced impact on the ecosystem [1].

The post-industrial revolution era has been characterized by rapid economic growth, propelling global energy demand to record levels. Fossil fuels, which account for 80% of this demand according to the IEA, contribute 40% to global carbon dioxide (CO₂) emissions [2] [3]. Recent research indicates that *Typha australis* provides effective thermal insulation. [4] Given the high cost and near-universal use of imported conventional insulation materials (polystyrene, polyurethane, glass, rock wool, etc.) [5], the use of plant fibers as an alternative is necessary. This study explores the integration of *Typha australis* fibers, clay, and limestone into the manufacture of medium-weight panels.

The objective of this work is to characterize medium density composite panels made from Thick clay, Bandia limestone and *Typha australis*, by studying the evolution of their mechanical and thermophysical properties for different formulations.

The specific objectives are as follows:

- characterize the raw materials by determining their natural water content, their particle size distribution and the Atterberg limits;
- develop three formulations of composite panels based on clay, limestone and *Typha australis*;
- determine their mechanical and thermophysical properties;
- analyze the evolution of panel properties in response to formulation changes.

1.1. Site Presentation

The soil in Senegal is rich and contains significant deposits of clay and laterite [6] [7]. The latter are used in road construction, while clay, once used in building construction, is now mainly reserved for pottery and tiles. Clay samples from Thick, located in the Thiès region (western Senegal, 14°50' N, 17°06' W [7]), served as the basis for this study. Clay deposits near the village of Thick, dating from the undifferentiated Upper Cretaceous, have been known for a long time. Bandia limestone was used in our research.

1.2. Raw Materials

The main components of this work are *Typha australis*, Thick clay, and Bandia limestone. Each was collected in quantities of 50 kg (two 25 kg bags) after clearing the surface layer to a depth of 0.50 m at their respective sites. The raw materials, collected and stored under cover, underwent an aeration phase followed by manual cleaning to remove residues. The mixture was then homogenized before precise weighing for each formulation. Originating from the Saint-Louis region and acquired from a supplier in Gendigal (Mbour), the *Typha australis* biomass used totaled 30 kg, divided into three 10 kg bundles. After cleaning and air drying, the plant was ground for incorporation into the mixtures.

1.2.1. Mineral Materials

Figure 1 shows the different materials used in the formulation of the panels, such as clay (a) and limestone (b).

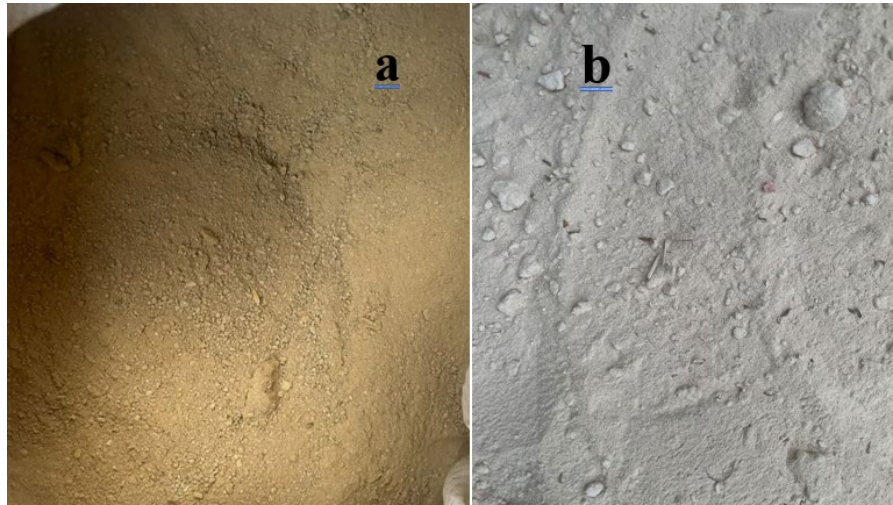


Figure 1. Raw materials to be used in the formulation of clay (a) and limestone (b) panels.

1.2.2. Plant Fibers

1. Typha

Figure 2 shows the distaff used to make the panels.



Figure 2. Typha.

2. Materials and Methods

2.1. Materials

The main equipment used in this study is as follows:

- A grinder used to reduce Typha into particles of a size suitable for the production of composite panels;
- The mixing tank and various containers are used to prepare the mud made from clay and limestone;
- The geotechnical laboratory is equipped with the necessary equipment to determine the Atterberg limits (liquid limit and plastic limit) and to perform particle size analyses by sieving and sedimentation;

- Manufacturing molds used to shape composite panels, and a mechanical press used for compression testing on test samples;
- A hot plate apparatus, with an asymmetrical design, is used to evaluate the thermal conductivity of the panels. A laboratory oven is used to dry the materials and measure their moisture content. A high-precision electronic balance is used to weigh the various components and samples;
- Dimensional measuring instruments, such as rulers and calipers, are used to measure the dimensions of samples. Laboratory accessories, such as spatulas, mixing bowls, standardized sieves, and sample preservation equipment, are also used.

Sampling, Preparation and Storage of Raw Materials

The components needed to produce the panels include *Typha australis*, as well as Thick clay and Bandia limestone, collected in quantities of 50 kg per material. These elements were cleaned of their surface residues and stored separately to guarantee their purity and integrity.

After collection, the clay and limestone were kept protected from the elements, then left in the open air before mixing to homogenize the materials and reduce variations in preservation.

The materials underwent manual cleaning to remove coarse elements and residues, followed by homogenization prior to weighing the quantities required for the different recipes.

Several samples were taken from the respective sites in order to obtain a representative sample, then grouped and homogenized before testing.

2.2. Methods

2.2.1. Geotechnical Study

1. Particle size analysis by sieving and sedimentation

Figure 3 shows the equipment used for particle size analysis.



Figure 3. Equipment used for particle size analysis.

The particle size distribution of the samples was established by combining two

complementary methods. The coarse fraction was determined by sieving, while the fine fraction, corresponding to particles smaller than 80 μm , was determined by sedimentation. The two distributions were then combined to establish the complete particle size distribution curve of the clay. The fraction smaller than 80 μm was analyzed by sedimentation according to standard NF P 94-057 of 1992 [8].

2. The limits of Atterberg

The Atterberg limits are essential physical parameters that determine the transition thresholds of soils between the liquid and plastic states (liquid limit WL) and between the plastic and solid states (plastic limit Wp). These tests identify the consistency limits—measured by water content—that separate the solid, plastic, and liquid states. The Atterberg limits apply to soil particles passing through a 400 μm sieve, and the difference between the liquid limit and the plastic limit is used to determine the plasticity index (PI), which assesses the range of water content within which the soil is in a plastic state.

$$I_{pl} = W_{Li} - W_{Pl} \quad (1)$$

where I_{pl} : plasticity index, W_{Li} : liquid limit and W_{Pl} : plastic limit.

It is therefore clear that the Atterberg limits and the plasticity index of a soil vary not only according to its clay fraction, but also according to the nature of the clay minerals and the adsorbed cations. For example, the highest values of this index are obtained with montmorillonites, in particular those loaded with sodium (Na) cations [9].

The characterization of clay materials through geotechnical and physicochemical tests is essential for assessing their suitability for construction applications [10].

2.2.2. Typha Australis Preparation

The Typha australis used for this study came from the Saint-Louis region and was purchased from a supplier in Gendigal, Mbour. The sample, consisting of three bundles weighing approximately 10 kg each (30 kg in total), was cleaned of all impurities and then naturally dried. After grinding with the equipment shown in Figure 4, a mallet was obtained with a particle size ranging from 0.5 to 1 cm.



Figure 4. Cattail grinder.

2.2.3. Preparation of the Clay Paste

A specific quantity of clay, limestone, and water was gradually mixed to obtain a homogeneous paste. The mixture was kneaded until the components were evenly distributed. The previously ground Typha was then gradually incorporated into the paste, and the mixture was blended until the fibers were evenly distributed within the clay matrix.

Figure 5 illustrates the preparation of the clay paste.



Figure 5. Preparing the clay paste.

2.3. Formulations for Medium-Density Panels

Table 1 presents the different formulations used to produce medium density panels.

Table 1. Formulation for medium density panels.

Formulation	Typha (%)	Clay (%)	Limestone (%)	Water (%)	Formulation
P1	7	22	17	54	P1
P2	8	22	17	53	P2
P3	9	22	17	52	P3

In the preceding table, the three formulations have a constant clay and limestone content, fixed at 22% and 17% respectively. The Typha content increases progressively from 7% for P1 to 9% for P3. This change is accompanied by a decrease in the water content, from 54% to 52%. Thus, formulations P1, P2, and P3 constitute three different compositions in which the variation in Typha content is associated with a variation in the water content.

2.3.1. Manufacturing, Drying and Packaging of Panels

The composite panels were made in a $60 \times 40 \times 10$ cm³ mold. The homogeneous mixture was gradually poured into the mold and then spread by hand to ensure the most uniform thickness possible. Compaction was carried out manually by successively applying pressure with the compaction tool shown in **Figure 6**. The compaction pressure was not measured using a measuring device; therefore, compaction was performed under the same manual conditions for all three formulations. Filling and compacting one panel took approximately 8 minutes. After compaction, the panels were carefully removed from the mold to minimize defor-

mation and cracking. They were then exposed to sunlight to dry. After drying, the panels were stored under ambient laboratory conditions until the preparation of the test specimens. After being cut from the panels and measured, the test specimens were stabilized under ambient laboratory conditions before testing to homogenize their moisture content. The panels were exposed to solar radiation for 7 days.



Figure 6. Compaction stage.

2.3.2. Density

Apparent density is the mass of an object per unit volume. The mass of the object is determined by weighing it on a precision balance with a resolution of 0.01 g. Density is calculated using the following formula:

$$\rho = \frac{m}{V} \quad (2)$$

m : Mass of the sample in kg; V : Sample volume in m^3 .

2.3.3. Natural Water Content

The moisture content of a soil indicates the amount of water present in the natural soil (sample).

The natural water content of a sample is determined by oven drying at a temperature of 105°C for 24 h. It corresponds to the ratio between the mass of water lost during drying and the dry mass of the sample [11]. It is calculated according to the following expression:

$$w = \frac{M_1 - M_2}{M_2} 100 \quad (3)$$

M_1 : mass of the wet sample before drying (g);

M_2 : mass of the dry sample after drying at 105°C for 24 h (g);

$M_1 - M_2$: mass of water lost during drying (g);

w : natural water content of the sample (%).

2.4. Panel Characterization

2.4.1. Mechanical Characterization

Mechanical tests were carried out using a 2000 kN press, according to a standard

protocol (see **Figure 7**). The test specimens were mounted and aligned on the machine platform using 10 cm adobe bricks. Compressive strength measures a material's ability to withstand a vertical load without excessive deformation in the longitudinal and transverse directions. The compression tests were performed 28 days after the panels were manufactured [12], and the compressive strength is calculated as the ratio of the maximum applied force to the cross-sectional area of the brick.



Figure 7. Mechanical press.

2.4.2. Thermal Characterization

The thermophysical parameters of a material can be determined using several techniques, including the transient hot plate method [13].

The hot plate method is an adaptation of the hot wire method to a planar geometry. Its principle is based on the use of a simple thin electrical resistor. A thermocouple, consisting of two wires 0.03 mm in diameter, is attached to the surface of the probe, approximately at its center. This probe is inserted between the sample of the material to be characterized ($10 \times 10 \times 1.7 \text{ cm}^3$ bricks) and a polystyrene block of the same cross-section and 4 cm thick. Contact between all the components is ensured by a clamp, which must be properly tightened after the various elements are stacked. The fundamental principle of this approach is to apply a constant heat flux to one face of the sample to be characterized, using a heating resistor, and to measure the temperature change $T(t)$ at the center of this resistor, where the thermocouple is located. **Figure 8** shows a photograph of the ESP-UCAD measurement device. Test specimens of $10 \times 10 \times 1.7 \text{ cm}^3$ were cut from the panels for thermophysical tests, then stabilized under ambient conditions to harmonize their moisture content before analysis.



Figure 8. Conductivity measuring device.

3. Results and Discussion

3.1. Particle Size Analysis of Clay

The particle size distribution curve shown in **Figure 9** is thus the result of combining the results obtained for the different particle size fractions. In this figure, the sieving results are for larger particles ($> 80 \mu\text{m}$) and the sedimentation results are for particles with a diameter of $< 80 \mu\text{m}$.

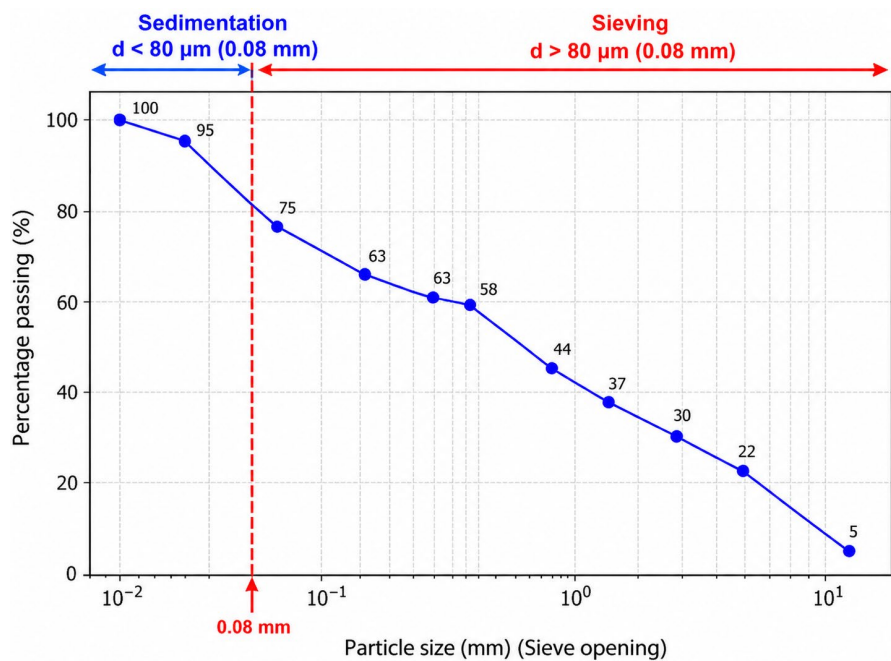


Figure 9. Particle size distribution curve of Thick clay obtained by combining sieving and sedimentation analysis.

The study of the particle size distribution reveals notable disparities between the Thick clay and the Bandia limestone: while the former is made up of 41% clay, 49% silt and 10% sand, the latter is distinguished by a high sand content (78%), complemented by 17% silt and 5% clay.

Table 2 shows the particle size composition and natural water content of the raw materials.

Table 2. Particle size distribution and natural water content of raw materials.

Raw material	Clay (%)	Silt (%)	Sand (%)	Water content (%)
Thick clay	41	49	10	4.71
Bandia limestone	5	17	78	5.93
Typha australis	–	–	–	13.12

Natural moisture levels (4.71% for clay, 5.93% for limestone and 13.12% for Typha) are incorporated into the preparation of the mixtures in order to analyze more precisely the moisture disparities between these materials.

3.2. Atterberg Limits

Table 3 presents the results of the liquid and plastic limits of Thick clay. These results allow us to determine the plasticity index and classify the material studied.

Table 3. Classification of clays.

Liquidity limit (wL) in (%)	77.01
Plastic limit (wP) in (%)	23.25
Plasticity Index (PI) in (%)	53.76
Classification	Very clayey

We found that the plasticity index of the clay (53.76%) is greater than 40%, meaning that the sampled clay is very clayey. Consequently, the risk of panel cracking due to the presence of clay will be very high.

3.3. Compression Result

Table 4 represents the average compression results of medium-weight panels.

Table 4. Average compression results for medium-weight panels.

Formulation	Test 1 (MPa)	Test 2 (MPa)	Test 3 (MPa)	Average resistance (MPa)	Density kg/m ³
P1	1972	1988	1995	1985	1123.50
P2	2,118	2,134	2,153	2.135	1073.85
P3	2,415	2,431	2,450	2,432	1014.15

Figure 10 represents the average compressive strength as a function of density.

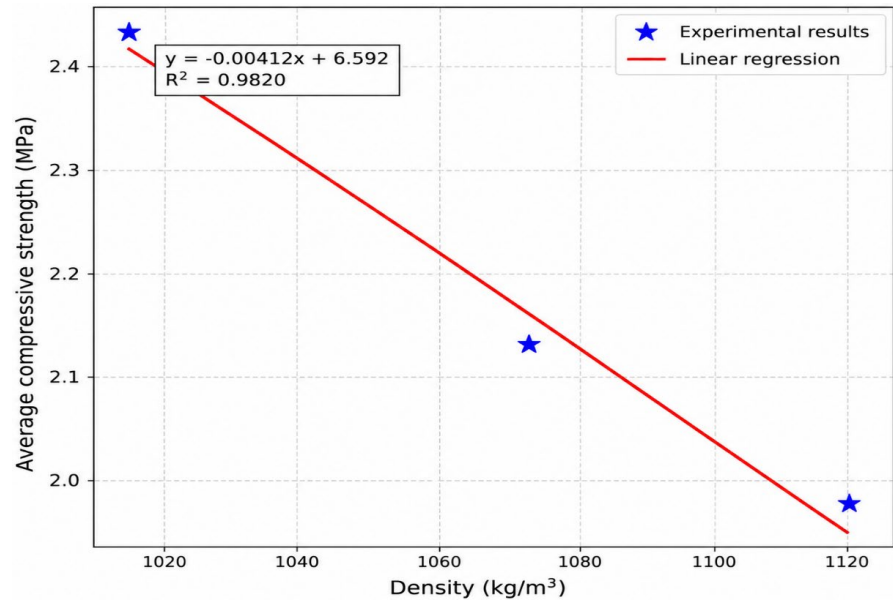


Figure 10. Mechanical resistance as a function of density.

The evolution of the average compressive strength of composite panels as a function of their density is illustrated in **Figure 10**. The coefficient of determination $R^2 = 0.9820$. The relationship between density and compressive strength is as follows: $f(x) = -0.00412x + 6.592$. This relationship shows a decrease in compressive strength as density increases within the studied range. Comparison of experimental values with those predicted by the model shows a standard deviation of the residuals of 0.051 MPa, indicating a low dispersion of the data around the regression line. Contrary to what is generally observed for conventional cementitious materials, a decrease in density leads to an increase in strength. For example, the density of P1 (1123.50 kg/m³) is greater than that of P3 (1014.15 kg/m³), while the average.

The strength increased from 1.985 MPa to 2.432 MPa. The increase in strength observed from P1 to P3 results from structural changes in the composite as well as the combined variations in Typha and water content. The increase in strength observed between P1 and P3 can be attributed to changes in composition and the combined variations in Typha and water content. The presence of plant fibers may help limit crack propagation and improve the mechanical behavior of the composite. However, under the experimental conditions of this study, the effect of Typha itself cannot be separated from that of the variation in water content.

These results corroborate the observations of Savastano *et al.* (2003) [13], and Millogo *et al.* (2014) [14] which highlight the advantages of plant fibers in composites: improved strength, toughness and ductility, while reducing density through mechanisms such as crack bridging and better stress distribution.

Current knowledge on reinforcement with plant fibers sheds light on the me-

chanical behavior of these materials, but it is not sufficient, in this work, to distinguish the impact of Typha from that of water content.

Figure 11 represents the average compressive strength of the different formulations P1, P2 and P3.

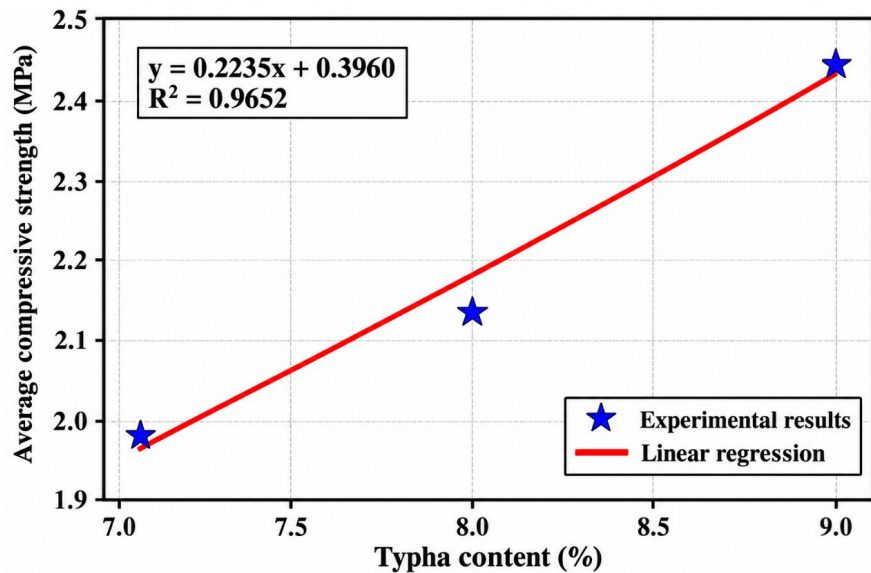


Figure 11. Average compressive strength of different panel formulations.

The results in **Figure 11** show an increase in average compressive strength between formulations P1, P2, and P3. The strength increases from 1.985 MPa for P1 to 2.135 MPa for P2 and reaches 2.432 MPa for P3. However, this change must be interpreted in light of the overall composition of the formulations. Indeed, the Typha content increases from 7% to 9%, while the water content decreases from 54% to 52%. Therefore, the observed variations in strength and density cannot be attributed solely to the increase in Typha content.

Under the conditions of this study, increasing the Typha content, combined with decreasing the water content, resulted in increased compressive strength and decreased density. The presence of fibers may help limit crack propagation and improve the material's mechanical behavior, but the effect of Typha itself cannot be separated from that of varying the water content with the formulations studied.

The differences observed between P1, P2 and P3 should therefore be considered as differences between composite formulations rather than as a direct measure of the isolated effect of Typha.

The work of Savastano *et al.* (2003) [13], and Millogo *et al.* (2014) [14] shows that plant fibers can contribute to improving the mechanical behavior of composites, particularly by controlling cracking and redistributing stresses. However, in the present study, these mechanisms do not allow us to distinguish the specific effect of Typha from that of variations in water content. Furthermore, the work of Arnaud and Gourlay (2012) [15] shows that plant fibers incorporated into earthy matrices can contribute to improving mechanical behavior, notably by limiting

crack propagation and promoting ductility.

3.4. Thermophysical Result

Table 5 represents the thermophysical results of medium-weight panels.

Table 5. The thermophysical results.

Formulation	λ (W/mK)	Effusivity (J/m ² ·K·s 0.5)	Water content (%)	Formulation
P1	0.255	580.0	8.5%	P1
P2	0.221	520.0	9.8	P2
P3	0.186	450.0	11.2	P3

Figure 12 represents the evolution of the thermal conductivity of the different formulations as a function of their density.

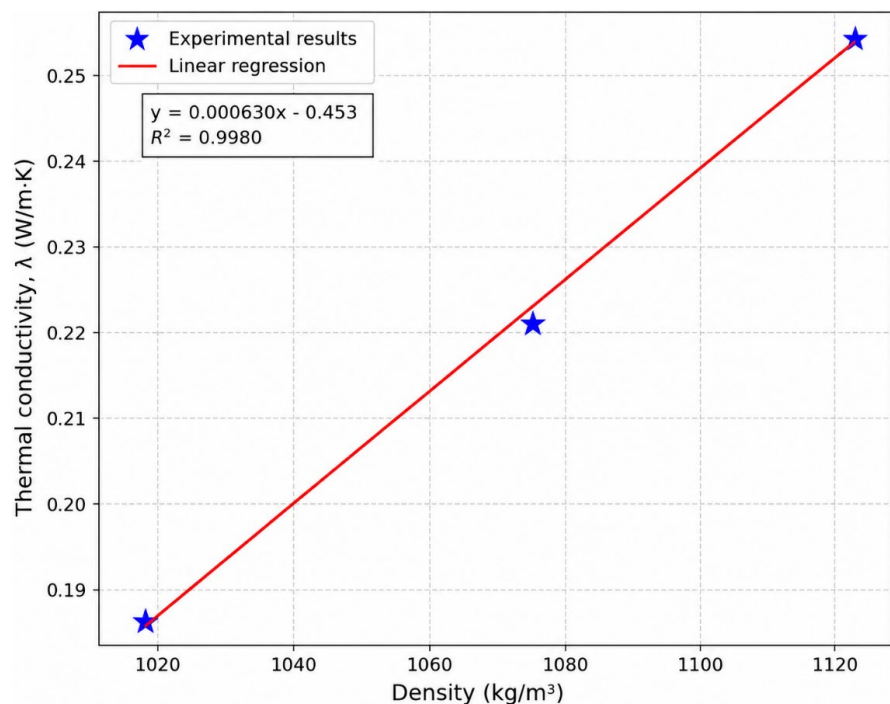


Figure 12. Evolution of the thermal conductivity of the different formulations as a function of their density.

The evolution of the thermal conductivity (λ) of the composite panels is presented as a function of their density. Analysis of the results reveals an extremely strong positive linear correlation between these two quantities, as evidenced by the coefficient of determination $R^2 = 0.9980$. The high R^2 value indicates a close linear relationship between density and thermal conductivity in the range of formulations studied. The material's internal structure, characterized by a lower density, leads to an increase in voids and trapped air. Air, being a poor thermal con-

ductor, limits heat exchange. Reduced density increases porosity and trapped air within the material, thus limiting thermal conductivity. Although the integration of plant fibers alters the internal structure, it is impossible to separate the specific impact of Typha from that related to fluctuations in water content in the tested samples.

These results corroborate the work of Asdrubali *et al.* (2015) on the thermal insulation of bio-based materials, which highlights the link between low density and low thermal conductivity. Furthermore, Korjenic *et al.* (2011) confirmed that plant fiber-based composites offer excellent thermal insulation properties, due to their porosity and low density.

The results show a direct relationship between the density and thermal conductivity of the composite panels, with a very high correlation ($R^2 = 0.9980$). A decrease in density is accompanied by a significant drop in thermal conductivity, thus improving the material's insulation performance. The formulations studied result in lighter panels with lower thermal conductivity. However, these performance characteristics result from the combination of compositional variations between P1, P2, and P3 and cannot be attributed solely to Typha. In accordance with the scientific literature, this study highlights the strong potential of bio-based cat-tail panels for the thermal insulation of sustainable buildings, particularly suited to hot climates where the reduction of heat transfer is paramount.

Figure 13 represents a comparison of the thermal conductivity of different panel formulations.

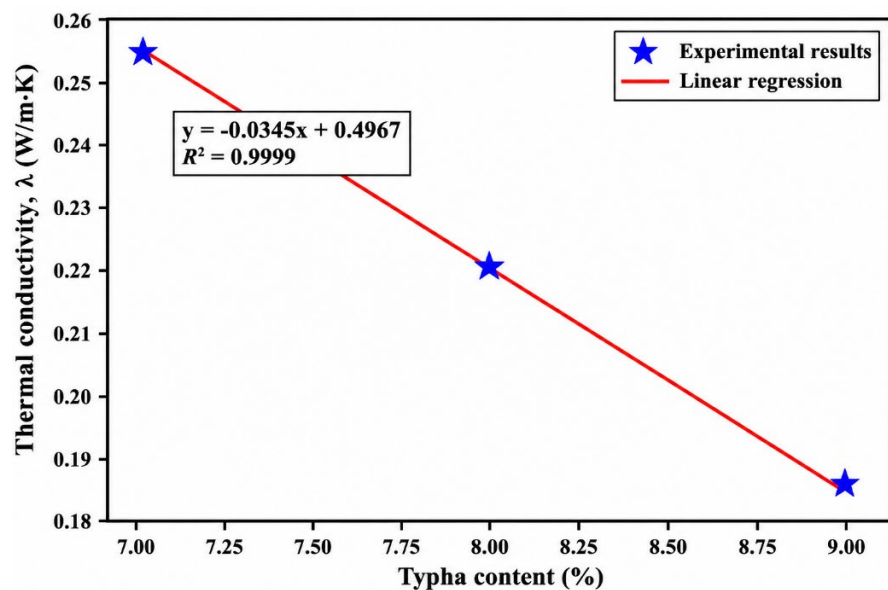


Figure 13. Comparison of the thermal conductivity of different panel formulations.

The thermophysical results presented in the figure show a decrease in thermal conductivity between the formulations studied. It decreases from $0.255 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for P1 to $0.221 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for P2 and to $0.186 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for P3. The thermal ef-

fusivity also decreases from 580 to 450 $\text{W}\cdot\text{s}^{-1/2}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$.

This evolution is associated with a decrease in panel density. Low density can promote the presence of voids and air within the material structure, which helps reduce heat transfer. The presence of plant fibers can also contribute to this evolution by modifying the composite's porous structure.

However, since the Typha content increases simultaneously with a decrease in the amount of water in the formulations, it is not possible to directly attribute the decrease in thermal conductivity to Typha alone. Rather, the results reflect the evolution of the thermal properties of the different clay-limestone-Typha formulations studied.

As demonstrated by Khedari *et al.* (2005) [16] in their study on plants, natural fibers, which are low-density and air-retaining, provide effective insulation by reducing thermal conductivity. Walker's (1999) study [17] confirms these results, which are corroborated by the observation that earth fiber-based materials have lower thermal conductivity than raw mineral materials. Within the range studied, the reduction in thermal conductivity follows the reduction in panel density. However, this effect cannot be attributed solely to Typha, as the increase in its content is accompanied by a reduction in the water content; the results therefore reflect the combined influence of the compositional changes between formulations P1, P2, and P3.

4. Conclusions

This research focused on characterizing composite panels made from Thick clay, Bandia limestone, and Typha australis, specifically evaluating the particle size distribution of the raw materials, their water content, and the Atterberg limits of the clay. Three formulations were analyzed by varying the Typha content (7 to 9%) and water content (54 to 52%), while maintaining a constant base of 22% clay and 17% limestone. The results showed an improvement in compressive strength, increasing from 1.985 to 2.432 MPa, while the density decreased from 1123.50 to 1014.15 kg/m^3 . Thermal and mechanical performance improves across the studied range, as evidenced by the decrease in conductivity (from 0.255 to 0.186 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and effusivity (from 580 to 450 $\text{W}\cdot\text{s}^{-1/2}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) observed between P1 and P3. However, since the increased proportion of Typha is correlated with a decrease in moisture content, the results reflect the combined impact of the formulation rather than the sole influence of Typha. While promising for thermal insulation, these clay-limestone-Typha mixtures require further research to isolate the compositional variables and evaluate the long-term durability and hygroscopic behavior of the panels.

Furthermore, this research highlights the potential of Typha australis, a common invasive plant in Senegal, as a viable source of high-quality, environmentally friendly building materials. Beyond energy efficiency gains, this approach promotes a reduced carbon footprint for the construction sector, supports the use of local resources, and encourages the development of new materials adapted to

tropical climates. Moreover, this study paves the way for improving production methods, assessing the long-term sustainability of these materials, and enabling their large-scale production.

Further research should isolate the influence of Typha content and water dosage, while examining the durability, hygroscopic properties, and longevity of the composite panels. Additional analyses, such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and micro-computed tomography (micro-CT), will be performed to deepen our understanding of their internal structure, the interactions between their components, and the evolution of their porosity. Studying their behavior in response to humidity and heat, as well as their long-term resistance, will also be essential. Finally, computer modeling and a life cycle assessment will allow us to evaluate their suitability for use in low-energy buildings.

Author Contributions

Hamidou SY: Methodology, Investigation, Experimental Characterization, Mechanical and Thermophysical Testing, Data Curation, Formal Analysis, Interpretation of Results, and Writing-Original Draft. **Mathioro FALL:** Supervision and Validation of the research work and manuscript. **Ali Fatim TOURE:** Writing-Review and Editing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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