



Analysis of the thermal performance of elements made with totora using different production processes

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ABSTRACT

Totora (*Schoenplectus californicus* (C.A. Mey.) Sojak) is a macrophyte that grows in lakes and ponds from California to Chile and some of the pacific islands. This plant has been used by traditional communities around the world for building a wide variety of objects, from handicrafts and mats, to boats and huts. Totora is a fast growing plant that can produce up to 50 t/ha/year, it can be harvested every 6 months, it has phytodepuration capabilities among other characteristics that make it an interesting material from a sustainable point of view. The internal structure of totora stems is made of the aerenchyma tissue, which is formed by thin cell walls that enclose air chambers. This tissue makes totora stems flexible and prevents the flood of internal organs of the plant. Because of this spongy tissue and the internal arrangement of air chambers, totora can be used as a natural thermal insulation material with low environmental impacts. In this study, the thermal performance of different elements made using totora stems with different production methods is analyzed. Thermal conductivity values vary from 0.05 W/(m.K) to 1.1 W/(m.K) depending on the density of the boards and the methods used to produce them. Totora boards made using crushed totora stems showed lower thermal conductivity than boards made with whole stems. Totora binderless boards showed higher thermal conductivity as their density increases.

1. Introduction

Construction sector is responsible for approximately 36% of the energy consumption and 37% of the greenhouse gas emissions [1]. During the use phase of the building, on average, the HVAC system is responsible for almost half of the total energy consumption [2]. This trend is expected to continue in rise due to the improvement of life standards and construction industry requirements.

Some of the most common materials used for thermal insulation in the construction industry are glass fiber, rock wool, expanded polystyrene, polyurethane foams, among others that are energy intensive and may pose some environmental concerns due to the use of oil-derived products or the use of chemical compounds in their production process [3].

In this scenario, the improvement of the thermal performance of buildings using natural materials with low environmental impacts is one of the key aspects that may help reduce the energy consumption and the carbon footprint in the construction sector [4–6].

Totora (*Schoenplectus californicus* (C.A. Mey.) Sojak) is a macrophyte that grows in lakes and ponds from California to Chile and some of the pacific islands [7]. Totora is a fast-growing plant that can produce up to 50 t/ha/year in favorable conditions, it can grow from the sea level to 4500 m above the sea level, it can be harvested every 6 months, it can be used as a phytodepuration species in artificial wetlands, among other environmentally beneficial features [8,9]. Through history, some traditional communities have used

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this plant for different applications, and have harnessed the versatility and resistance of this plant for producing a wide variety of objects. Among the traditional uses of this plant are handicraft making, mat weaving, boats and huts construction. In the case of the Uros Islands in Peru, the local communities use totora to build even the artificial floating islands where they live [7].

Anatomically, totora stems have two main parts, the pith or internal spongy part and the rind which is a harder cortex. The pith part is made of the aerenchyma tissue which is a type of parenchyma formed with thin cell walls that enclose small air chambers forming a spongy tissue inside the stems. This structure makes the stems flexible and reasonably resistant with very low bulk density, which is around 70–80 kg/m³ [9,10]. As a comparison, this density is nearly half the density of balsa wood which is around 178 kg/m³, being it one of the least dense wood species [11]. The aerenchyma tissue also helps with the flotation of the plant, the prevention of organs damage by flood, and favors the gas exchange along the stems [10]. The rind of the stems is a protective layer where most of the lignified structural fibers, and nutrient and gas exchange functions are concentrated [12]. The combination of the internal spongy pith and the harder cortex makes possible that the totora stems can reach heights of 3 m on average with a cross section of 2 cm in diameter on average, and be able to resist the bending and flexural stress generated by wind or waves [13].

The combination of an acceptable toughness, flexibility and low density of this plant has made possible its use in some demanding applications such as the traditional totora boats construction, where the totora stems are compressed to form a compact body which constitutes the hull of balsas and boats [14,15]. Some boats built with these techniques have been used in transoceanic experimental expeditions to demonstrate the seafaring capabilities of these kinds of vessels. The tested boats have withstood the wave's impacts and crew loads during these trips demonstrating the resistance that can be achieved when totora stems are tied tightly enough to form a compact body [16].

The fast growing rate, fast renovation capacity, low density, spongy internal structure and the weight-resistance relation make this material an interesting option to be studied for thermal insulation applications in the construction sector.

[17] addressed the thermal performance of traditional totora mats called “quesanas” in the Peruvian highlands, and obtained a thermal conductivity value of approximately 0.083 W/(m.K) measured in accordance with the ASTM Standard C1155–95:2013 “Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data” [18]. It is important to note that the traditional quesana is made by weaving the totora stems with a thin rope or thread. This technique leaves holes in the element through which the heat can escape. Therefore, the thermal conductivity of the final element is affected by the construction technique used to make it. Other studies conducted by Ref. [19] have addressed the feasibility of using the quesanas as thermal insulation in case studies in the Peruvian Highlands, where constructive systems using the locally produced totora mats as insulation layers on roofs and walls were tested. Although the first results showed an improvement of the thermal conditions, the values did not reach the recommended comfort levels, which in this case was considered between 8 °C and 10 °C in the coldest registered days, taking into account the adaptive comfort ranges in relation to the external temperatures [20]. In recent studies conducted by Ref. [20] some improvements were made on the same case studies addressing air tightness and increasing the materials' thickness that showed a considerable improvement of the thermal performance, which may indicate the possibility of reaching the minimum ranges of adaptive comfort, which in this case was determined between 8 °C and 10 °C, using local materials and simple construction techniques.

To optimize the thermal performance of these insulation materials, it is worth considering the methods by which the totora stems can be formed into feasible constructive elements such as boards applicable in construction as thermal insulation elements. Additionally, to reduce the possible environmental impacts of these materials the forming process should consider the reduction of certain chemicals or glues that could affect the life cycle of the final element, especially on its recyclability or end of life management. Considering that many construction materials in underdeveloped countries, where there is no recycling facilities, end up being disposed of in landfills, it is of interest to develop materials that do not generate much impact when sent to a landfill in their end of life scenario. To address the possibility of making a fully compostable material, the feasibility of using different bio-based glues such as fish glue, extracted from fish skin; sodium alginate glue, extracted from seaweed; bone glue, extracted from bone and animal tissue; and gum arabic, extracted from the sap of acacia tree was studied to produce different totora particleboards. Other studies have analyzed animal-based glues on their mechanical performance and biocompatibility [21,22]. Gum Arabic has been tested as an additive for straw bales performance enhancer, showing its compatibility with straw-like materials and its applicability in low-income countries [23]. Sodium alginate has been studied as a composite binder for bio-based insulation materials using vegetal pith, showing its suitability for this application [24].

Another production method studied was to use the different tissues of totora stems, ground to fine particles and hot-press them to produce binderless boards under conditions that promote the self-bonding of the totora particles with no additional glues.

In this study, an analysis of the thermal performance of totora boards made with bio-based glues and binderless processes is presented and discussed addressing the influence different production methods and particle types may have on the final thermal performance of these elements. The data has been collected from previous works developed by the authors [16,25], in this case focusing on the thermal performance of these materials, compiling the results into one document offering new statistical analyses and comparisons.

2. Materials

2.1. Totora stems

Stem samples were produced using totora (*Schoenoplectus californicus* (C.A. Mey.) Soják) taken from Lake Titicaca in Peru (15.9254° S, 69.3354° W) and the Paccha zone in Ecuador (2.8978° S, 78.9345° W) in 2016.

Although some studies have analyzed the morphological and chemical differences between totora stems collected from different lakes and different water quality substrates, the general structure of the plant and the configuration of its aerenchyma tissue, which is

of interest for the thermal insulation property, was not significantly influenced by their growing location [26,27]. However, a deeper study about the influence the location or substrate type may have on the chemical structure and mechanical characteristics of the plant would be of interest to determine possible effects on composite materials.

Stems were cut during the flowering season. The cut was made at 5 cm above the water level. Stems were dried using the traditional method which consists on leaving the stems spread on the ground to open-air sun drying for three months and then taken to a covered space to complete the drying process for another three months [28,29]. Raw totora stems are shown in Fig. 1.

2.2. Glues

Fish glue in powder was obtained from the provider Kremmer Pigmente under the commercial name Fischleim. The glue was prepared mixing the powder with hot water at 50%–50% proportion in weight. Once the water reached the boiling point, the glue was added and the mixture was stirred for 3 min until the complete dissolution of the glue.

Bone glue in pearls was obtained from the provider Productos de Conservación under the commercial name Cola Fuerte. The glue used was prepared mixing the pearls with hot water at 50%–50% proportion in weight. Once the water reached the boiling point, the glue was added and the mixture was stirred for 3 min until the complete dissolution of the glue.

Gum Arabic in powder was obtained from the provider Quimics Dalmau under the commercial name Goma Arábica. The glue used was prepared mixing the powder with hot water at 50%–50% proportion in weight. Once the water reached the boiling point, the glue was added and the mixture was stirred for 3 min until the complete dissolution of the glue.

Sodium alginate in powder was obtained from the provider Cargill under the commercial name Algogel. The glue was prepared using these proportions in weight: 40% of sodium alginate, 7% of calcium sulfate, and 3% of sodium citrate to control the gel setting process. Finally 50% of water at ambient temperature was added to dissolve the compounds following the process described by Ref. [24].

3. Samples production

3.1. Glued particleboards and whole stem boards production

Dry totora harvested in Peru was used to produce the particleboards at the Universitat Politècnica de Catalunya in Barcelona, using the different glues previously described, and totora particles.

Particleboards were made using ground stems sieved to different particle sizes. The stems were ground using a 50 g grinder machine of the brand Taurus. The particles were air dried before the sieving process. Particle sizes were separated using a vibrating sieve with sieves of 3.2 mm, which collected the particles greater than 3.2 mm; the 2 mm sieve where particles between 3.2 mm and 2 mm sizes were collected; the 1.19 mm sieve where the particles between 2 mm and 1.9 mm sizes were collected; and the bottom were all the particles smaller than 1.19 mm were collected. Particle types obtained are shown in (Fig. 2a).

Different proportions of bio-based glues, were added following the proportions shown in Table 1. Glue and fiber proportion percentages are calculated by mass in all cases. The mixture was then formed into a board like shape using a metallic mold with wood tops. Samples were compressed at ambient temperature using a vertical hydraulic press of the brand Sekaisa, model SKE-GN (Fig. 3a), using a pressure of approximately 0.5 kg/cm² until the desired thickness was reached, then the pressure was kept for 5 min. After this time, the samples were removed from the mold and left to dry at ambient temperature in vertical position for 48 h (Fig. 3b).

Whole stem boards with different glues were also produced in Barcelona. To produce the whole stem boards samples the rind of the stem had to be sanded to remove the waxy outer layer of the rind which prevented the glues to achieve the necessary bonding. Af-



Fig. 1. Dry totora stems.

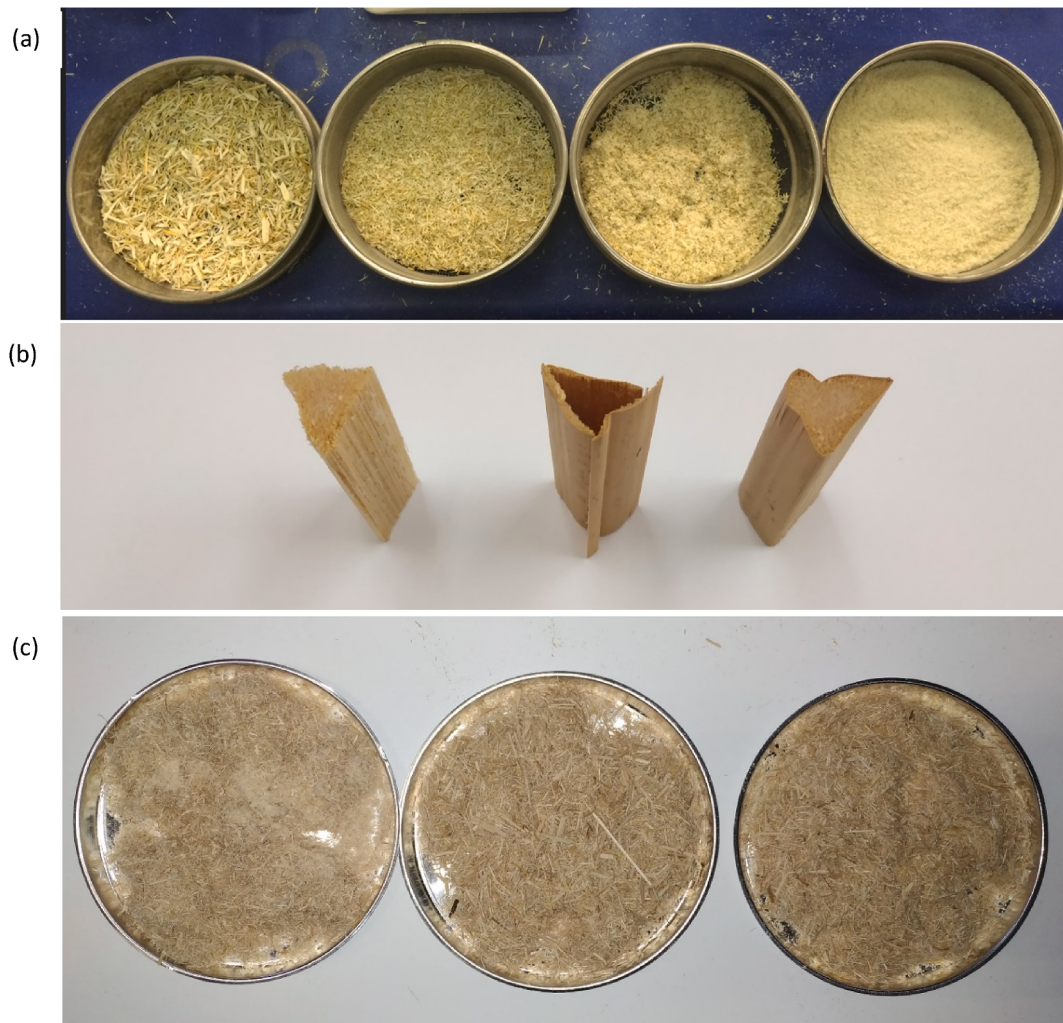


Fig. 2. (a) Whole totora stem particles 3.2 mm, 2 mm, 1.19 mm, 0 mm; (b) Peeled Pith, Separated Rind and Whole stem; (c) Pith, Rind, and Whole stem ground tissues.

ter this sanding process the stems were covered with the selected glues and then placed in layers in perpendicular directions forming a board like shape as shown in Fig. 3c. The stems were then compressed at ambient temperature using a hydraulic press of the brand Sekaisa, model SKE-GN, with a load of approximately 0.5 kg/cm^2 and was kept in the press for 5 min. Then the samples were taken out and left to dry in vertical position for 48 h.

A summary of the particleboards and whole stem boards production parameters is shown in Table 1. The reported density in this table is apparent density, which is the common reported value for construction elements.

3.2. Binderless boards production

Dry totora harvested in Ecuador was used to produce the binderless boards using different parts of the totora stems, without any glues, using only heat and pressure. These boards were produced at the Universidad Miguel Hernandez in Orihuela-Spain.

To produce these boards the different tissues of the totora stems were separated by peeling off the rind of the stems using manual tools. In Fig. 2b it can be noted that the pith tissue makes up most of the volume of the stem, while the rind is a thin cortex that surrounds the pith. The pith volume is 70% of the stem section. However, due to the low density of the aerenchyma tissue that constitutes the most part of the pith, the total weight of the pith is only 50% of the whole stem. The chemical properties of these tissues have been investigated by Ref. [9]; where it was mentioned that the pith tissue has higher cellulose concentration, while lignin and extractives such as waxes or protective substances are concentrated on the rind of the plant. These differences can be studied to use each part of the plant in the adequate applications or industries, the same way we separate the sapwood from hardwood and cortex from a wood tree to harness the best properties of each part. Pith and rind tissues separated, and a whole stem are shown in Fig. 2b.

Once the pith and rind tissues were separated, all three feedstock types namely, the pith, rind and whole stem, were ground to fine particles using a ring-knife shredding machine with a 5 mm sieve. Then the particles were sieved for 10 min using a vibrating sieve of the brand Filtra. The material used for each feedstock were the fine particles that passed through the 2 mm sieve and were retained in the bottom container. Three feedstock types were obtained namely pith, whole stem, and rind particles that are show in Fig. 2c.

Table 1
Glued boards' production parameters.

Board type	Code	Whole stem particles' sizes					Glue proportion %	Glue type	Thickness mm	Density g/cm ³
		whole stem %	> 3.20 mm %	3.20–2.00 mm %	2.00–1.19 mm %	< 1.19 mm %				
Particleboard	PB1					50	50	fish glue	18.2	0.122
Particleboard	PB2					50	50	fish glue	18.1	0.109
Particleboard	PB3					56	50	fish glue	17.0	0.149
Particleboard	PB4		50				50	fish glue	22.0	0.115
Particleboard	PB5				50		50	fish glue	18.0	0.098
Particleboard	PB6				56		50	fish glue	17.3	0.103
Particleboard	PB7			25	22	16	38	fish glue	17.8	0.098
Particleboard	PB8			16	22	25	38	fish glue	18.0	0.107
Particleboard	PB9					19	80	alginate	15.1	0.107
Particleboard	PB10					28	70	alginate	16.1	0.096
Particleboard	PB11			11	16	18	54	fish glue	18.8	0.104
Particleboard	PB12			20	18	13	54	fish glue	18.4	0.114
Particleboard	PB13					45	50	bone glue	15.4	0.171
Particleboard	PB14				50		50	bone glue	16.9	0.158
Particleboard	PB15			20	18	13	50	bone glue	16.1	0.141
Particleboard	PB16			13	18	20	50	bone glue	15.0	0.157
Particleboard	PB17					33	66	gum arabic	12.8	0.179
Particleboard	PB18					45	55	gum arabic	16.1	0.136
Particleboard	PB19					33	66	gum arabic	14.7	0.193
Particleboard	PB20					45	55	fish glue	15.0	0.217
Particleboard	PB21					45	55	bone glue	11.8	0.247
Whole stem board	WS1 95						5	fish glue	14.8	0.140
Whole stem board	WS2 95						5	bone glue	14.8	0.136
Whole stem board	WS3 93						7	bone glue	15.0	0.164
Whole stem board	WS4 97						4	fish glue	14.9	0.191

The particles were placed into molds to form a mat (Fig. 4a) that was dried to 3% of moisture content and hot pressed at 150 °C with a pressure of 30 kg/cm² for approximately 5 min. Then the press was carefully opened and the samples were left to cool down in vertical position for about 1 h (Fig. 4b).

A summary of the binderless boards' types and production parameters are shown in Table 2. The reported density in this table is apparent density, which is the common reported value for construction elements.

4. Methods

Thermal conductivity of particleboards and whole stem boards samples produced in Barcelona was measured using a Quickline-30 Thermal Parameter Analyzer equipment, made in America by Anter Corporation. The measuring probe used was the Isomet Surface Probe API 210411, suitable for samples of at least 60 mm in diameter, with a measuring range of 0.04–0.3 W/(m.K), made in Slovakia by Applied Precision, which determines the thermal conductivity by the transient hot wire principle, detecting the temperature difference on different parts of the sample's surface. This equipment is shown in Fig. 5.

The conductivity of binderless boards samples produced in Orihuela was measured using a NETZSCH Instruments, model HFM 436 Lambda equipment, made in Germany by Netzsch. This equipment measures the thermal conductivity by the Heat Flow Meter principle using a hot plate and a heat flux meter.

Statistical analyses were conducted using the IBM SPSS Statistics software, developed by IBM. The tests included correlation analysis to determine the influence the different variables may have on the conductivity of the samples. ANOVA tests and regression were used to determine the significance of different factors on the final conductivity of the samples.

Since the production method of binderless boards was fundamentally different, and the density of these samples was much higher than the density of the glued boards, the statistical analyses of the binderless samples were conducted separately. However, some discussion is presented as a results' comparison between boards of each kind. Additionally, an analysis is presented regarding the characteristics of different tissues of the stems that generate different thermal conductivity properties of the studied binderless boards, and can be applicable to produce glued boards as well.

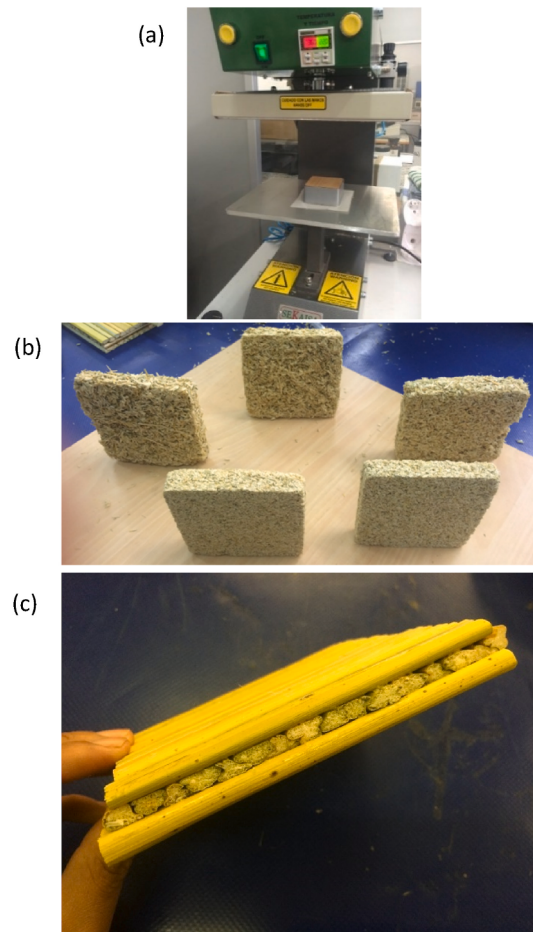


Fig. 3. (a) Press mold; (b) Totora particleboards' drying process; (c) Whole stem totora board.

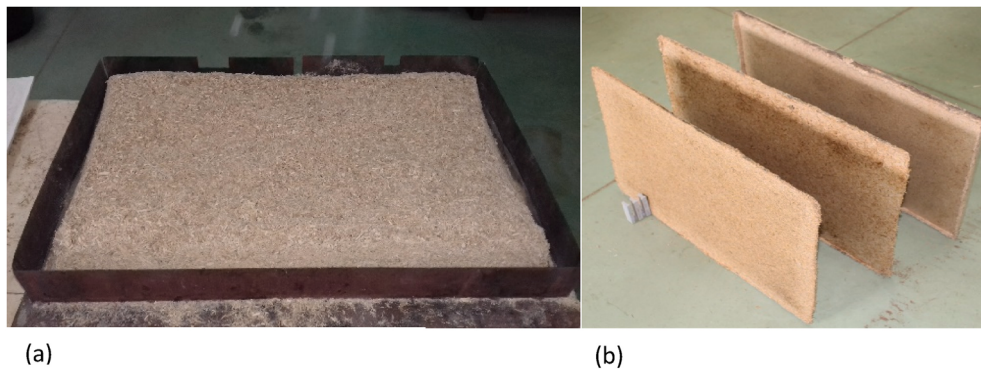


Fig. 4. (a) Totora particles mat before hot pressing; (b) Totora binderless boards drying process.

5. Results and discussion

Mean value of the thermal conductivity of glued particleboards was 0.054 W/(m.K) with a standard deviation of 0.006 . Mean value of the thermal conductivity of glued whole stem boards was 0.06 W/(m.K) with a standard deviation of 0.010 . Glued boards showed more variability in their thermal conductivity values than binderless boards, which could be because glued boards are produced with whole stems or partially shredded particles that could retain some of the plants own variability in terms of the configuration of the aerenchyma tissue, which is the characteristic that may have the higher impact on the boards' thermal conductivity. Binderless boards, on the other hand, showed higher conductivity values which is in direct relation to their higher density, which is a result of their production process. Mean value of the thermal conductivity of pith binderless boards was 0.097 W/(m.K) with a standard deviation of 0.002 . Mean value of the thermal conductivity of rind binderless boards was 0.109 W/(m.K) with a standard deviation of 0.002 .

Table 2

Binderless boards' production parameters.

Board type	Code	Particle sizes	Thickness	Density
		mm	mm	g/cm ³
Pith binderless board	BLP1	< 2.00	4,1	0,85
Pith binderless board	BLP2	< 2.00	3,8	0,87
Pith binderless board	BLP3	< 2.00	4,0	0,87
Rind binderless board	BLR1	< 2.00	4,2	1,03
Rind binderless board	BLR2	< 2.00	3,6	1,08
Rind binderless board	BLR3	< 2.00	3,8	1,07
Whole binderless board	BLW1	< 2.00	3,8	0,94
Whole binderless board	BLW2	< 2.00	4,1	0,93
Whole binderless board	BLW3	< 2.00	4,2	0,96

**Fig. 5.** Quickline-30 Thermal Parameter Analyzer with an Isomet surface probe API 210411.

tion of 0.004. Mean value of the thermal conductivity of whole stem binderless boards was 0.102 W/(m.K) with a standard deviation of 0.003. In the case of binderless boards variability is lower than glued boards because binderless boards used only one kind of tissue shredded to fine particles smaller than 2 mm, that were hot-pressed under high pressures. This process could have eliminated the natural variability of the plant's tissues, generating boards with a more uniform and compact structure than glued boards. Therefore, the thermal conductivity values of binderless boards made with one kind of tissue showed less variability. Although the equipment used to measure the thermal conductivity of glued boards made in Barcelona, and binderless boards made in Orihuela are different and use different measuring principles, it is important to mention that the samples' types in these cases are of different nature due to their production processes. Therefore, the use of different measuring equipment is not considered as detrimental to the obtained data or analyses. In Fig. 6 are shown the mean values and error bars of conductivity values of each board type.

From the results' analyses it could be observed that, as it is the case with other common insulation materials, there is a positive correlation between the density of the samples and the conductivity value [30,31]. Pearson correlation tests were conducted and determined that particleboards and whole stem boards showed a moderate correlation between density and thermal conductivity with a correlation coefficient of 0.625 with a significance determined by a p value of <0.001. Correlation graph of these two variables of particleboards and whole stem boards samples is shown in Fig. 7a. Binderless boards showed a strong correlation between density and thermal conductivity with a correlation coefficient of 0.9 and a significance determined by a p value of <0.001. Correlation graph of these two variables of binderless boards is shown in Fig. 7b. In the study conducted by Ref. [32] an initial comparison of different bio-based insulation materials is presented where this trend is detected and corroborated in its experimental tests about a hemp-lime bio-based thermal insulation material [33]. In their review article about different bio-based materials, indicate that the air contained in the sample is one significant factor for the insulation capacity of the samples. When a material is highly compressed, the internal air content is also reduced and the particles of the material have more contact area that promote the thermal transfer by contact inside the element.

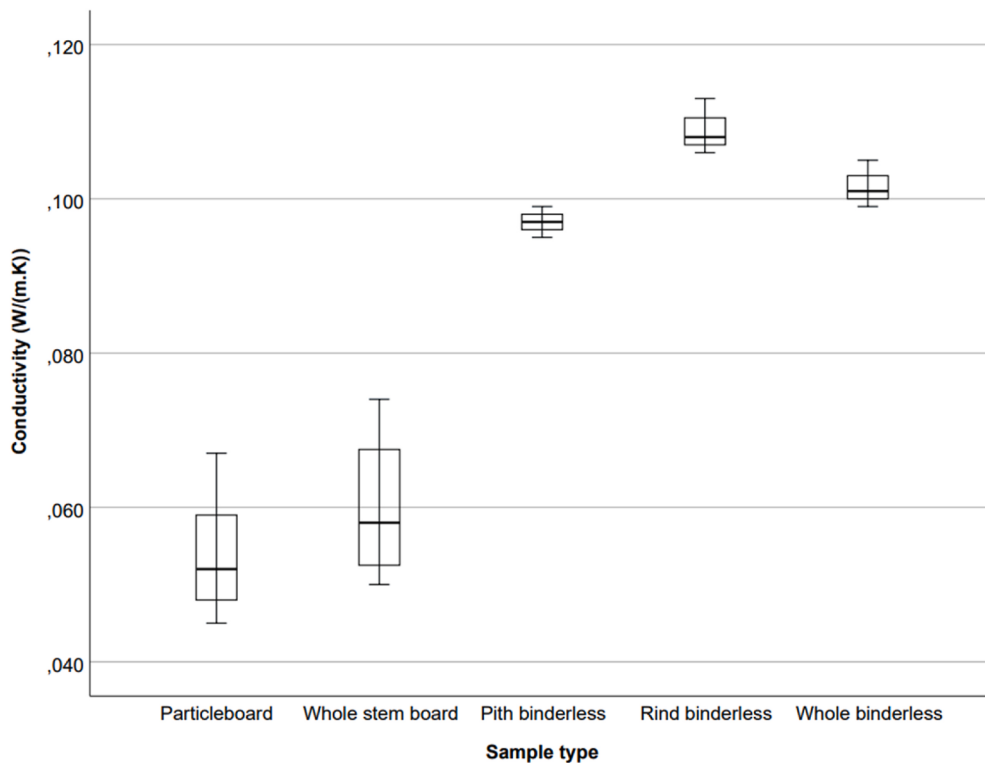


Fig. 6. Thermal conductivity values of each sample type.

It is worth noting that the glued particleboards and glued whole stem boards were produced using adhesives which does not require high pressures to achieve the bonding. This generates samples with lower density than the samples made using the binderless process, which requires smaller particle sizes, more pressure to achieve the needed contact between particles and heat to promote the release of internal compounds that promote the self-bonding and board formation. This process reduces the air contained between particles and increases the boards density [34].

In the correlation matrix obtained from the SPSS software (Fig. 8) we can observe that it is difficult to identify a clear correlation between variables and the thermal conductivity values. However, regression and ANOVA tests were conducted to analyze the possible statistical correlations and significance of each variable.

Individual tests using ANOVA or regression were conducted to identify possible correlations between variables with thermal conductivity. Thickness showed a negative correlation with a p value of 0.033, and density showed a strong positive correlation with a p value of <0.001.

Several studies have pointed out the direct correlation between the density and thermal conductivity of different materials [35,36]. On the other hand, the sample thickness, in principle should not be a significant factor of the thermal conductivity.

To confirm these correlations in a model that considers the different variables, linear regression analysis with different variables was conducted. Regression tests have been previously tried with similar compounds by Ref. [34] to determine possible correlations in a model that considers several variables. Results showed that the only significant variable in this model was the density of the samples with a p value of 0.012, while thickness was not considered significant with a p value of 0.144.

Binderless boards were analyzed using the same procedures. In the correlation matrix obtained from the SPSS software (Fig. 9) we can identify a positive correlation between density and thermal conductivity, and there could also be a correlation between the particle type and the thermal conductivity. Regression and ANOVA tests were conducted to analyze the significance of each variable.

In this case, we can observe that the density of the samples is affected by the kind of particles used for each sample. The pith tissue is much lighter and has cellular air chambers in its structure while the rind tissue is denser and more compact. Comparing binderless boards made with the different tissues it could be observed that with the same production process and parameters the pith samples have less density than the rind samples, while the boards made with the whole stem have a medium density value. ANOVA test to identify the effect of the particle type on the density of the samples showed a p value of <0.001 which confirms the significance of this factor. Regression was used to analyze the correlation between the density and the thermal conductivity of samples which showed a p value of <0.001 which indicates the significance of the correlation between density and the thermal conductivity. This correlation confirms the principle that a material that contains more air spaces in its structure will have lower thermal conductivity than a more compact one.

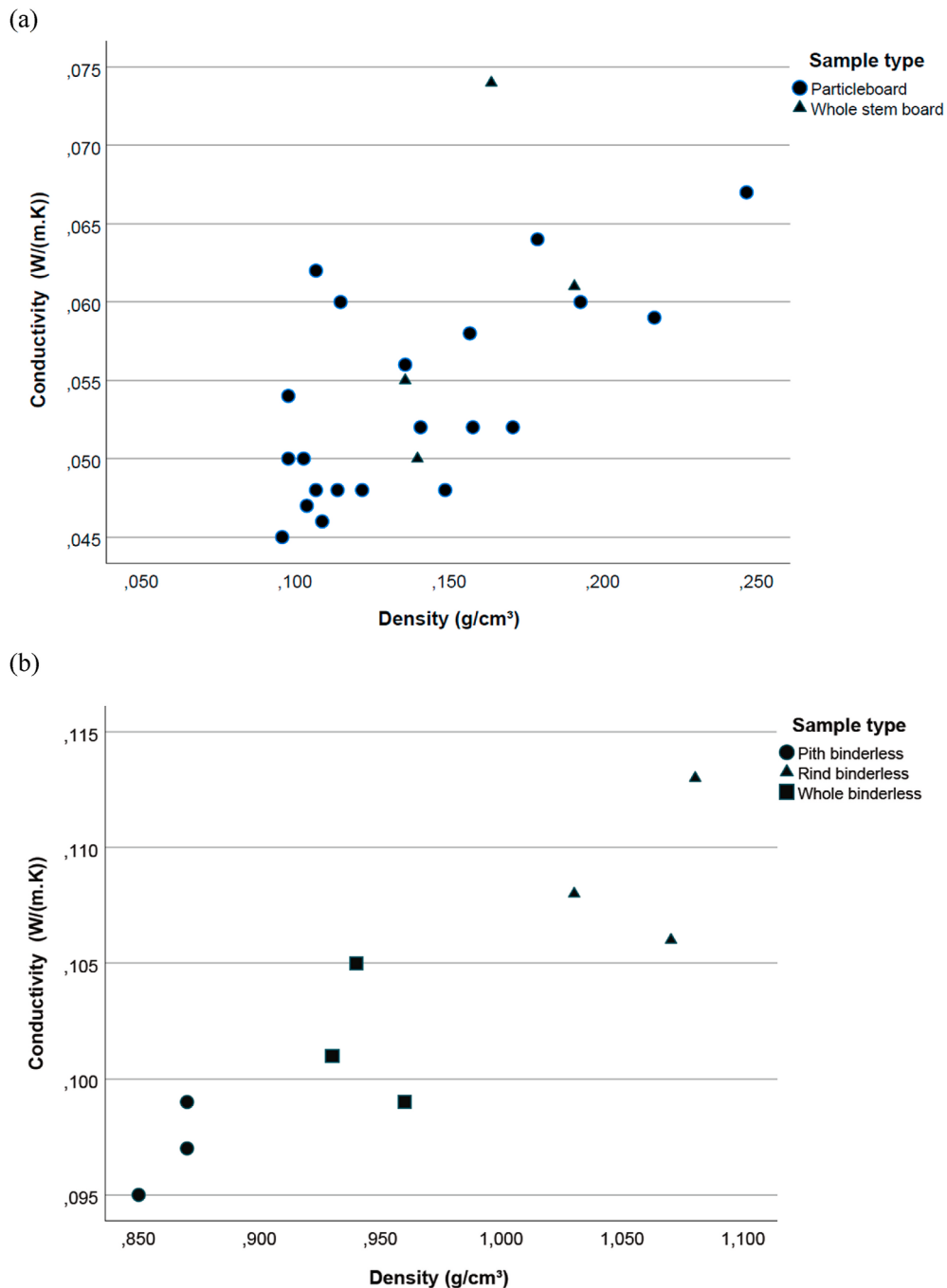


Fig. 7. (a) Totorá particleboards and whole stem boards correlation Density-Thermal Conductivity; (b) Totorá binderless boards correlation Density-Thermal Conductivity.

6. Conclusions

In this paper, different boards produced with totora stem particles and natural binders have been studied, specifically on their thermal insulation properties. Thermal conductivity values of glued boards are on average 0.057 W/(m.K) which is similar to other conventional thermal insulation materials. This may indicate that the production process that does not include a high compression of the material is suitable for producing elements that can be used as thermal insulators in the construction industry. Binderless boards showed an average thermal conductivity of 0.103 W/(m.K), which is similar to dense woods. However, the use of the pith tissue, which showed the lowest thermal conductivity values in this kind of boards, can be studied with less compression during the production process to obtain less dense boards and improve their thermal performance. The fact that these boards use only natural binders or

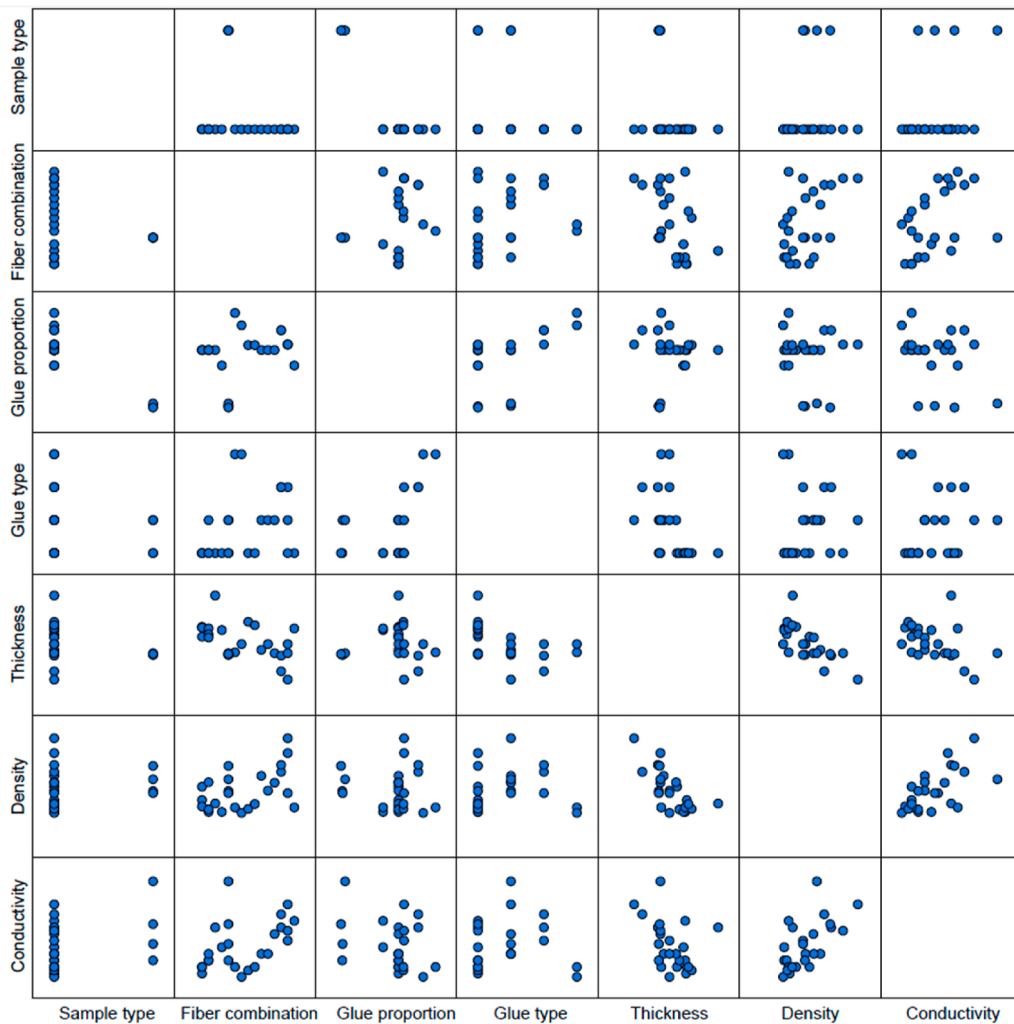


Fig. 8. Correlation matrix of thermal conductivity of particleboards and whole stem boards.

binderless processes, make them fully biodegradable, which is an interesting feature for the construction industry considering the end of life stage of building materials. Natural binders studied were obtained from animal sources in the case of fish glue and bone glue, and from vegetal sources in the case of gum arabic and sodium alginate. Binderless boards used only heat and pressure to release the natural compounds that promote the self-bonding of these boards.

From the results of glued totora boards it could be observed that:

- There was not a correlation between the glue type used in particleboards and the final thermal conductivity value.
- Samples made using full stems were the ones that used the least amount of glue. Which may indicate the possibility to save energy and glue by using full stems instead of ground stems, without affecting the final thermal conductivity of the board.
- Particleboards can be made using the waste of other industries such as handicraft production or mat weaving.

From the results of binderless totora boards it could be observed that:

- Density of these boards is higher than particleboards because of the production process that requires high pressures and temperature to achieve the self-bonding.
- Different tissues of the stem have different physical and thermal properties.
- The pith of the plant can be separated to obtain lighter elements with better thermal insulation properties.
- Rind tissue is stiffer and more resistant than pith. It can be used for other applications that require mechanical strength or plant extractives utilization.

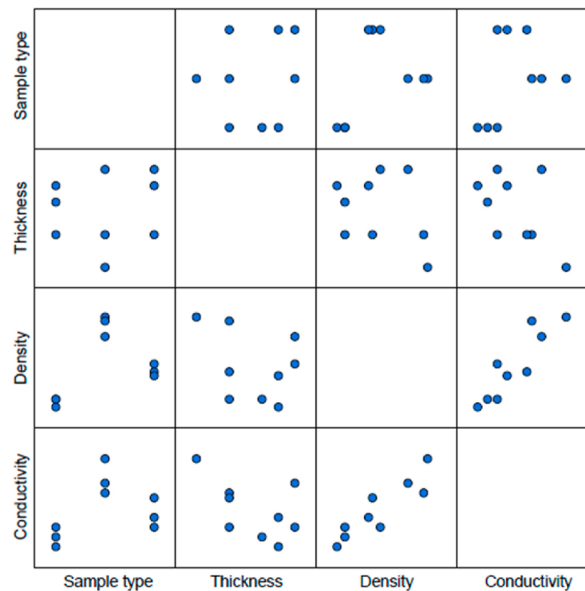


Fig. 9. Correlation matrix of thermal conductivity of binderless totora boards.

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CRediT author statement

Hidalgo-Cordero: Conceptualization, Methodology, Writing- Original draft preparation, Validation, Formal analysis, Investigation, Writing –Review & Editing, Visualization, Resources, Aza-Medina.: Conceptualization, Methodology, Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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