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Influence of Particle Size on the Properties of Boards Made from Washingtonia Palm Rachis with Citric Acid

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Abstract: The manufacture of technical materials of mineral and synthetic origin currently used for thermal insulation in buildings consumes a large amount of energy and they are not biodegradable. In order to reduce the environmental problems generated by their manufacture, an increasing amount of research is being carried out on the use of renewable and ecological resources. Consequently, the use of plant fibers and natural adhesives in the development of new thermal insulating products is increasing worldwide. Palm trees were used as a replacement for wood in some traditional constructions in places with scarce wood resources. This paper discusses the use of palm pruning waste in the manufacture of particleboards, using citric acid as a natural binder. Five particle sizes of Washingtonia palm rachis were used as the raw material for manufacturing the boards and the citric acid content was set at 10% by weight, in relation to the weight of the rachis particles. Single-layer agglomerated panels were made, applying a pressure of 2.6 MPa and a temperature of 150 °C for 7 min. Twenty panels were produced and their density, thickness swelling, water absorption, modulus of rupture, internal bonding strength and thermal conductivity properties were studied. Smaller particle size resulted in better mechanical properties. The boards had an average thermal conductivity of 0.084 W/m·K, meaning that these boards could be used for thermal insulation in buildings.

Keywords: thermal insulation; plant waste; particleboards; properties; *Washingtonia robusta* H. Wendl

1. Introduction

The growing concern to reduce energy consumption and enhance energy efficiency in buildings is increasing research to improve the thermal enclosure of buildings, in order to limit the energy required to achieve the desired thermal well-being. This is usually achieved using commercial technical materials that offer good insulating properties, including those of plastic origin (polyurethane foam, polystyrene, etc.) and mineral origin (vermiculite, rock wool, fibre glass, etc.), which not only have a high energy consumption during their manufacture, but also have the disadvantage of not being biodegradable. In order to reduce the environmental problems resulting from their manufacture, new renewable and ecological resources such as plant fibers are being sought for use as a natural insulation material for construction, because, in addition to their thermal function, they also have many other features that make them a good alternative to combat CO₂ emissions.

Palm trees were used as a replacement for wood in some traditional constructions in places with scarce wood resources. As in most Mediterranean countries, palm trees are widely used in urban landscaping in south-eastern Spain. Palm tree trunk was used in floor beams in old buildings (and it is

observed that they remain in good strong condition) and the leaves were used as a roofing material on farm buildings [1].

Washingtonia robusta H. Wendl (Washingtonia palm) is one of the most abundant species. It is a species of the family Arecaceae or Palmae that is native to the south of the Baja California Peninsula (Mexico) and its stipe reaches a height of 30 m and a diameter of 25 cm [2]. Their correct management involves pruning their old leaves (fronds) and inflorescences at least twice a year, which generates a large amount of biomass, that is disposed of in landfills or burned at the collection site [3].

The Washingtonia palm is a fast-growing species. Its management produces an average of 35.70 kg of dry mass per tree each year [4]. According to the European List of Wastes [5], this biomass is classified as urban waste. Several research studies have been carried out, focusing on the manufacture of building materials using different types of palm waste. Particleboards with different manufacturing procedures and synthetic adhesives have been studied, using fibers or chips from Washingtonia palm [4,6–9], Canary Islands palm [9–12], date palm [9,13–21] and oil palm [22–30] trees. Other works have been carried out using palm pruning waste for reinforcement in plaster [31] in concrete [32–34] and in the manufacture of different composites [31–39]. Many of these studies were aimed at using palm waste to produce thermal insulating materials [8,9,12,18,28–31,34–39]. These studies showed different results according to the species of palm tree and the part of the plant used.

Most of the adhesives currently used for wooden boards are resins that come from fossil fuel-derived materials (isocyanate, vinyl acetate and formaldehyde). Although these adhesives are economical and offer good performance, their use will be restricted in the future, because they are highly pollutant, and reserves of these non-renewable resources are in decline. This has led to a significant increase in research aimed at using natural adhesives such as lignin [40], tannins [41] and starch [42]. In recent studies, citric acid has been used as a natural adhesive for wood [43,44], giant reed [45], sorghum bagasse [46] and bamboo [47]. Citric acid is a tricarboxylic organic acid that is present in most fruits, especially in citrus fruits such as lemons, oranges and tangerines, and it is obtained in industry through the fermentation of sugars such as sucrose and glucose by a microfungus called *Aspergillus niger*. In the aforementioned works [43–47], it is stated that the binding of the particles was favored by the ester bonds formed when the hydroxyl groups of the plant fibers reacted with the carboxyl groups of the citric acid, thus improving the properties of the boards containing them.

This study analyses the physical, mechanical and thermal properties of boards made from Washingtonia palm pruning particles, using citric acid as an adhesive, with a manufacturing process that requires less energy than that used for commercial wooden boards. The aim is to obtain a new biodegradable material that can be used as a building material.

2. Materials and Methods

The materials used in this work were Washingtonia palm leaf rachis particles, water obtained from the municipal mains water supply and citric acid monohydrate purchased from the company Diasa Industrial, S.A. (Murcia, Spain), with a minimum purity of 99.5%.

The Washingtonia palm rachis was obtained from pruning operations carried out by the Higher Technical College of Orihuela at Universidad Miguel Hernández, Elche. The pruning waste was left to dry outdoors for 6 months (Figure 1). It was then shredded in a blade mill. The particles obtained were sorted into five particle sizes by a vibrating sieve. The approximate moisture content of the particles was 9%.

The manufacturing process used consisted of mixing Washingtonia palm particles with 10% by weight of citric acid (in relation to the weight of the palm particles). Then, 10% by weight of water (in relation to the palm particles) was sprayed onto the mixture, homogenizing it by stirring manually for 5 min. The boards were manufactured using a $600 \times 400 \text{ mm}^2$ mold, to which a temperature of 150°C and a pressure of 2.6 MPa were applied for 7 min in a hot plate press to obtain rigid panels of agglomerated particles. The panels were then left to cool in a vertical position. The particleboards consisted of a single layer and their approximate dimensions were $600 \times 400 \times 10 \text{ mm}^3$. Five types of

panels were manufactured according to the particle size used, the characteristics of which are shown in Table 1. Four panels of each type were manufactured.



Figure 1. Photographs of palm rachis being air dried.

Table 1. Types of board manufactured.

Type	Particle Size (mm)	Quantity g/100 g of Particles		Temperature (°C)	Pressure (MPa)	Time (min)	Number of Boards
		Citric Acid	Water				
1	<0.25	10	10	150	2.6	7	4
2	0.25 to 1						4
3	1 to 2						4
4	2 to 4						4
5	4 to 8						4

Subsequently, the samples were cut to the appropriate dimensions, as indicated in the European standards [48], in order to carry out the tests needed to characterize the mechanical, physical and thermal properties of each of the 20 boards being studied. Figure 2 shows a sample of each type of board manufactured.



Figure 2. Photograph of Samples of the 5 types of board tested.

Before testing, the samples were placed in a JP Selecta refrigerated cabinet (model Medilow-L, Barcelona, Spain), at a temperature of 20 °C for 24 h and a relative humidity of 65%.

The properties of wood particleboards were determined and evaluated by applying the current European standards [49,50]. The density [51], water absorption and thickness swelling after 2 and 24 h immersed in water [52], modulus of elasticity (MOE) and modulus of rupture (MOR) [53], internal bonding strength (IB) [54] and thermal conductivity [55] were measured.

An Imal laboratory moisture meter (model 200, Modena, Italy) was used to obtain the water content and a tank heated to a water temperature of 20 °C was used to perform the water immersion test.

The mechanical tests were performed with the Imal universal testing machine (model IB600, Modena, Italy) and the thermal conductivity tests were performed with a heat flow meter (NETZSCH Instruments Inc., Burlington, MA, USA).

SPSS v.26 software (IBM, Chicago, IL, USA) was used to perform the statistical analysis of variance (ANOVA) for a significance level of $\alpha < 0.05$.

3. Results and Discussion

3.1. Physical Properties

The density, thickness swelling and water absorption results are shown in Table 2.

Table 2. Average results of physical properties.

Type of Board	Density (kg/m ³)	TS 2 h (%)	TS 24 h (%)	WA 2 h (%)	WA 24 h (%)
1	812.20 (23.10)	16.40 (1.00)	19.60 (0.70)	56.10 (4.00)	72.20 (6.60)
2	779.40 (50.50)	22.10 (4.80)	31.40 (8.90)	58.90 (12.10)	79.40 (12.90)
3	801.30 (15.70)	34.40 (3.30)	51.00 (9.60)	87.90 (8.80)	94.30 (13.40)
4	777.70 (35.50)	38.10 (4.50)	52.60 (4.80)	91.40 (6.10)	99.30 (9.50)
5	687.10 (48.10)	48.60 (9.30)	94.10 (5.00)	99.30 (26.50)	127.50 (9.50)

TS: thickness swelling. WA: water absorption. (..): standard deviation.

The Washingtonia palm pruning particleboards were successfully manufactured, with densities ranging from 687.10 kg/m³ to 812.20 kg/m³; they can therefore be classified as medium-density boards.

As can be seen from the results in Table 2, higher densities are obtained with a smaller particle size, and this contributes to the formation of a more compact board.

The mean thickness swelling (TS) values in % after 2 h and 24 h immersed in water show that high values, between 19.60% and 94.10%, are achieved after 24 h. The mean water absorption % (WA) values indicate that Washingtonia palm rachis boards with citric acid absorb large amounts of water, and their parameters after 24 h range from 72.20% to 127.50%. Better TS and WA values are obtained in boards with smaller particle sizes.

As can be seen from the ANOVA in Table 3, all the physical properties depend on the particle size. Lower-density boards have fewer particles than other boards, which causes air spaces to form inside them, causing the particles to swell. The high values obtained for TS and WA are due to the high porosity of the board and because water-repellent chemicals were not used during the panel's manufacture. Water-repellent substances are commonly used in the manufacture of commercial wooden boards to increase their stability against water.

As shown in Table 4, the TS and WA values obtained in this work are similar to those achieved in other studies using plant fibers. In particular, the type 1 boards in this work have better TS and WA properties than most of those achieved in other research with different plant fibers.

Table 3. ANOVA of the results of the tests.

Factor	Properties	Sum of Squares	d.f.	Half Quadratic	F	Sig.
Particle size	Density (kg/m ³)	36,307.134	4	9076.784	6.233	0.004
	TS 2 h (%)	2290.956	4	572.739	27.009	0.000
	TS 24 h (%)	10,878.540	4	2719.635	27.433	0.000
	WA 2 h (%)	6227.561	4	1556.890	10.635	0.001
	WA 24 h (%)	10,307.592	4	2576.898	25.264	0.000
	MOR (N/mm ²)	329.155	4	82.289	98.983	0.000
	MOE (N/mm ²)	14,180,000.000	4	3,545,000.000	59.048	0.000
	IB (N/mm ²)	0.600	4	0.150	6.945	0.002
	Thermal C. (W/m·K)	0.001	4	0.000	14.192	0.000

d.f.: degrees of freedom. F: Fisher–Snedecor distribution. Sig.: significance.

Table 4. Thickness swelling (TS) and water absorption (WA) values obtained with plant fiber boards.

Name	TS 24 h (%)	WA 24 h (%)	Source
Date palm	32.0	61.3	[9]
Canary Islands palm	38.2	71.2	[9]
Oil palm	20.0	70.5	[23]
Tobacco straw	22.0	-	[55]
Cotton stalks	24.0	93.6	[56]
Sunflower stalk	25.0	95.0	[57]
Cotton carpel	26.0	153	[58]
Wheatgrass	41.7	-	[59]
Vine prunings	25.8	65.6	[60]
Washingtonia palm	38.3	72.7	[9]
	19.6	72.2	This work (type 1)

3.2. Mechanical Properties

According to the European standards [54], the minimum requirements for general use in dry conditions are an MOR value of 10.5 N/mm² and an IB value of 0.28 N/mm² (Grade P1). An MOR value of 11.0 N/mm², an MOE value of 1800 N/mm² and an IB value of 0.40 N/mm² are the minimum requirements for furniture manufacturing (Grade P2). For load-bearing boards (Grade P3), the MOR, MOE and IB values are 15.0 N/mm², 2050 N/mm² and 0.45 N/mm², respectively.

The best mechanical performance (Table 5) is achieved with the smallest particle size (type 1 board), with a MOR of 12.5 N/mm², a MOE of 2640 N/mm² and an IB of 0.60 N/mm².

Table 5. Mean values of mechanical and thermal properties.

Type of Board	MOR (N/mm ²)	MOE (N/mm ²)	IB (N/mm ²)	Thermal Conductivity (W/m·K)
1	12.5 (0.4)	2640 (276)	0.60 (0.06)	0.089 (0.003)
2	12.01 (1.4)	1860 (385)	0.30 (0.24)	0.086 (0.004)
3	7.36 (0.8)	1240 (150)	0.14 (0.08)	0.082 (0.003)
4	3.71 (1.0)	675 (72)	0.15 (0.06)	0.080 (0.003)
5	2.77 (0.30)	445 (54)	0.14 (0.09)	0.079 (0.001)

MOR: modulus of rupture. MOE: modulus of elasticity. IB: internal bonding strength. (..): standard deviation.

As shown in Table 6, the type 1 board could be classified as P2. It cannot be classified as P3, because it does not reach the required minimum TS 24 h value, so it would be advisable to use some kind of water-repellent product, such as those used in the wood industry, in order to achieve this classification. The type 2 board could be classified as Grade P1 for general use. All the mechanical properties depend on the particle size (Table 3).

Table 6. Characteristics of type 1 and 2 boards and classification according to the European regulations [47].

Type of Board	MOR (N/mm ²)	MOE (N/mm ²)	IB (N/mm ²)	TS 24 h (%)
1	12.5	2640	0.60	19.6
2	12.1	1860	0.30	31.4
Grade P1	10.5	-	0.28	-
Grade P2	11.0	1800	0.40	-
Grade P3	15.0	2050	0.45	17.0

According to the analysis carried out by several investigators [21,61], one of the most important factors when manufacturing boards is the particle size, reaching similar conclusions to this work, where the best mechanical properties are achieved with a smaller particle size.

While Pintiaux et al. [62] state that high temperatures, above 180 °C, are needed to manufacture plant fiber boards with other ecological adhesives (tannins, lignin, etc.), the Washingtonia palm rachis particleboards produced in this work were manufactured with citric acid at a temperature of 150 °C and could be used as stipulated in the specifications of the European standards [50].

The addition of citric acid favors the binding of the particles and this may be due to the chemical reaction between the carboxyl groups of the citric acid and the hydroxyl groups of the Washingtonia palm. Thus, the more particles the board contains, the better its mechanical properties will be. Table 5 shows that there is a considerable difference between the MOE and MOR values obtained, and this result can be explained by the fact that the greater the number of particles (smaller particles), the higher the density. Likewise, the boards with a lower density have more pores, so there is a lower particle content to resist stress.

3.3. Thermal Conductivity

The results of the conductivity tests are shown in Table 5, offering mean values ranging from 0.079 to 0.089 W/m·K, so all the boards could be used as a thermal insulating material. These values depend on the particle size (Table 3).

Increasing the density increases the thermal conductivity. Therefore, lower-density boards achieve better thermal performance, which could be explained by the greater air content inside the board. Table 7 shows the average thermal conductivity value achieved by the boards manufactured and those made from other types of plant and wood fibers used as insulating materials in construction. The thermal conductivity value was similar to that obtained for plant fibers, with a density that lies within the range of densities obtained in this study, and slightly higher than that of kenaf, flax, cotton and hemp, although these materials have no mechanical strength, so they can only be used as a filler or if coated with other stronger materials.

The boards produced in this work have better thermal performance than those achieved with commercial wood particleboards that are manufactured using urea formaldehyde as an adhesive, although the use of this adhesive is increasingly limited due to the environmental problems it causes. Furthermore, more energy is used during the shredding process, since the trunk of a tree species is more difficult to shred than the rachis of the Washingtonia palm tree and, having shredded the material in this study, it did not undergo a drying process. Finally, the pressing temperature used to manufacture industrial boards (180 °C) is higher than the temperature used to produce the boards of this work (150 °C).

The esterification that occurs during the board production process [43] may be the cause of the citric acid performing well as an adhesive, since it has been observed in this work that the palm rachis particles are bonded. However, further investigation into the behaviour of this adhesive will be required, in order to improve the properties of the boards.

Table 7. Thermal conductivity of different materials.

Name	Density (kg/m ³)	Thermal Conductivity λ (W/m K)	Source
Hemp	5–100	0.040 to 0.094	[63]
Flax	5–100	0.038 to 0.075	[63]
Cotton	150–300	0.059 to 0.074	[64]
Kenaf	150–250	0.051 to 0.058	[65]
Sugarcane bagasse	350–500	0.079 to 0.098	[43]
Rice Straw	980–1148	0.076 to 0.091	[66]
	300	0.070	[67]
Wood particleboards	600	0.120	[67]
	900	0.180	[67]
Washingtonia palm rachis	687.10–812.20	0.079 to 0.089	This work

4. Conclusions

In this paper, the mechanical, physical and thermal properties of particleboards made from Washingtonia palm (*Washingtonia robusta* H. Wendl) rachis have been analyzed, concluding that, by using a manufacturing process with a low pressing temperature, it is possible to manufacture particleboards from biodegradable materials. This particleboard could replace traditional wood materials used in construction, contributing to a reduction in deforestation.

All the properties analyzed—density, TS, WA, MOR, MOE, IB and thermal conductivity—depend on the particle size used. Smaller particle sizes should be used to obtain stronger boards, while larger particle sizes should be used to achieve boards that offer better thermal performance. Therefore, two- or three-layer boards should be tested in future studies, to try to combine both applications.

Type 1 boards can be classified as Grade P2 (non-structural boards for indoor use) and have good thermal performance, so that they could be used as interior enclosures in buildings (vertical and horizontal) without the need for coatings. In future research, some kind of water-repellent product could be added or a composition could be sought to achieve boards with appropriate properties for outdoor use.

Using Washingtonia palm pruning waste to manufacture hard-wearing materials such as particleboards could be beneficial to the environment, as it helps reduce air pollution and it reduces the amount of waste that ends up in landfills.

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