Materiales de Construcción
Vol. 73, Issue 352, October-December 2023, e331
ISSN-L: 0465-2746
https://doi.org/10.3989/mc.2023.346323

Eco-efficient thermoacoustic panels made of totora and gypsum for sustainable rural housing ceilings

S. Huaquisto-Cáceres [a] ✉, D.K. Pari-Quispe [b], R.A. Cruz-Maron [a]

a. Escuela Profesional de Ingeniería Civil, Universidad Nacional del Altiplano, (Puno, Perú)
b. SICAC Grupo de investigación, Universidade de Brasília, (Brasilia, Brasil)
✉: shuaquisto@unap.edu.pe

Received 19 January 2023
Accepted 18 June 2023
Available on line 2 November 2023

ABSTRACT: The energy deficiency in rural housing in the Andes of Peru is recurrent. In this context, local and low environmental impact materials present an opportunity. This research evaluated the properties of five panels composed of totora and gypsum for ceiling applications. Firstly, the physical and durability properties were obtained. Then, impact and fire resistance were evaluated. Finally, thermoacoustic properties were assessed. The results showed a moisture level of 10.25%, water absorption of 354.85% which is considered high, and a dry density of 292.84 kg/m^3. Adequate durability to fungus with resin on both sides. The panels' fire resistance is superior to 60 minutes, with a safe impact criterion for 10 N and a functionality criterion for 5 N. The average values for the panels were 0.061 W/m·K for thermal insulation and 0.54 for NRC. Therefore, it is possible to produce an insulating material for thermoacoustic improvement.

KEY WORDS: Thermal insulation; Plant fibers; Fiber panels; Sustainable materials; Rural housing.

Citation/Citar como: Huaquisto-Cáceres, S.; Pari-Quispe, D.K.; Cruz-Maron, R.A. (2023) Eco-efficient thermoacoustic panels made of totora and gypsum for sustainable rural housing ceilings. Mater. Construcc. 73 [352], e331. https://doi.org/10.3989/mc.2023.346323.

RESUMEN: *Paneles termoacústicos ecoeficientes de totora y yeso para cielo raso en viviendas rurales sostenibles.* La deficiencia energética en la vivienda rural de los andes de Perú es recurrente. En este contexto, los materiales locales y de bajo impacto ambiental constituyen una oportunidad. La presente investigación evaluó las propiedades de cinco paneles compuestos de totora y yeso para cielo raso. Primeramente, se obtuvieron las propiedades físicas y de durabilidad. Seguidamente se evaluó la resistencia al impacto y al fuego. Finalmente se evaluaron propiedades termoacústicas. Los resultados muestran humedad de 10.25%, absorción de agua de 354.85% considerada alta y densidad seca de 292.84 kg/m^3, así como una adecuada durabilidad al hongo con resina en ambas caras. La resistencia al fuego de los paneles es superior a 60 minutos, criterio seguro al impacto para 10 N y criterio de funcionalidad para 5 N. Se obtuvieron además valores medios de los paneles de 0.061 W/m·K para el aislamiento térmico y 0.54 de NRC. De esta forma, es posible producir un material aislante para la mejora termoacústica.

PALABRAS CLAVE: Aislantes térmicos; Fibras vegetales; Paneles de fibra; Materiales sostenibles; Vivienda rural.

1. INTRODUCTION

The rural housing located in the highlands of the Andes, such as the Mesoandean and Altoandean zones in the department of Puno, Peru, corresponding to bioclimatic zones 4 and 5 according to Peruvian Norm EM.110 (1), is characterized by recurrent energy poverty inside the homes, which leads to health problems for its occupants (2). Heating the home can be difficult and costly, particularly for those on low incomes (3). The outdoor temperatures in the aforementioned zones drop below 0 °C due to a recurring climatic phenomenon called "frost" (4). This phenomenon has an impact on housing because it lacks thermal protection in its envelope, and over time has lost its vernacular legacy that involved insulated roofs with Ichu, a local abundant straw. The housing has adobe walls and makes massive use of metal coverings commonly known as "calamina", which significantly raises indoor temperatures during the day, but that gain is quickly lost in the early hours of the night (5). This change worsens the thermal performance of rural houses. Field measurements during the coldest months showed indoor temperatures around 0 °C at night (6). Considering that for this type of single-story housing, the greatest thermo-energy losses occur in the following order: through the roof, walls, and air infiltration through carpentry (7). The roofs assume the true protagonist in the formation of interior space at the thermal level (8, 9). It is necessary to give importance to materials that allow for the conservation of the heat gained during the day and to conserve it at night (10). In addition, they should avoid large thermal fluctuations when the occupants spend most of their time inside.

Currently, there are a large number of conventional materials used as thermal and acoustic insulation in buildings, with high energy consumption in their processing and problems of reuse that affect the environment. This is due to the requirements of standardization and acceleration of the building process, which often ignores local reality in international architecture. In the context of civil construction, natural fibers could be explored to allow architecture a more sustainable future (11). Nowadays, the use of natural materials and incorporation of plant fibers in the production of numerous systems is intensifying. By using compounds in construction that can be used as sustainable and low-cost substitutes (12).

Lake Titicaca, located in Peru, South America, offers a valuable resource in the form of totora. This plant is a potential insulation material that compares favorably with industrialized and commercialized thermal insulators. It is a highly sustainable and low-cost alternative, capable of greatly improving energy efficiency in areas close to its growth or cultivation (13-15). Several traditional communities, such as those near Lake San Pablo in Ecuador or the Uros in Lake Titicaca, have used this plant for a long time, and some still use it today (16). The Titicaca National Reserve (TNR) has approximately 16,058.62 hectares of totora beds (17). Currently, there is a waste and burning of totora during the dry season, mainly in the months of september and october, caused by communities located along the lake's shore. They burn the mature and dry stems to obtain tender regrowth, which constitutes a problem and a threat to the local ecosystem (18).

Studies carried out in extremely cold regions of the Peruvian highlands, based on the conception of passive strategies and the almost exclusive use of local and natural materials such as totora, gypsum and adobe in the building envelope, allowed for an increase in the indoor temperature of multi-use spaces in rural households (5, 19). Therefore, these materials are presented as potential solutions in the area.

The objective of the study is to evaluate the physical properties of moisture, absorption, density, durability against fungus, thermal and acoustic insulation, fire resistance, and impact resistance of the combined material of totora and gypsum applied in the ceiling of typical rural houses in the department of Puno.

2. MATERIALS AND METHODS

A characterization of the main raw materials used in the present study was conducted. We have the totora and gypsum. The "totora" is an erect herbaceous plant that grows in flooded areas, streams, wetlands, and sandy areas, belonging to the Juncaceae family (13). In the available literature, according to the Word Checklist of Selected Plant Families (WCSP), it has been identified with different taxa, such as Scirpus californicus var. Tatora (Kunth) Barros, S. californicus subesp. Tatora (Kunth) T. Koyama, and Schoenoplectus tatora (Kunth) Palla, which are synonyms for Schoenoplectus californicus (14). However, the most abundant taxon in Lake Titicaca is Schoenoplectus Tatora (13, 20). The availability of this material in rural communities is extensive, as well as its traditional use.

The insulation capacity of totora and its suitability for use as an insulating material in the highlands of Puno, Peru, were analyzed. The tests were conducted in a laboratory at the University of Minnesota following the standard ASTMC1155-95:2013, which determines the thermal resistance of building envelope components based on in-situ data. The reported conductivity from these tests was 0.083 W/m·K (13), indicating its good thermal performance for insulation purposes. The fast growth rate, high renovation capacity, low density, spongy internal structure, and the favorable weight-resistance ratio make this material an intriguing option for studying its application in thermal insulation in the construction sector (21).

Another versatile material known for its properties, which can change repeatedly through a reversible hydration reaction and is totally and infinitely recyclable, is the dihydrate calcium sulfate ($CaSO_4{\cdot}2H_2O$) commonly known as gypsum (22). The material has transitioned from artisanal to industrial, being one of the most common mineral binders with energy savings in its manufacturing process and low CO_2 emissions. It has a neutral pH and is usually white with desirable decorative properties. It is an excellent material for molding, fire resistance, and noise reduction. However, gypsum products have low water resistance (23). Several authors have studied the use of gypsum in combination with organic materials, such as incorporating wood waste into the gypsum matrix, for the development of false ceiling boards with improved thermal and acoustic properties (24). Gypsum boards are used in walls or ceilings with light gauge steel structure as the main fire-resistant material, in addition to thermal protection (25). Low thermal conductivity values for gypsum of 0.17 W/m·K have been recorded, indicating that it behaves as a good thermal insulator (26). For standard gypsum boards for ceilings according to the UNE-EN 12667 Standard, thermal conductivity values of 0.30 W/m·K have been shown. A Noise Reduction Coefficient (NRC) according to the EN ISO 10534-2 Standard of 0.12 (27) and density of 810 kg/m^3 (28) have been registered. Its use in the study area would be appropriate due to its good thermal acoustic response properties and local availability in combination with totora.

The study was carried out in three stages. Firstly, the study location for the extraction of raw materials and the procedure for obtaining the panels according to the most commonly used weaving techniques by the local community were defined. For this purpose, the community of Chimu was chosen, located in the coastal area of Lake Titicaca at a latitude of 15° 51' 18.3" South, a longitude of 69° 57' 56.3" West, and an altitude of 3909 meters above sea level. The town is home to single-family rural dwellings and residents engaged in the extraction and weaving of totora blankets, as shown in Figure 1.

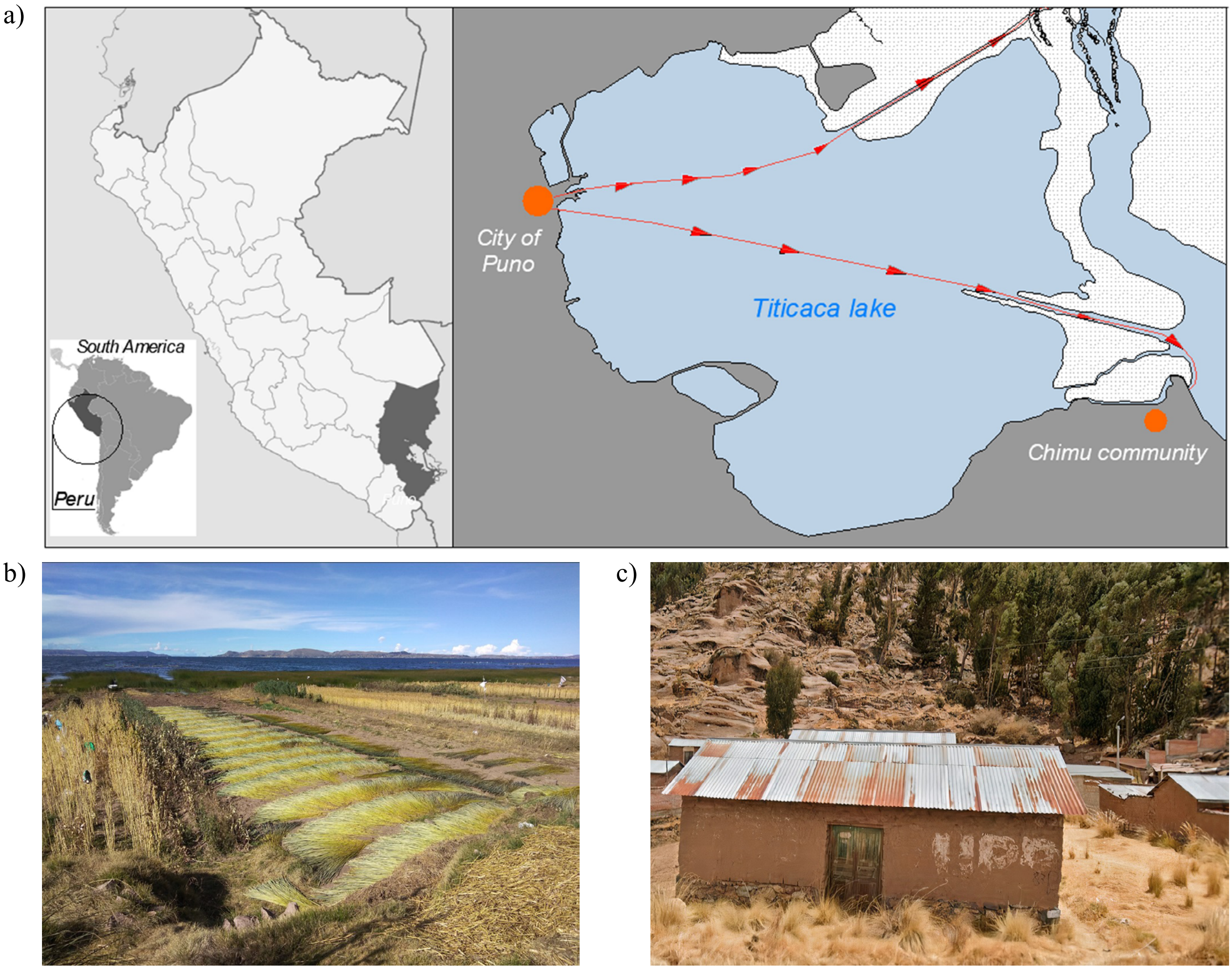
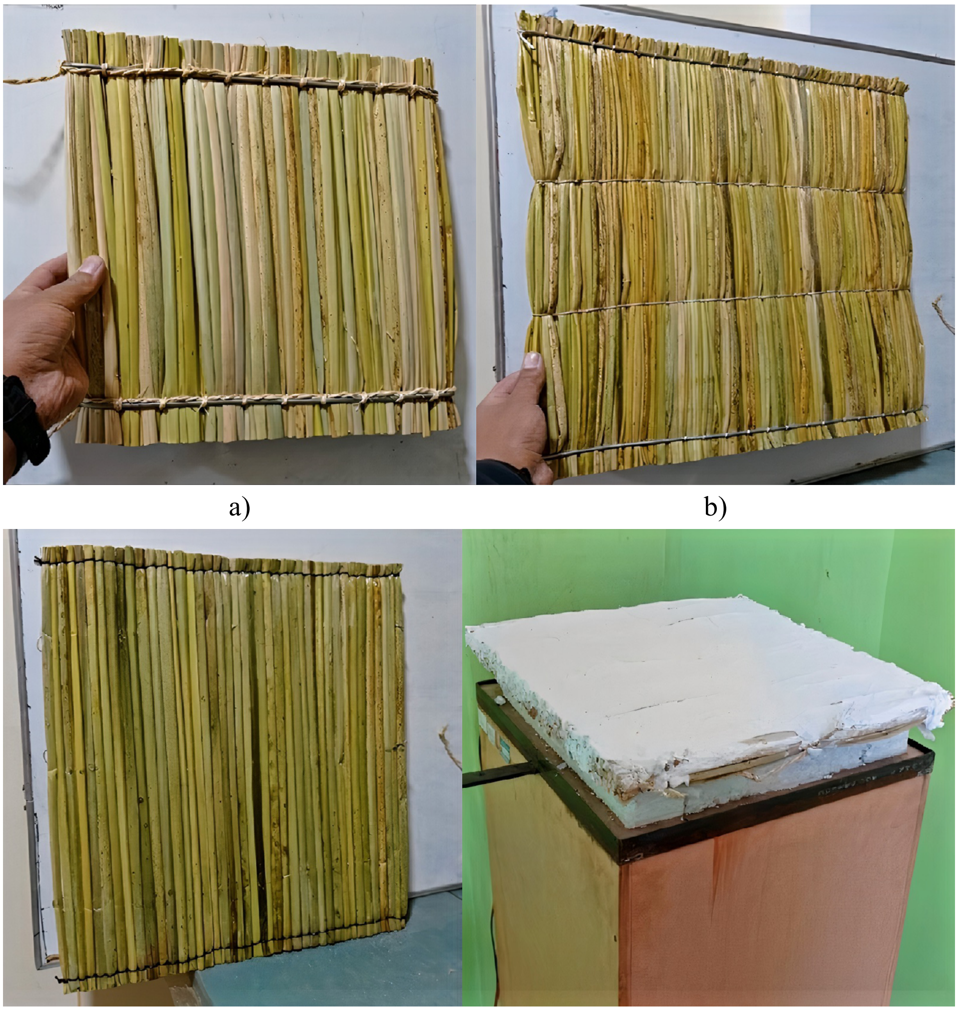


Figure 1. a) Study location. b) Extraction and drying of totora. c) Single-family rural housing.

Table 1. Panel types and sizing.

Type of totora panel	Technique real-ized	Long (mm)	Width (mm)	Thickness (mm)	Gypsum layer (mm)
T1	Kesana	310	310	25	5
T2	Kesana	310	310	20	5
T3	Hilada	460	460	20	5
T4	Hilada	460	460	15	5
T5	Hicalina	460	460	10	10



a) b) c) d)

Figure 2. Totora panels. a) Kesana (T1 and T2). b) Hilada (T3 and T4). c) Hicalina (T5). (d) Combined panel (totora with gypsum coating).

Three types of weaving techniques were chosen, called “Kesana”, “Hilada”, and “Hicalina”, for the evaluation of five types of panels named T1, T2, T3, T4, and T5, to which a layer of gypsum was added. Table 1 and Figure 2 show the details of the panels.

The following dimensions and thicknesses were considered to verify the behavior of each one in the testing process and to analyze which ones could self-support better. It was also determined which one responds better to the tests performed compared to the standard suspended modular ceiling panel that is placed on a support structure, the modules are supported without fixings and can be uninstalled freely (29). This arrangement is the most commonly used and the one that is desired to be replaced.

The assembled panels were taken to the laboratory to obtain their physical and durability properties. The moisture content of the totora panel was determined by calculating the ratio between its water content after natural drying and its weight in a dry state in an oven. Regarding water absorption, the guidelines suggested by ASTM C127-15 (30) for aggregates were considered, as there is no standardized procedure addressing water absorption by totora. Additionally, the apparent density was determined by weighing the dried totora-gypsum panel and dividing it by its apparent volume, which takes into account the pores or voids in the material. The durability against the fungus Rhizopus Stolonifer was tested following the ASTM D 2017-05 (31) and UNE-EN 350 (32) standards over a period of ten weeks. A piece was extracted from each panel every two weeks and observed under a microscope to verify the resulting damage. Three types of samples were used, referred to as M1, M2, and M3. Sample M1 consisted of totora without resin, M2 consisted of totora with a thin resin on one side, and M3 consisted of totora with resin on both sides. The resin used was varnish.

Next, the fire resistance properties were analyzed with reference to DIN 4102-1 (33) and ASTM E119-20 (34) for both exposed and non-exposed sides of the five types of combined panels, as well as impact resistance according to the Technical Report (35). Finally, the thermoacoustic properties were evaluated. For thermal insulation, thermal conductivity was assessed using the Thermal Conductivity Apparatus (36), which measured the amount of heat transferred by conduction through the material being studied, determining the time in which a mass of ice melted. To evaluate acoustic insulation, the NRC coefficient for materials was considered using a Soundproof Chamber (37).

3. RESULTS AND DISCUSSION

3.1. Moisture content and absorption of totora panels

Totora, as an organic material in its natural state when extracted from its place of origin, have a high moisture content and degree of saturation which must be dried in the sun before being formed into panels. Table 2 shows some basic properties of the totora panels formed after being sun-dried.

The average moisture content of the totora panels is 10.25%, which is suitable for the placement and setting of gypsum on one of its faces. The average water absorption of the panels is 354.85%, which is considered high and can negatively influence the behavior of the panel when exposed to outdoor conditions of high humidity and precipitation, given that it is an organic material with a high content of voids. The tissue mostly consists of air chambers arranged vertically along the culm, divided approximately every 2.50 mm by perpendicular diaphragms (14, 38). It can absorb water into the follicles or pores, affecting the gypsum layer, so its use is recommended only in indoor environments of the dwelling.

3.2. Density

For gypsum boards incorporating wood chips, densities ranging from 702 to 1250 kg/m^3 were obtained, while those incorporating sawdust with proportions ranging from 40% to 2.5% by weight of gypsum resulted in densities from 802 to 1266 kg/m^3 (24). Another study on 12.5 mm and 15.8 mm gypsum boards used in fire-resistant assemblies reported average densities ranging from 687 kg/m^3 to 811 kg/m^3 (39). On the other hand, panels made from fibrous vegetable waste materials such as esparto, cane, fig tree, olive leaves, and wood shavings indicate lower densities ranging from 47.34 kg/m^3 up to 256.71 kg/m^3 for sheep's wool (40). Insulating panels made of narrow-leaf totora fibers, measuring 350x350x10 mm, showed densities of 200-400 kg/m^3 (41). The addition of organic materials leads to a decrease in density, resulting in a lighter final product (42). These values are similar to the densities of totora panels without gypsum reported in this study, as they fall within these ranges. For the different types of totora panels studied, dry densities ranging from 99.48 to 107.70 kg/m^3 were obtained, with an average of 104.71 kg/m^3, while for combined totora-gypsum panels, densities ranged from 220.10 to 463.85 kg/m^3, with an average of 292.84 kg/m^3, as shown in Table 3.

Table 2. Moisture percentage and absorption of the panels according to type and thickness.

Type of totora panel	Moisture (%) - IC	Absorption (%) - IC
T1	8.85 (7.61; 10.10)	335.18 (314.45; 355.91)
T2	8.11 (5.96; 10.26)	360.09 (324.18; 396.00)
T3	13.33 (11.17; 15.48)	372.57 (336.66; 408.48)
T4	11.27 (9.12; 13.43)	342.38 (306.50; 378.30)
T5	9.70 (8.18; 11.23)	364.01 (338.60; 389.40)
Average	10.25	354.85

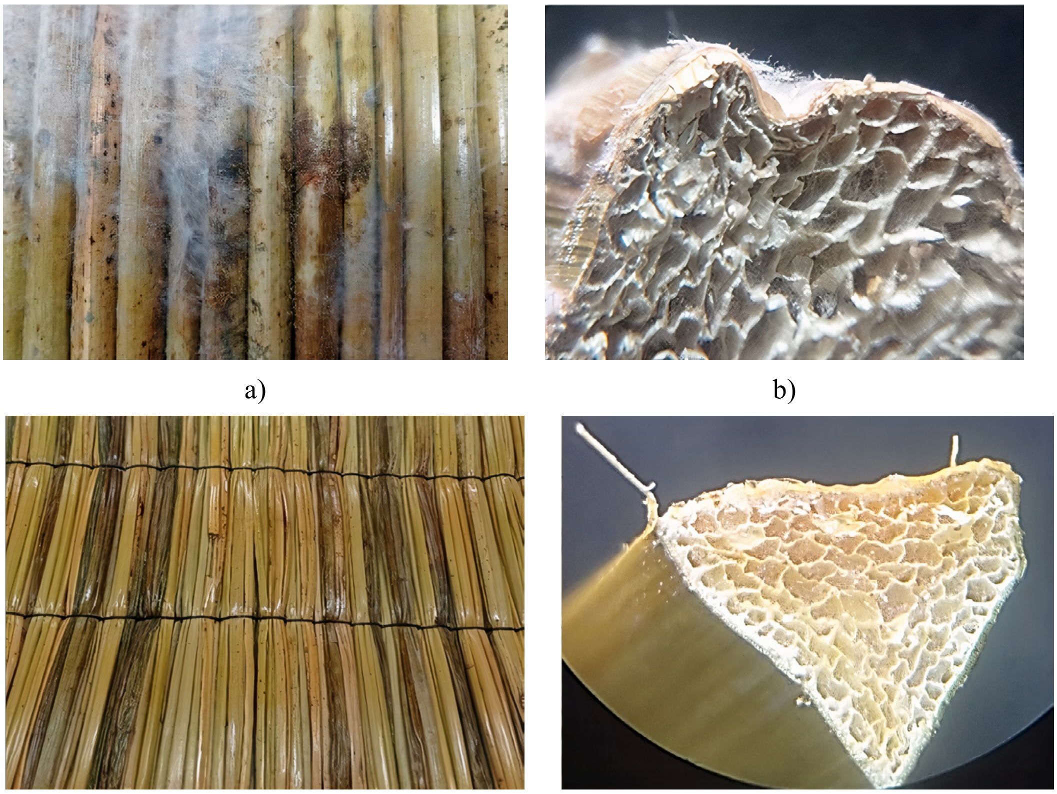
Table 3. Density of totora panels and combined totora-gypsum panels.

Type of totora panel	Bulk dry density of the totora panel (kg/m^3)	Bulk dry density of totora and gypsum panels (kg/m^3)
T1	100.12 (96.07; 104.16)	220.10 (217.68; 222.52)
T2	99.48 (92.48; 106.48)	243.58 (239.39; 247.77)
T3	109.89 (102.88; 116.89)	251.91 (247.72; 256.10)
T4	106.38 (99.38; 113.39)	284.79 (280.60; 288.98)
T5	107.70 (102.74; 112.65)	463.85 (460.89; 466.81)
Average	104.71	292.84

The variability in density is due to the thickness of the totora and gypsum that make up the panel. Panel T1 is the lightest because it has a thickness of 25 mm of totora and 5 mm of gypsum, while T5 is the heaviest due to its thickness of 10 mm of totora and 10 mm of gypsum. The densities reported in this study indicate that the totora and gypsum panels are very light compared to other panels made with organic materials in their composition.

3.3. Durability against fungus

The totora panel can become moistened due to external factors, which can make it susceptible to fungal attacks. A cultivation was conducted on the totora panel for 10 weeks using the "Rhizopus stolonifer" fungus. The results of the durability test against the fungus indicate that, in the case of the totora panel without resin (M1), it showed damage and was attacked by the fungus, resulting in weight losses of up to 31.8%. The totora panel M2, which was coated with a thin layer of resin on one side, also experienced damage and losses of 25.8%. However, the totora panel M3, which was covered with resin on both sides, did not suffer any damage from fungal attacks. It maintained its internal structure with minimal losses, reaching up to 14.0% by the fourth week and remaining constant at 14.1% until



d)

Figure 3. a) Sample M2 of the thin resin panel, b) Cross-sectional cut of M2 panel with fungal attack and 10X magnification, c) Sample M3 of the double resin panel, and d) Cross-sectional cut of M3 panel without fungal attack and 10X magnification.

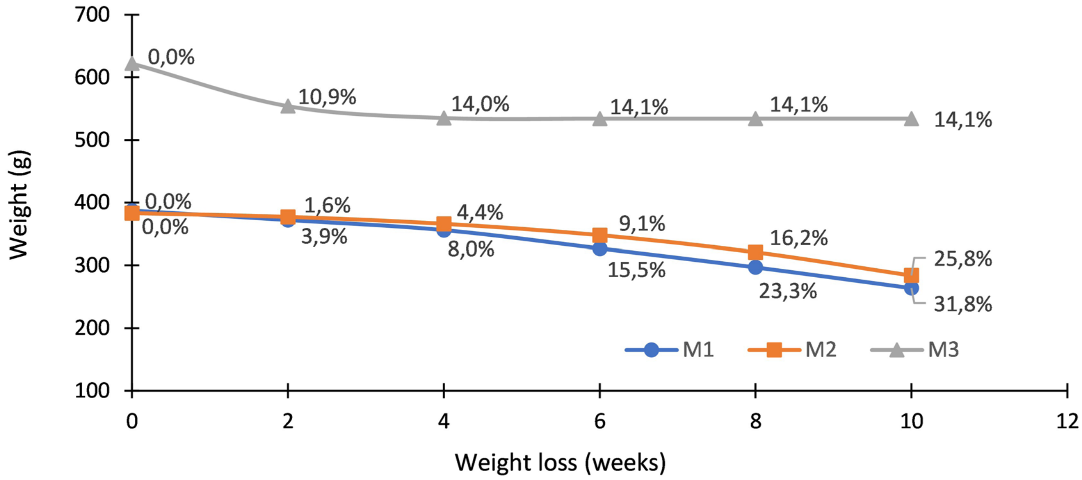


Figure 4. Durability of totora panels against fungus.

the tenth week. Therefore, coating the panels with resin on both sides is crucial to preserve them and enhance their durability. Please refer to Figure 3 and Figure 4 for more details.

3.4. Fire resistance

Understanding the behavior of gypsum at high temperatures and developing analytical methods that can capture the thermal and structural behavior of gypsum boards under fire conditions is essential (43). According to the UNE-EN 13501-1 standard (44), the fire resistance of a material can be evaluated by considering several parameters such as temperature increase, rate of mass loss, heat release, smoke production, etc. Or by using standard specifications for gypsum panels as per ASTM C36-C 36M (45). Studies suggest that the peak in the specific curve around 700-800 °C corresponds to the decomposition of the calcium carbonate and magnesium carbonate content of the gypsum boards, and their quantities can be deduced from thermogravimetric analysis (28).

The results shown in Figure 5, indicate that the totora-gypsum panels withstand fire for at least 60 minutes at different temperatures generated on the exposed (Exp) and unexposed (No Exp) faces, complying with specifications for ceilings. Panel T5 shows better fire behavior on the unexposed face, with a duration evaluated at 60 minutes reaching a temperature of 96.74 °C and at 120 minutes

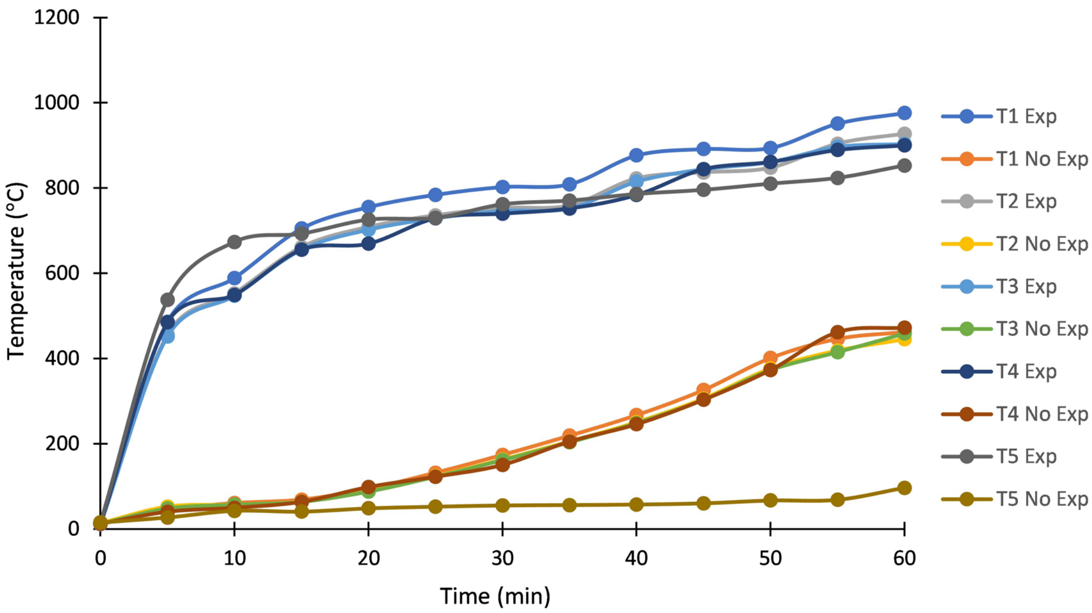


Figure 5. Resistance to high temperatures of totora-gypsum panels.

reaching 436.64 °C, followed by panels T1, T2, T3, and T4 on the unexposed face reaching average temperatures of 459.59 °C at 60 minutes of duration and average burn radii of 71.4 mm. Therefore, the totora-gypsum panel exhibits better fire behavior on the unexposed face compared to the exposed face, which generates higher burning temperatures.

Fire causes significant damage to panels, and depending on their composition, it can modify their structure. For instance, fire resistance tests were conducted on gypsum coating with rubber, where the heat transfer due to fire exposure considerably modifies the chemical composition of the coating. Studies report that, on the non-exposed side to fire, the amount of gypsum equivalent to the mass loss obtained through thermogravimetric analysis (TG) due to water released by these coatings was between 5.4 and 7.2 times lower than that of conventional gypsum coatings (46). Other studies on Type X gypsum boards (gypsum board material used in fire-resistant assemblies) can provide up to 90 minutes of fire protection for building assemblies (39). Based on this, panel T5 meets or exceeds the threshold for fire resistance established by the ASTM C 36/36M-03 standard test method.

3.5. Impact resistance

The importance of this qualitative evaluation lies in the fact that the totora-gypsum panels may be subjected to external forces that could damage its configuration, rendering it unusable and therefore not meeting the specifications indicated in the previous paragraphs. The properties observed in the impact resistance test were obtained using spherical steel balls weighing 5 and 10 N, which were impacted onto the gypsum face of the panel from a height of 1.02 m. The results of the safety criteria in use and the functionality criterion for the five types of proposed panels indicate adequate resistance by not exhibiting any breakage, penetration, or degradation, and no visible projection. Therefore, it is shown to be favorable for use in the ceiling, Table 4.

3.6. Thermal insulation

The aim of thermal insulation systems and materials is to reduce the transmission of heat flow, which is evaluated through thermal conductivity (λ). Thermal conductivity is defined as the “steady-state heat flow passing through a unit area of a homogeneous material with a thickness of 1 m, induced by a temperature difference of 1 K between its faces”, and it is expressed in W/m·K. A material is considered a thermal insulator if its conductivity is lower than 0.07 W/m·K (47). According to the UNE-EN 12664 Standard (48), thermal conductivity is categorized as low thermal resistance, medium thermal resistance, and high thermal resistance (49-51).

Various studies indicate that the formation of composite panels made from vegetal residues combined with gypsum shows that as the percentage of residues increases, thermal conductivity decreases, resulting in better thermal performance of the material (42). One study indicates that the thermal conductivity of pure gypsum with a thickness of 15 mm is 0.481 W/m·K, which decreases by 36% with the incorporation of chicken feathers, reaching 0.309 W/m·K due to the creation of air-filled pores inside the material (52). Other studies on fibrous vegetal residues report similar thermal conductivities ranging from 0.044 to 0.091 W/m·K (40). Insulating panels made of narrow-leaf totora fibers with dimensions of 350x350x10 mm exhibit low thermal conductivities between 0.0438 and 0.0606 W/m·K compared to other cellular fibrous materials such as wheat straw boards, durian husk boards, coconut fiber boards, etc. (41).

Therefore, it is advisable to use compositions that facilitate and improve the thermal properties of the panel, making it necessary to use hybrid compounds that aim for the low thermal conductivity of the material. It should be noted that these studies do not combine vegetable fiber panels with other materials that provide rigidity, such as gypsum. The totora-gypsum panel proposed in this study proves to be a suitable alternative for use in ceilings. This category includes Kesana and Hilada composite panels

Table 4. Impact resistance of totora-gypsum panels.

Panel type	Criteria safe in use 10 N			Functionality criterion 5 N	
	No breakage	No penetration	No projection	No penetration	No degradation
T1	Yes	Yes	No	Yes	Yes
T2	Yes	Yes	No	Yes	Yes
T3	Yes	Yes	No	Yes	Yes
T4	Yes	Yes	No	Yes	Yes
T5	Yes	Yes	No	Yes	Yes

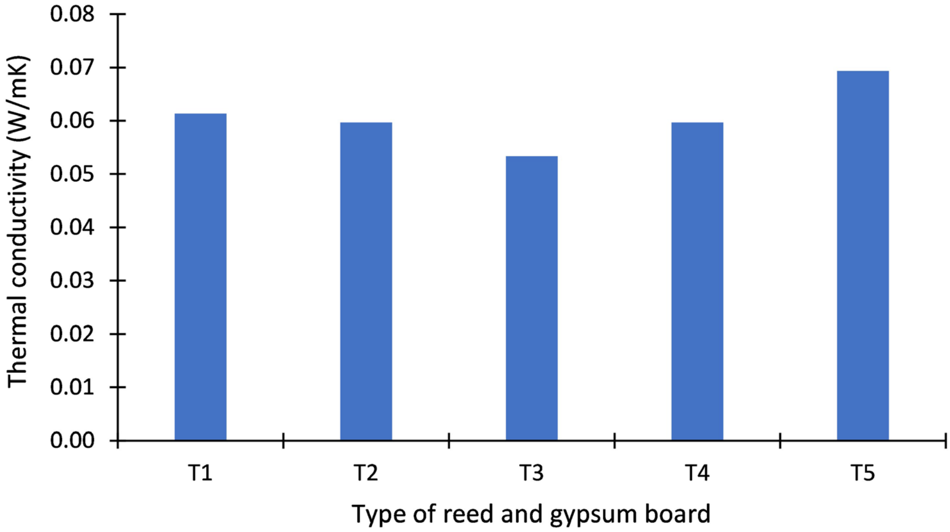


Figure 6. Thermal conductivity of totora-gypsum panels.

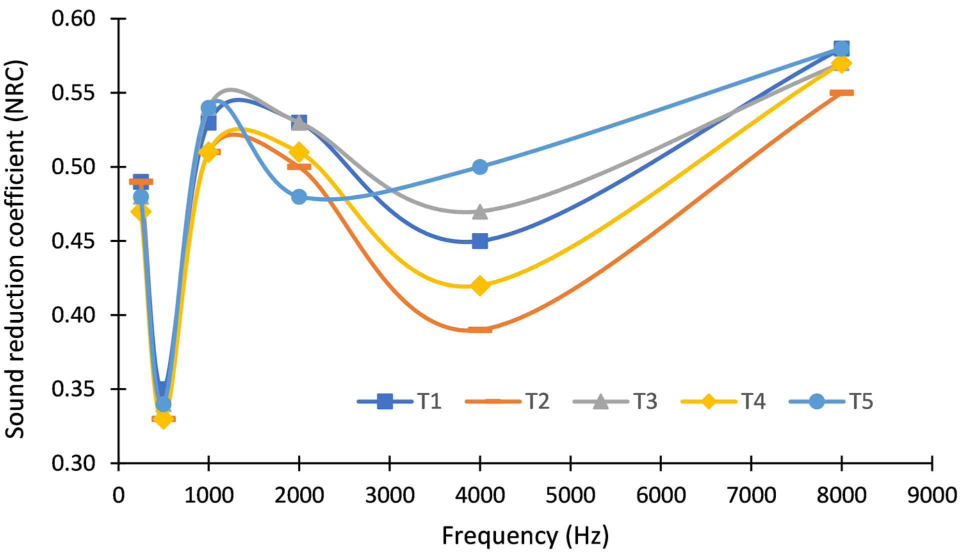


Figure 7. Sound reduction coefficients of totora-gypsum panels.

with gypsum (T1, T2, T3, and T4) due to their thermal conductivity values below 0.061 W/m·K. The indicated panels have a higher totora thickness compared to panel T5, which has a thermal conductivity of 0.069 W/m·K, Figure 6.

3.7. Acoustic insulation

In the case of the acoustic insulation property of the material, the UNE-EN ISO (53-56) and ASTM C423-09 (57) standards are taken into consideration. The Noise Reduction Coefficient (NRC) is a material property used to evaluate its acoustic insulation and is defined as the ability of a material to prevent the passage of sound. Higher values of this index indicate better acoustic insulation of the material. The NRC is the arithmetic mean of the absorption coefficients measured in octave bands between 250 and 2000 Hz.

The results of the studied panels showed satisfactory acoustic performance, as their NRC coefficients are compatible and even in some cases higher than those presented by conventional materials. In Figure 7, NRC coefficients with values of up to 0.58 can be observed over a frequency range of 250 to 8000 Hz, and 0.54 for a mid-frequency range of 250 to 2000 Hz according to ASTM C 423 for the five types of tested totora-gypsum panels. It is also observed that there is lower sound absorption in the low frequency range.

The coefficient of acoustic absorption is commonly measured in the impedance tube for some durable and natural materials, such as chips and sawdust woods, where there is an incidence of thickness (58). Studies conducted on coconut, sheep wool, and gypsum ceiling panels indicate NRC coefficients of 0.25 for a low-frequency range of 0 to 1500 Hz, NRC values of 0.25 and 0.32 for the range of 1500 to 3000 Hz, and an NRC of 0.35 at a frequency of 5500 Hz (26). Accordingly, these values are comparatively lower than the results found for the panels in the present study. However, to increase the NRC of the panel, it can be modified, such as with perforated gypsum ceiling panels with weighted sound absorption coefficients of 0.65 and 0.70 for frequencies of 125 to 4000 Hz, depending on the thickness, opening, perforation ratio, type, and location of the porous material (59). Other studies on acoustic panels made from agricultural waste (rice husk, vine pruning, cork, and prickly pear agglomerated with resin) to be used as ceiling tiles showed NRC results close to 0.80 in the frequency range of 200 Hz to 6400 Hz (60). Similarly, studies on the acoustic behavior of materials based on fibrous plant waste such as esparto grass, cane, fig tree, olive tree, olive leaves, and sawdust show good acoustic performance with an NRC in the range of 0.60-0.90 for mid-range frequencies (40). Therefore, it can be stated that panels made entirely of plant fiber materials have better sound insulation compared to panels combined with other materials.

4. CONCLUSIONS

This research presents the analysis of panels composed of totora and gypsum for use in ceiling applications in local rural housing, using different thicknesses to evaluate desirable properties. The tests conducted demonstrate that it is possible to produce a component that meets the established requirements according to current regulations. The suitability of using natural composite materials was found to be more convenient compared to conventional materials such as polystyrene or plastic foam. This implies a good alternative for the local community due to the easy availability of totora in the area, low cost, proximity to cultivation in Lake Titicaca, and high acceptance among the population.

Totora is a locally available material with beneficial properties that can contribute to the sustainability of rural housing. The totora panel alone has good insulation properties, but when combined with gypsum, it demonstrated even better performance. By forming a composite material that meets the requirements of lightness, durability, and strength, satisfactory results were achieved. With proper treatment and manufacturing, both materials can greatly improve the thermal and acoustic conditions of the common multipurpose spaces found in rural homes, and consequently the health of their occupants.

Considering that the greatest energy losses in rural dwellings in the mentioned areas occur through roof infiltrations, it is important to pay attention to this part of the building envelope and propose alternatives that can mitigate these losses. It should be taken into consideration that the implementations carried out must be accompanied by the care of the house's carpentry and the management of the openings so that the panels can work properly. Panels are presented as a viable alternative to improve thermal and acoustic conditions with environmental and social benefits.

ACKNOWLEDGEMENTS

The authors would like to thank the Universidad Nacional del Altiplano Puno, for making this research a reality.

AUTHOR CONTRIBUTIONS:

Conceptualization: S. Huaquisto, D.K. Pari. Data curation: S. Huaquisto, R.A. Cruz. Formal analysis: S. Huaquisto. Funding acquisition: R.A. Cruz. Investigation: S. Huaquisto, D.K. Pari. Methodology: S. Huaquisto, D.K. Pari. Project administration: R.A. Cruz. Resources: R.A. Cruz. Supervision: S. Huaquisto, R.A. Cruz. Validation: D.K. Pari, R.A. Cruz. Visualization: S. Huaquisto. Writing, original draft: S. Huaquisto, D.K. Pari. Writing, review & editing: S. Huaquisto, D.K. Pari.

REFERENCES

1. EM 110. (2014) Confort térmico y lumínico con eficiencia energética. Reglamento Nacional de edificaciones (RNE), Perú. Retrieved from: https://www.gob.pe/institucion/munisantamariadelmar/informes-publicaciones/2619729-em-110-confort-termico-y-luminico-con-eficiencia-energetica (Accessed: May 1, 2023).
2. Bernáldez, J.P.; Ruiz, M.V.L. (2016) Repercusiones de la pobreza sobre la salud de los individuos y las poblaciones. *FMC Atención Primaria.* 23 [2], 50-60. https://doi.org/10.1016/j.fmc.2015.04.010.
3. UCL (2014) Local action on health inequalities: Fuel poverty and cold home-related health problems. Retrieved from: https://www.instituteofhealthequity.org/resources-reports/local-action-on-health-inequalities-fuel-poverty-and-cold-home-related-health-problems/read-the-report.pdf (Accessed: May 1, 2023).
4. DS 047. (2022) Plan multisectorial ante heladas y friaje 2022-2024. El peruano, Perú. Retrieved from: https://cdn.www.gob.pe/uploads/document/file/3066879/PMHF%20 2022-2024.pdf.pdf (Accessed: May 1, 2023).
5. Wieser, M.; Rodríguez-Larraín, S.; Onnis, S. (2021) Estrategias bioclimáticas para clima frío tropical de altura. Validación de prototipo de vivienda. Puno, Perú. *Estoa.* 10 [19], 9-19. https://doi.org/10.18537/est.v010.n019.a01.
6. Jimenez, C.; Wieser, M.; Biondi, S. (2017) Improving thermal performance of traditional cabins in the high-altitude peruvian andean region. PLEA Conference. 4101-4108. Retrieved from: https://repositorio.pucp.edu.pe/index/handle/123456789/187754 (Accessed: May 1, 2023).
7. Pari, D.K. (2021) Estrategias bioclimáticas pasivas para el confort térmico en viviendas de interés social Mesoandinas -

caso ciudad de Puno. M.Sc. Thesis, Universidade de Brasilia, Brasil.
8. Serra, R. (1999) Arquitectura y climas. Fourth ed., GG Básicos, Barcelona, España.
9. Jirón, P.; Toro, A.; Caquimbo, S.; Goldsack, L.; Martínez, L. (2004) Bienestar habitacional: guía de diseño para un hábitat residencial sustentable. First ed., Instituto de la Vivienda F.A.U, U. de Chile.
10. García A. (1983) Bases para el diseño solar pasivo: equipo de investigación de ahorro de energía en el edificio. First ed., Instituto Eduardo Torroja de la Construcción y del Cemento, Madrid, España.
11. Steffens, F.; Steffens, H.; Oliveira, F.R. (2017) Applications of natural fibers on architecture. *Procedia Eng.* 200, 317-324. https://doi.org/10.1016/j.proeng.2017.07.045.
12. Balogun, O.A.; Daramola, O.O.; Adediran, A.A.; Akinwande, A.A.; Adesina, O.S.; Folorunsho, O.E.; Adetula, Y.V.; Kolawole, O.E. (2022) Development of sustainable polymeric materials for ceiling tiles application and optimization by digital logic method using thermal insulation properties as the functional requirement. *Mater. Today Proc.* 65 [3], 2254-2259. https://doi.org/10.1016/j.matpr.2022.07.092.
13. Ninaquispe-Romero, L.; Weeks, S.; Huelman, P.H. (2012) Totora: A sustainable insulation material for the andean parts of Peru. PLEA Conference [Proceedings]. Retrieved from: https://plea-arch.org/ARCHIVE/websites/2012/files/T02-20120130-0067.pdf (Accessed: May 1, 2023).
14. Hidalgo-Cordero, J.F.; García-Navarro, J. (2018) Totora (Schoenoplectus californicus (C.A. Mey.) Soják) and its potential as a construction material. *Ind. Crops Prod.* 112, 467-480. https://doi.org/10.1016/j.indcrop.2017.12.029.
15. Aza-Medina, L.C.; Palumbo, M.; Lacasta, A.M., González-Lezcano, R.A. (2023) Characterization of the thermal behavior, mechanical resistance, and reaction to fire of totora (Schoenoplectus californicus (C.A. Mey.) Sojak) panels and their potential use as a sustainable construction material. *J. Build. Eng.* 69, 105984. https://doi.org/10.1016/j.jobe.2023.105984.
16. Hýsková, P.; Gaff, M.; Hidalgo-Cordero, J.F.; Hýsek, Š. (2020) Composite materials from totora (Schoenoplectus californicus. C.A. Mey, Sojak): Is it worth it? *Compos. Struct.* 232, 111572. https://doi.org/10.1016/j.compstruct.2019.111572.
17. Ministerio del Ambiente. (2020) Plan maestro de la Reserva Nacional del Titicaca 2021-2025. SERNANP, Perú.
18. Loza-del Carpio, A.; Roque, B. (2022) Effect of prescribed burning on the nutritional value of aerial Schoenoplectus tatora stems, Lake Titicaca, Peru. *Bioagro*. 34 [3], 253-264. https://doi.org/10.51372/bioagro343.5.
19. Molina-Fuertes, J.; Horn-Mutschler, M.; Gómez-León, M. (2017) Evaluación sistemática del desempeño térmico de un módulo experimental de vivienda alto andina para lograr el confort térmico con energía solar. *Tecnia.* 30 [1], 70-79. http://doi.org/10.21754/tecnia.v30i1.841.
20. Goyzueta, G. (2009) Totorales del lago Titicaca importancia, conservación y gestión ambiental. First ed., Universidad Nacional del Altiplano de Puno, Perú. Retrieved from: https://catalogobiam.minam.gob.pe/cgi-bin/koha/opac-detail.pl?biblionumber=2059 (Accessed: May 1, 2023).
21. Hidalgo-Cordero, J.F.; Aza-Medina, L.C. (2023) Analysis of the thermal performance of elements made with totora using different production processes. *J. Build. Eng.* 65, 105777. https://doi.org/10.1016/j.jobe.2022.105777.
22. Jiménez, A.; Sathre, R.; García, J. (2016) Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resour. Conserv. Recycl*. 108, 171–181. https://doi.org/10.1016/j.resconrec.2016.01.014.
23. Lushnikova, N.; Dvorkin, L. (2016) Sustainability of gypsum products as a construction material. Sustainability of Construction Materials, Second ed., Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100370-1.00025-1.
24. Pedreño-Rojas, M.A.; Morales-Conde, M.J.; Pérez-Gálvez, F.; Rodríguez-Liñán, C. (2017) Eco-efficient acoustic and thermal conditioning using false ceiling plates made from plaster and wood waste. *J. Clean. Prod.* 166, 690–705. https://doi.org/10.1016/j.jclepro.2017.08.077.
25. Abeysiriwardena, T.; Mahendran, M. (2022) Numerical modelling and fire testing of gypsum plasterboard sheathed cold-formed steel walls. *Thin-Walled Struct.* 180, 109792. https://doi.org/10.1016/j.tws.2022.109792.
26. Guna, V.; Yadav, C.; Maithri, B.R.; Ilangovan, M.; Touchaleaume, F.; Saulnier, B.; Grohens, Y.; Reddy, N. (2021) Wool and coir fiber reinforced gypsum ceiling tiles with enhanced stability and acoustic and thermal resistance. *J. Build. Eng.* 41, 102433. https://doi.org/10.1016/j.jobe.2021.102433.
27. Rodrigo-Bravo, A.; Cuenca-Romero, L.A.; Calderón, V.; Rodríguez, Á.; Gutiérrez-González, S. (2022) Comparative Life Cycle Assessment (LCA) between standard gypsum ceiling tile and polyurethane gypsum ceiling tile. *Energy Build.* 259, 111867. https://doi.org/10.1016/j.enbuild.2022.111867.
28. Ghazi, K.; Hugi, E.; Wullschleger, L.; Frank, T. (2007) Gypsum board in fire - Modeling and experimental validation. *J. Fire Sci.* 25 [3], 267–282. https://doi.org/10.1177/0734904107072883.
29. Cámara Chilena de la Construcción. (2011) Cielos falsos: rasos y modulares, recomendaciones técnicas. Second ed., Corporación de Desarrollo Tecnológico, Chile.
30. ASTM C127-15. (2015) Standard test method for relative density (specific gravity) and absorption of coarse aggregate. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0127-15.
31. ASTM D 2017-05. (2005) Standard test method of accelerated laboratory test of natural decay resistance of woods (Withdrawn 2014) ASTM International, West Conshohocken, PA.
32. UNE-EN 350. (2017) Durabilidad de la madera y de los productos derivados de la madera. AENOR, Madrid.
33. DIN 4102-1. (1998) Fire behaviour of building materials and elements. DIN Deutsches Institut für Normung e.V., Berlin.
34. ASTM E 119-20. (2020) Standard test methods for fire tests of building construction and materials. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/E0119-20.
35. EOTA TR 001. (2003) Determination of impact resistance of panels and panel assemblies. EOTA - European Organisation for Technical Assessment, Avenue des Arts 40 Kunstlaan, Brussels.
36. Ostachuk, A.; Di Paolo, L.; Orlando, U. (2000) Una manera simple de determinar la conductividad térmica de los materiales. Retrieved from: https://www.fisicarecreativa.com/informes/infor_termo/conduc_term.pdf (Accessed: May 1, 2023).
37. Gonzáles, H.A.; Salazar, E.G.; Cabrera, C.H. (2008) Cálculo del coeficiente de reducción de ruido (NRC), de materiales, utilizando una cámara de insonorización. *Scien. Tech.* 14 [38], 119–124. Retrieved from: https://www.redalyc.org/articulo.oa?id=84903821 (Accessed: May 1, 2023).
38. Corsino, B.; Boeger, M.R.T.; Maranho, L.T. (2013) Arquitetura do escapo de Schoenoplectus californicus (C.A. Mey.) Soják (Cyperaceae) *Iher. Ser. Bot*. 68 [1], 27-35. Retrieved from: https://isb.emnuvens.com.br/iheringia/article/view/36 (Accessed: May 1, 2023).
39. Thomas, R.; Sultan, M.; Latour, J. (2005) Impact of the variability of type X gypsum board. Fire and Materials Conference. 131-137. Retrieved from: https://nrc-publications.canada.ca/eng/view/accepted/?id=adf8ff33-6f92-49ea-8956-1c37f16b06f8 (Accessed: May 1, 2023).
40. Bousshine, S.; Ouakarrouch, M.; Bybi, A.; Laaroussi, N.; Garoum, M.; Tilioua, A. (2022) Acoustical and thermal characterization of sustainable materials derived from vegetable, agricultural, and animal fibers. *Appl. Acoust*. 187, 108520. https://doi.org/10.1016/j.apacoust.2021.108520.
41. Luamkanchanaphan, T.; Chotikaprakhan, S.; Jarusombati, S. (2012) A study of physical, mechanical and thermal properties for thermal insulation from narrow-leaved cattail fibers. *APCBEE Proc.* 1, 46–52. https://doi.org/10.1016/j.apcbee.2012.03.009
42. Morales-Conde, M.J.; Rodríguez-Liñán, C.; Pedreño-Rojas, M.A. (2016) Physical and mechanical properties of wood-gypsum composites from demolition material in rehabilitation works. *Constr. Build. Mater.* 114, 6–14. https://doi.org/10.1016/j.conbuildmat.2016.03.137.
43. Rahmanian, I. (2011) Thermal and mechanical properties

of gypsum boards and their influences in fire resistance of gypsum board based systems. Ph.D. Thesis, University of Manchester, UK.

44. UNE-EN 13501-1. (2007) Clasificación en función del comportamiento frente al fuego de los productos de construcción y elementos para la edificación. Parte 1: Clasificación a partir de datos obtenidos en ensayos de reacción al fuego. AENOR, Madrid.
45. ASTM C36/C36M-03e1. (2003) Standard specification for gypsum wallboard. ASTM International, West Conshohocken, PA.
46. Castellón, F.J.; Ayala, M.; Lanzón, M. (2022) Influence of tire rubber waste on the fire behavior of gypsum coatings of construction and structural elements. *Mater. Construcc.* 72 [345], e275. https://doi.org/10.3989/mc.2022.06421.
47. Asdrubali, F.; D'Alessandro, F.; Schiavoni, S. (2015) A review of unconventional sustainable building insulation materials. *Sustain. Mater. Technol.* 4, 1–17. https://doi.org/10.1016/j.susmat.2015.05.002.
48. UNE-EN 12664. (2002) Materiales de construcción. Determinación de la resistencia térmica por el método de la placa caliente guardada y el método del medidor del flujo de calor. Productos secos y húmedos de baja y media resistencia térmica. AENOR, Madrid.
49. UNE-EN 12667. (2002) Materiales de construcción. Determinación de la resistencia térmica por el método de la placa caliente guardada y el método del medidor de flujo de calor. Productos de alta y media resistencia térmica. AENOR, Madrid.
50. UNE-EN 12939. (2001) Materiales de construcción. Determinación de la resistencia térmica por el método de la placa caliente guardada y el método del medidor del flujo de calor. Productos de espesor alto de resistencia térmica alta y media. AENOR, Madrid.
51. ASTM C518-21. (2021) Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0518-21.
52. Ouakarrouch, M.; El Azhary, K.; Laaroussi, N.; Garoum, M.; Kifani-Sahban, F. (2020) Thermal performances and environmental analysis of a new composite building material based on gypsum plaster and chicken feathers waste. *Therm. Sci. Eng. Prog.* 19, 100642. https://doi.org/10.1016/j.tsep.2020.100642.
53. UNE-EN ISO 717-1. (2013) Acústica. Evaluación del aislamiento acústico en los edificios y de los elementos de construcción. Parte 1: Aislamiento a ruido aéreo. AENOR, Madrid.
54. UNE-EN ISO 10140-1. (2016) Acústica. Medición en laboratorio del aislamiento acústico de los elementos de construcción. Parte 1: Reglas de aplicación para productos específicos. AENOR, Madrid.
55. UNE-EN ISO 10534-2. (2002) Acústica. Determinación del coeficiente de absorción acústica y de la impedancia acústica en tubos de impedancia. Parte 2: Método de la función de transferencia. AENOR, Madrid.
56. UNE-EN ISO 354. (2004) Acústica. Medición de la absorción acústica en una cámara reverberante. AENOR, Madrid.
57. ASTM C423-09. (2009) Standard test method for sound absorption and sound absorption coefficients by the reverberation room method. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0423-09.
58. Boubel, A.; Garoum, M.; Bousshine, S.; Bybi, A. (2021) Investigation of loose wood chips and sawdust as alternative sustainable sound absorber materials. *Appl. Acoust.* 172, 107639. https://doi.org/10.1016/j.apacoust.2020.107639.
59. Kłosak, A.K. (2020) Design, simulations and experimental research in the process of development of sound absorbing perforated ceiling tile. *Appl. Acoust*. 161, 107185. https://doi.org/10.1016/j.apacoust.2019.107185.
60. Maderuelo-Sanz, R.; García-Cobos, F.J.; Sánchez-Delgado, F.J.; Meneses-Rodríguez, J.M.; Mota-López, M.I. (2022) Mechanical and acoustical evaluation of bio-based composites made of cork granulates for acoustic ceiling tiles. *Mater. Construcc.* 72 [347], e295. https://doi.org/10.3989/mc.2022.15221.