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INVESTIGACIÓN

Homogenization Analysis in Particle Boards with Rice Husk Reinforcement

Análisis de homogenización en paneles aglomerados con refuerzo de cascarilla de arroz

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Abstract

Objective: To morphologically analyze, by means of scanning electron microscopy (SEM), agglomerated boards made from rice husk and Hidropul 400, as well as boards made from wood fibers and glue.

Methodology: For each 7,3 x 3,6 x 1,5 cm test piece, two samples were taken from the external and internal sections of each one of the boards to be analyzed. Thin-layer graphite coatings were made to each one of them, and, by means of SEM, micrographic shots were obtained in the range from 50x to 2000x.

Results: It was evidenced that the panel made from rice husk had damage to its internal structure due to its porosity, the waxy layers of its coating, the high presence of silica, and the presence of water inside the adhesive, showing irregularities in adhesion between particles and low mechanical properties.

Conclusions: Although the studied rice husk panel did not achieve the adequate structural properties, it has great applications for interior design. Additionally, due to its porous structure, its potential as a sound-absorbing material is considered. In the same way, the material can be improved by pre-treating the husk or combining it with other, more woody plant fibers such as wood waste, bamboo, coconut fiber, among others.

Keywords: SEM, agglomerate, husk, rice, homogenization, particle board

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Resumen

Objetivo: Analizar morfológicamente, por medio microscopía electrónica de barrido (SEM), tableros aglomerados elaborados con cascarilla de arroz e Hidropul 400, así como tableros elaborados a partir de las virutas de madera y pegamento.
Metodología: Para cada cada probeta de 7,3 x 3,6 x 1,5 cm, se tomaron dos muestras en las secciones externas e internas de cada uno de los paneles a analizar. Se realizaron recubrimientos de capa fina de grafito a cada una de ellas y, mediante SEM, se realizaron tomas micrográficas en rangos de 50x a 2000x.
Resultados: Se evidenció que el panel fabricado con cascarilla de arroz presentaba afectaciones en su estructura interna debido a la porosidad, las capas cerosas de su recubrimiento, la alta presencia de sílice y la presencia de agua dentro del adhesivo, mostrando irregularidades en adherencia entre partículas y bajas propiedades mecánicas.
Conclusiones: Aunque el panel a base de cascarilla de arroz estudiado no obtuvo las propiedades estructurales adecuadas, tiene grandes aplicaciones para el diseño de interiores. Además, por su estructura porosa, se considera su potencial como material absorbente del sonido. De igual forma, se puede mejorar el material al hacer un pretratamiento de la cascarilla o combinarla con diferentes fibras vegetales más leñosas como desperdicios de madera, bambú, fibra de coco, entre otros.

Palabras clave: SEM, aglomerado, cascarilla, arroz, homogenización, tablero de partículas

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INTRODUCTION

Currently, population growth and the need to satisfy its subsequent demand generates an overexploitation of natural resources while waste production increases. In this context, one of the most demanded natural resources is wood. The excessive use of this resource has caused deforestation, soil erosion, and a drop in biodiversity, which has awakened the interest of the scientific community for implementing new materials that replace the use of wood, thus encouraging the use of natural organic matter or agricultural waste.

Colombia, due to its great biodiversity and agriculture, possesses several organic materials based on vegetal fibers such as cotton, sugarcane, fique, banana, yute, palm, and guadua, as well as a wide range of residues from wheat, rice, peanut, coconut, corn, and coffee, among others. Therefore, this country has great potential for generating high value-added products that would allow profiting and achieving significant biotechnological developments.

There are several studies at the national level based on the exploitation of these raw materials. For example, Álvarez *et al.,* 2007 analyzed the influence of a pre-treatment with banana fiber coming from the central leaf vein with the purpose of developing composed materials. Through physical-mechanical tests and SEM analyses, it was found that free radicals were generated on the surface of the lignin and that they were coupled during the high-temperature pressing process, thus generating polymerization or crosslinking, which improves material properties. Vargas-Ortiz, 2015 studied the physical and mechanical properties of Chontaduro palm fibers to determine the viability of their use as an alternative material for civil works construction, concluding that they have a great potential as reinforcement of composed polymeric-matrix and cementile materials. Cuéllar & Muñoz, 2010 studied the effect of *Guadua angustifolia* fiber with and without chemical treatment, employing sodium hydroxide over the mechanical properties of a polymeric matrix reinforced with 10 and 20 % in weight of fiber, thus concluding that it represents a viable alternative as a potential reinforcement material for polymeric matrixes.

Regarding agricultural waste, there are numerous studies that could be applied as large-scale technologies in the future. For example, Coral, 2019 made normal-concrete specimens with the addition of coffee husk vegetal fiber as a replacement for thick aggregates, which achieved a good resistance for non-structural elements. Furthermore, Segura, 2019 fabricated ceiling panels reinforced with peanut husk and eggshells. This study concluded that these panels slow down heat transference, so they contribute to maintaining rooms warm.

Colombia ranks 21^{st} in the world in the production of rice, considering that it is a fundamental product in the domestic consumption of the country (Becerra *et al.,* 2018). According to DANE and Fedearroz, rice production in Colombia is around 2.000.000 tons per year, and 400.000 of them correspond to rice husk residues, which are not used properly (Fedearroz, 2018). These residues are generally used as fuel to be burned in grain drying processes, and commercialized for use in aviculture, gardening activities, among others. Therefore, given the biomass available in the country, there is currently an insufficient capacity for the total consumption of this product.

In Colombia, research on the use of agricultural residues as reinforcement of the polymeric matrix on composed materials has been focused on the physical and mechanical properties of rice husk. As an example, Serrano *et al.,* 2012 used rice husk with and without pretreatments to manufacture light mortars, finding that, due to the morphology and water absorption of rice husk, the elaboration of composites based on it requires the addition of tensoactive substances to the mixture. These mortars reached densities in the range of 1,1-1,3 g/cm^3, with mechanical resistances between 2 and 4 MPa, which led to conclude that they do not have the mechanical properties of traditional mortars and concretes, although they can still be utilized as light construction components. Proaños & Sandoval, 2010 manufactured compression-resistant acoustic panels made of rice husk, cement, and sand. They established the technical feasibility of rice husk as an insulating material, given its ability to reduce sound. These panels constitute an alternative for users with fewer resources in the acoustic insulation of homes. Gutiérrez-M.D. *et al.,* 2014 treated rice husk using starches to obtain a material with adequate physical stability, without affecting its insulating capacity. They found that the composed material shows a good resistance to bending. Bedoya-Hincapié *et al.,* 2009 developed the prototype of an agglomerated composed material based on products from the coffee axis (Colombia), such as rice husk, clay, sand, and aloe gel, thus establishing that its mechanical and thermal properties are close to those of Sajo, Ciprés, Machare, or Nogal Cafetero woods; the agglomerated material showed a modulus of elasticity similar to those of the aforementioned wood species.

Although there are several studies that characterize physical and mechanical properties, there are very few that have thoroughly analyzed the distribution, homogenization, and internal structure of the particles and fibers within these materials, as well as their interaction with different adhesives and binders used in chipboard manufacturing. Analysis through homogenization allows identifying the properties of composed materials that cannot be determined by mechanical tests, since it is necessary to observe the behavior of the materials within their structure by using different technologies such as optical microscopy, scanning electron microscopy, and other advanced methods that include X-ray spectrometry and confocal scanning (Alemdar *et al.,* 2008,Badel *et al.,* 2008).

Some international researchers, such as (Kurokochi & Sato, 2015a), have analyzed the internal structure of rice husk panels, mainly finding that their porous structure drastically affects its strength due to the presence of trichomes and silica protuberances, as well as a thin layer of wax that prevents the particles from making contact with each other. (Hwa-Hyoung & Kie-Sun, 200) found that the elaboration of a composed board with husk reinforcement required eliminating the trichomes and silica to achieve a significant increase in its mechanical properties. Their research evinced that the panel contained less lignocellulosic materials and more ashes and extracts with lighter-than-wood molecular weights. Its hollow structure also affected the non-uniform resin distribution, thus resulting in a disrupted glue line between the particles (Zhang *et al.,* 2011). The high content of ashes, mainly silica, also contributed to the non-uniform resin distribution (Hiziroglu & Suzuki, 2007). Due to this porous structure, panels composed of rice husk and sawdust are considered for their potential as sound-absorbing materials (Kang *et al.,* 2012).

In light of the above, the purpose of this research is to analyze homogenization through scanning electron microscopy (SEM), as well as to acquire data on the typology of external and internal surfaces, weave organization, and particle distribution of a board manufactured from rice husk and Hidropul water-based binder. A comparison with a traditional wood-based board is made, highlighting main differences and similarities contributing to accept or improve the studied material.

METHODOLOGY

Materials

For the homogenization analysis, two types of boards with adhesive resins were selected: one made from rice husk and the other from wood fibers. These boards were of medium density. The rice husk board was manufactured from a fine selection of particles coming from the mills and processing plants of the municipality of Espinal, Tolima, Colombia. The selected residue was free of impurities, with an average size of 4 to 12 mm. The binder used was Hidropul 400 HTR (water-based polyurethane glue) plus a vulcanizing agent (AQ212 Polyisocyanate) for wood obtained from the Pegaucho S. A. company (Alféres-Rivas, 2017). Table 1 presents the physical and mechanical properties of the board agglomerated from rice husk.

For the agglomerated board made from wood fibers and adhesive resin, the manufacturer Celulosa Arauco S. A. was selected. This panel is of general use in dry environments, with physical properties that meet the MDF standard. Table 2 presents the physical and mechanical properties of the wood fiber agglomerated board.

Table 1. Technical sheet for the rice husk agglomerated board

<table>
<tr><th colspan="4">TECHNICAL SPECIFICATIONS</th></tr>
<tr><th>PRODUCT</th><th colspan="3">DIMENSIONS</th></tr>
<tr><td rowspan="5">RICE HUSK PARTICLEBOARD-HIDROPUL-400HTR</td><td>THICKNESS(mm)</td><td>LENGTH(m)</td><td>WIDTH(m)</td></tr>
<tr><td>15</td><td>2,44</td><td>1,83</td></tr>
<tr><td colspan="3">TOLERANCES</td></tr>
<tr><td>THICKNESS(mm)</td><td>LENGTH(mm)</td><td>WIDTH(mm)</td></tr>
<tr><td>+/- 0,2</td><td>+/- 2</td><td>+/- 2</td></tr>
<tr><th colspan="4">PHYSICAL MECHANICAL PROPERTIES</th></tr>
<tr><th>PROPERTY</th><th>UNIT</th><th colspan="2">VALUE</th></tr>
<tr><td>Density</td><td>Kg/m^3</td><td colspan="2">649,3</td></tr>
<tr><td>Internal Bond</td><td>N/mm^2</td><td colspan="2">0,7</td></tr>
<tr><td>M.O.E</td><td>N/mm^2</td><td colspan="2">2.140,8</td></tr>
<tr><td>M.O.R</td><td>N/mm^2</td><td colspan="2">15,67</td></tr>
<tr><td>Edge</td><td>N</td><td colspan="2">1.033,97</td></tr>
<tr><td>Side</td><td>N</td><td colspan="2">1.447,95</td></tr>
</table>

Source: Authors.

Table 2. Technical sheet for the commercial agglomerated fiber board (MDF-Arauco)

TECHNICAL SPECIFICATIONS			
PRODUCT	**DIMENSIONS**		
ARAUCO STANDARD MDF- ADHESIVE RESIN	THICKNESS(mm)	LENGTH(m)	WIDTH(m)
	15	2,44	1,83
	TOLERANCES		
	THICKNESS(mm)	LENGTH(mm)	WIDTH(mm)
	+/- 0.2	+/- 2	+/- 2
PHYSICAL MECHANICAL PROPERTIES			
PROPERTY	**UNIT**	**VALUE**	
Density	Kg/m^3	680	
Internal Bond	N/mm^2	0,7	
M.O.E	N/mm^2	2.400	
M.O.R	N/mm^2	28	
Swelling	%	<11	
Edge(N)	Kg	>85	
Side(N)	kg	>105	

Source: Authors.

From the selection of agglomerated boards, as well as from the technical information supplied by the manufacturers, the homogenization analysis of agglomerated particles was performed.

Morphology (SEM)

Observations were conducted on the probe specimens of both board types using a FEI QUANTA 200 scanning electron microscope property of Universidad Nacional de Colombia, Bogotá branch. Two samples were taken from each panel, corresponding to the internal and external surfaces of the material, which allowed understanding the morphology and homogenization of the particles. The samples were subjected to a thin layer coating of graphite approximately 0,1 mm thick in order to achieve current conductivity between them. The SEM images were analyzed on various scales in a range from 50x to 2000x. The equipment was calibrated for 50x to 2,00 mm, and for 2000x to 50 μm.

Results

Morphological analysis of the rice husk and Hydropul 400 panel (external section)

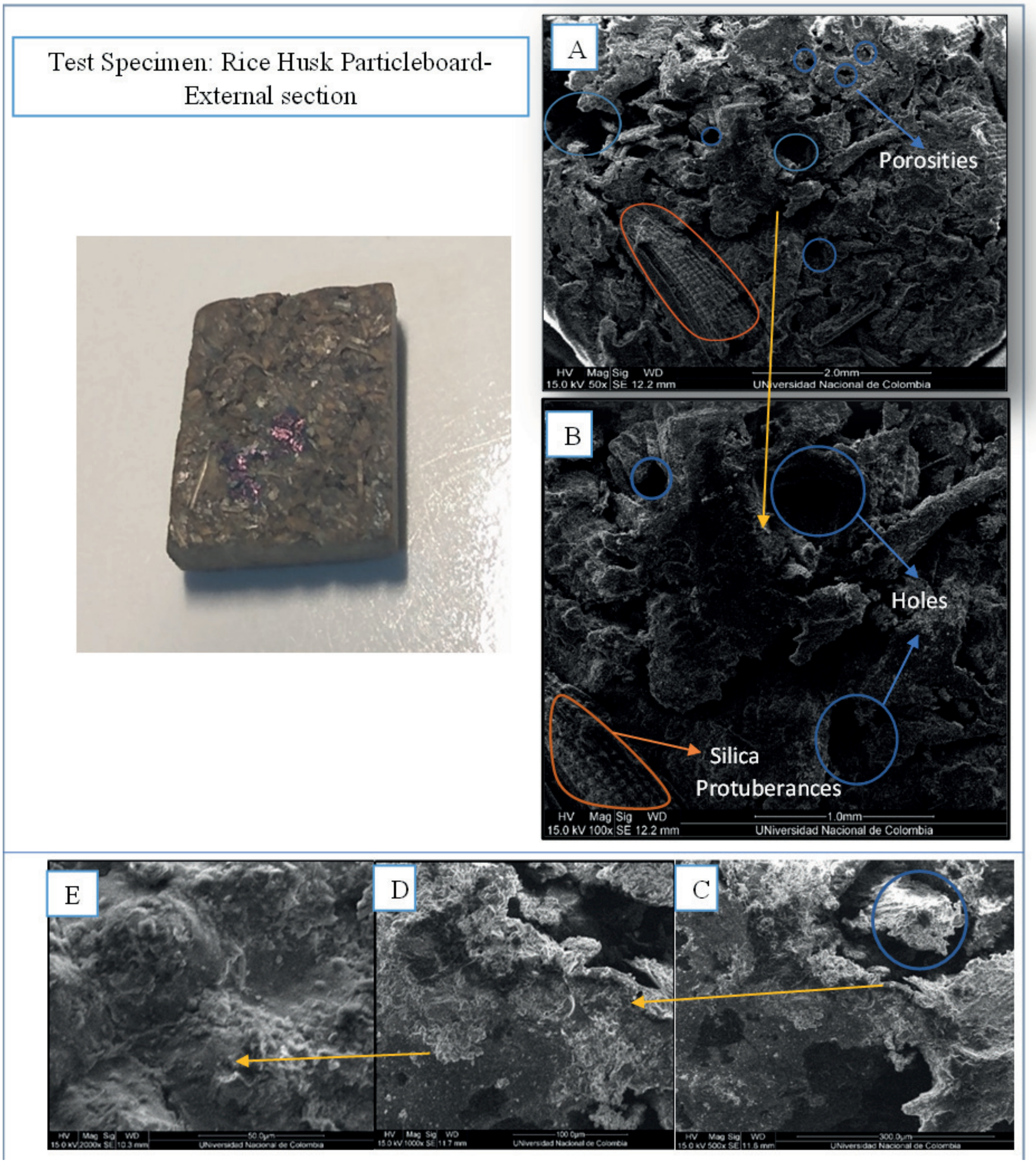

Figure 1. SEM micrographs of the external section of the rice husk + Hidropul 400 panel Magnification: A (50x, 2 mm); B (100x, 1 mm); C (500x, 300 μm); D (1000x, 100 μm); E (2000x, 50 μm)

Source: Authors.

Figure 1 shows the morphological state of the external section of the panel. The probe specimen was brought to dimensions of 11 x 8 x 4 mm. The micrographs were taken from the upper face of the specimen. Figure 1a presents the structure from a general perspective, and Figure 1b is a detail of 1a at a 100x larger scale and shows a uniform dense mass throughout the structure, with some holes due to the fact that the rice husk did not completely cover the spaces during hot pressing. Likewise, in the lower zone of the Figure, it is possible to see the rice husk abaxial or the external surface of the exocarp, which is characterized by a symmetrical structure constituted by convex cells, separated by furrows, and grains composed of silicon that are dispersed over the entire surface (Arcos *et al.,* 2007). Although porosities are observed within the structure, the sample externally presents a good packing of the particles.

In Figures 1c, d, and e, observations were made on the same sample, but with larger scales. Figure 1c was taken at a 500X scale with a calibration of 300 µm. The inner portion of this Figure (indicated inside the circle) corresponds to the section of pressed husk covered with adhesive (Hidropul 400), and the white phase corresponds to adhesive extending along the ends of the irregular surface. Finally, the dark-colored phases correspond to the rice husk particles.

In Figure 1d, a portion of 1c is observed with a scale of 1000x, presenting the same characteristics. As for Figure 1e, in which the magnification is 2000x, dome-shaped protrusions are observed, which correspond to the silica from the shell covered by uniformly dispersed adhesive with micro-cracks in its grooves. This characteristic may be present when the used adhesive ages.

Morphological analysis of the rice husk and Hidropul 400 panel (internal section)

Figure 2 presents the morphological state of the internal section of the panel; it is the SEM micrograph of the panel's structure, which is obtained at a depth of 5 millimeters from the outer surface. Figure 2a shows porosities because the shell was not properly packed during hot pressing. Some of these holes (yellow circles) tend to be characterized by having smooth inner surfaces, which, in this case, corresponds to bubbles (Serrano *et al.,* 2012). These could be formed by the mixture of adhesive (Hidropul 400) and the vulcanizing agent.

The internal agglomeration shows a non-homogeneus particle distribution due to the large number of irregularities and structures that collapsed under heat and pressure during pressing. de Barros Filho *et al.,* 2011 argue that the number of collapsed thin-walled fibers depends on the degree of damage caused by hot pressing, which could lead to more intimate contacts between fiber and matrix. This results in a better union and compaction in between fibers. Moreover, the collapse of the cell walls can cause more mechanical damage, such as a reduction in the rupture modulus and, in some cases, an increase in the thickness of the agglomerated piece.

Figures 2b, c, d, and e correspond to the internal samples of the test probe. These shots were taken at larger scales (100x, 500x, 1000x and 2000x, respectively). In Figure 2b, porosities that can be produced by a poor bond between particles and adhesives are observed. Likewise, the distribution

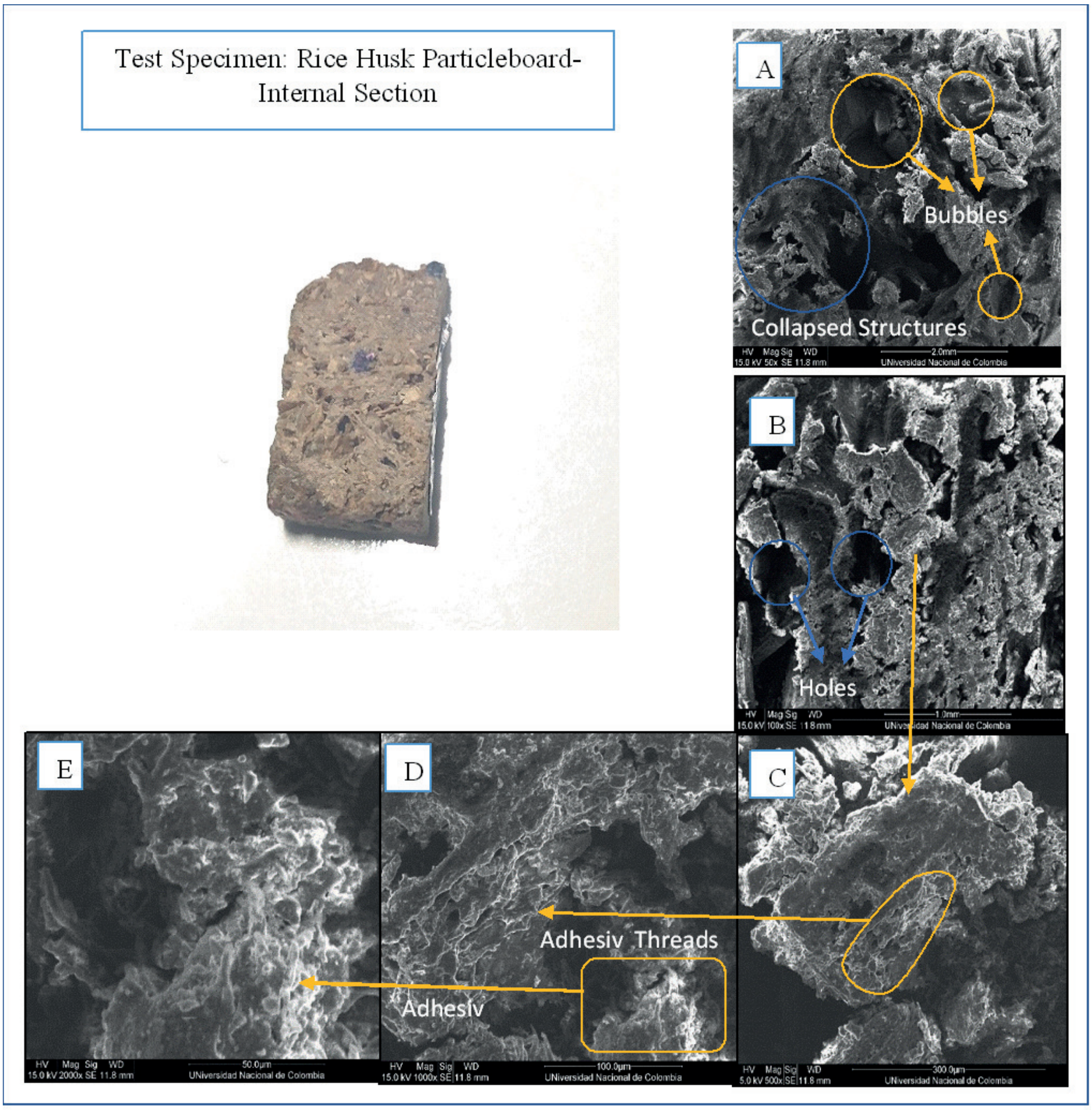

Figure 2. SEM Micrographs of the internal section of the rice husk + Hidropul 400 panel Magnification: A (50x, 2 mm); B (100x, 1 mm); C (500x, 300 μm); D (1000x, 100 μm); E (2000x, 50 μm)

Source: Authors.

of the adhesive throughout the surface (white phase) can be seen in less detail. It was also present in a greater proportion, tending to agglutinate at the edges of the surface of the compressed husk flakes.

Figure 2c presents a detailed view of a portion of Figure 2b, where the surface of the pressed husk fibers is shown with a high concentration of adhesive at their ends. This due to the fact that the adhesive penetrated mainly between the fiber walls' regions and irregularities. In wood agglomerates, the penetration of the adhesive between cell walls and intermolecular spaces is important since it invol-

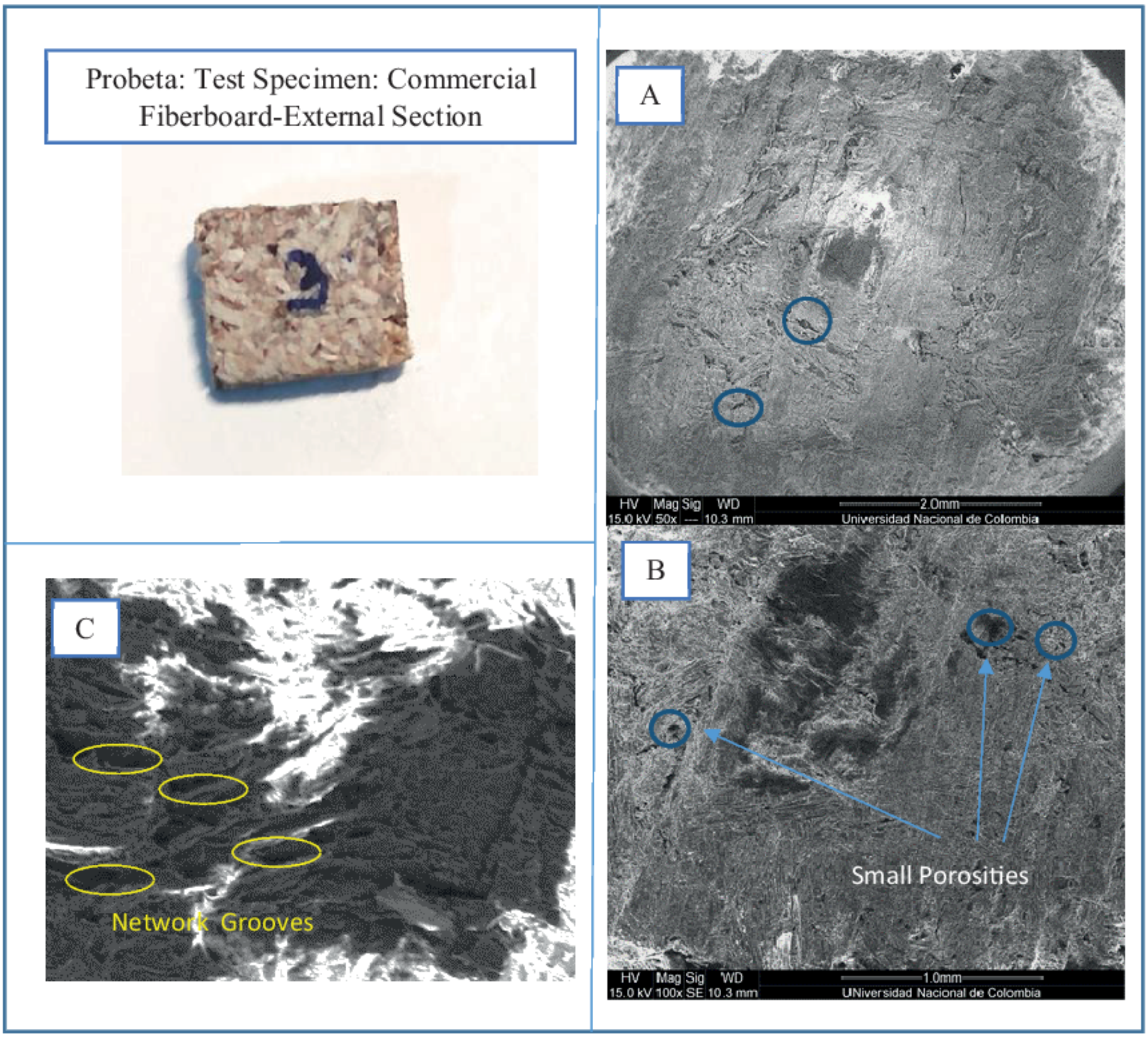

Figure 3. SEM micrographs of the external section of the commercial agglomerated panel Magnification: A (50x, 2 mm); B (100x, 1 mm); C (500x, 300 μm)

Source: Authors.

ves both physical and chemical bonds, which strengthens the adhesive bond (Singh *et al.*, 2015). For this reason, the possibility of this same behavior for the rice husk particle board could be evaluated.

Figure 2d refers to 2c with a 1000x scale, which allows the detailed visualization of the cavities and porosities present in the sample, clearly showing the layers of rice husk and adhesive, which were applied simultaneously, one on top of another. Therefore, through hot pressing, its final sandwich structure (Figure 2c) managed to form a better bond with the rice husk fiber, as well as a uniform distribution in ad hesive threads. The manufactured sandwich structure, using compression molding techniques, allows the fabricated material to be lightweight with practical mechanical properties (Li *et al.*, 2010).

Figure 2e presents a portion of 2c at a scale of 2000x, in which the binder impregnated in the husk nanoparticles is visualized at a higher concentration, due to penetration and absorption into the irregular parts and walls. As explained in Figure 2b, there is better wetting in the fibers by the adhesive, observing a tendency towards heterogeneous distribution as a consequence of a higher binder content in this section.

Morphological analysis of commercial fiberboard (MDF-Arauco) (external section)

Figure 3 shows the external section of the commercial fiberboard, with sample dimensions 10 x 9 x 4 mm. Figures 3a and b show very good homogenization and distribution of particles with very small porosities on the surface and only a few roughnesses, thus allowing the visualization of a good compaction technique. Surface characteristics in terms of roughness play an important role in determining product quality of commercial MDF. The degree of surface roughness depends on the characteristics of the raw material, such as species, particle size, fiber distribution; as well as on manufacturing variables, including pressing parameters, resin content, and other processes (Hiziroglu & Suzuki, 2007). This shows the high-quality standards with which the panel was manufactured.

In Figure 3c (500x scale), the porosities become more evident, although they remain generally small and of homogeneous size. Moreover, cell walls are distinguished between wood fibers, forming elongated grooves that establish a network of wood fibers oriented in the direction of the cavities between cell walls. (Sliseris *et al.,* 2016) state that a slight difference in the orientation of fiber can significantly affect the mechanical properties of MDF, so it is concluded that the panel shows good properties if oriented in a single direction.

Morphological analysis of commercial Fiberboard (MDF-Arauco) (internal section)

Figure 4 corresponds to the sample from the internal structure of the commercial agglomerated fiberboard, with a depth of 5 mm from the external surface. Figure 4a shows an almost compact structure, which contributes to a homogeneous distribution and a better interfacial bond, thus improving the mechanical properties of the material (Madyan *et al.,* 2020). Although valleys are observed on the surface, they are due to the geometry formed between fibers. As for the porosities, given their size, they are almost imperceptible at this scale.

In Figure 4b, due to the increase in scale (100x), the valleys, as well as some porosities observed in 4a, become more evident. In the same way, the cell walls can be seen in more detail, with large volume that is slightly collapsed. This contributes to the good resistance of the wood particles against pressing, thus obtaining good flexural properties (de Barros Filho *et al.,* 2011). In another zone of this micrograph, the wood is seen to take the form of threads (gray circle). These are a result of the detachment of particles when taking the sample from the original test piece, which means that they are very well embedded into the matrix of the agglomerated panel. As for the adhesive, the resin is

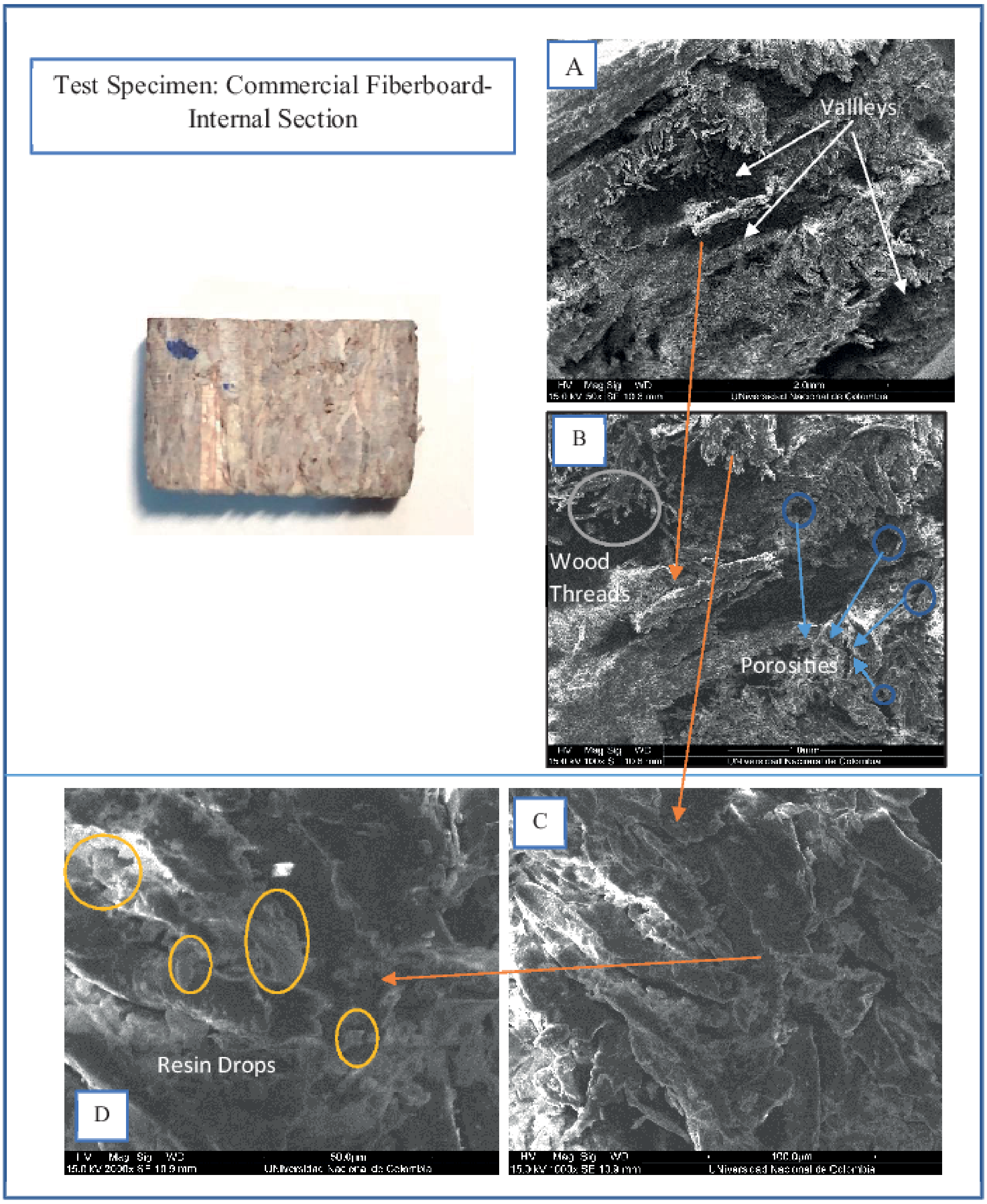

Figure 4. SEM micrographs of the internal section of the commercial agglomerated panel Magnification: A (50x, 2 mm); B (100x, 1 mm); C (1000x, 100 μm); D (2000x, 50 μm)

Source: Authors.

detailed as the bright spots that are distributed at a greater concentration at the ends of the chips, particles, and cracks. However, in general terms, they are equally dispersed throughout the entire surface of the sample.

Figure 4c shows the zoned detail of 4b (a part of a chipped surface), clearly distinguishing thin and long wood chips with good contact between them. The adhesive is distinguished by its white phase at its ends, covering the spaces between particles. The formation of interlocking networks by the particles can be observed. In general, the amount of adhesive distributes equally without excessive concentrations.

Figure 4d shows the drops of adhesive in more detail, concentrated mainly in the cracks between chips, with flat and cylindrical shapes of equal size and small and thin particles in a lower proportion, where the adhesive tends to concentrate in larger quantities. According to previous research, fine particles tend to absorb much of the resin in the particleboard (Evans *et al.,* 2010).

Discussion

By comparing the external section of both materials on the same scales (50x and 100x), it was determined that the commercial fiberboard presented a surface without holes and small porosities, whereas the rice husk particleboard showed greater irregularities, holes, and large porosities. It should be noted that both materials were manufactured in specialized plants for the manufacture of MDF. Therefore, they were subjected to high manufacturing standards. For Abdul Khalil *et al.,* 2010 and Fiorelli *et al.,* 2019, a greater contact between fibers during hot pressing reduces the content of holes and porosities, thus yielding a higher material density. This is why, when reviewing the corresponding technical sheets of the commercial and rice husk boards, densities of 680 and 649 kg/m^3 are found, respectively. This suggests a relationship between the resulting imperfections of the rice husk board and its low density. According to the literature, this is due to the silica in the form of grains (as observed in Figure 1b) and a thin layer of wax, which prevent penetration of the adhesive (Hidropul 400) to bind with the hydroxyl groups of cellulose present in the husk (Cheng *et al.,* 2004, El-Kassas & Mourad, 2013, Zheng *et al.,* 2009).

Regarding the external distribution of the adhesive, the large amount of Hidropul 400 resin (white phase in Figure 1c) used in the rice husk board becomes evident when comparing the two materials, since no adhesive resin is observed at the same scale (500x) in the commercial board; a closer approach (1000x) to its internal part is therefore necessary to observe resin particles. For this reason, it was determined that the amount of adhesive in the husk board is greater than in the commercial one. Therefore, a greater amount of resin is needed for adequate penetration between particles, since mechanical properties improve by increasing the levels of adhesive (Ye *et al.,* 2007). However, rice particleboards do not have commercial acceptance due to the substantially higher amounts of adhesive required to acquire acceptable properties (Kwon *et al.,* 2013).

The homogenization and distribution of particles on the external surface of the commercial board is superior to that of the rice husk. This is due to the fact that it shows a strong and well-organized fiber network structure, unlike the rice husk, represented only by a compact mass. The reason for this is the size of the wood fibers, which are finer and lengthier than rice particles (Kang *et al.,* 2012). According to (Battegazzore *et al.,* 2018), fiber boards have proved to be more rigid than particleboards, thus indicating their ability to maintain more than three times the load. This means that the shape of the raw material affects its mechanical properties.

The internal section of the rice husk panel is more irregular than its surface, as it has a large number of holes and larger porosities. Likewise, the commercial panel has a different internal structure since it is more compact and less fibrous than on its external side. However, the large amounts of internal imperfections present in the rice husk panel are due to the silica and wax present in the husk, thus causing the adhesion between particles to be poorer internally than externally. This is because, internally, there are more layers of husk. Moreover, at the time of hot pressing, the press acts directly over the panel's surface, making the adhesion better on the surface. The size of the holes present is due to the fact that the rice particles, being wider, form holes of greater dimensions than those formed by the wood fibers (Kang *et al.,* 2012).

Wood and rice husk, as well as other plant fiber materials, are considered lignocellulosic materials, which consist mainly of three chemical components: cellulose, hemicellulose, and lignin. They are responsible for the mechanical, structural, and durability behavior, thus giving good resistance, rigidity, and stability to the fiber (Sánchez *et al.,* 2017). A high content of these components has desirable properties for use as reinforcement in composite materials (Bogoeva-Gaceva *et al.,* 2007). As the amounts of cellulose and lignin are lower in husk than in wood, they make the rice board supports lower pressure at the moment of hot pressing. Consequently, the fiber walls collapse in a greater degree than rice husk. This is due to its non-homogeneous structure, as discussed in the results section. It is important to mention that, due to their porous structure, particleboards that comprise only rice husk have 1/3 of the strength of wood-based particleboards (Kang *et al.,* 2012).

Internally, at scales of 1000x and 2000x, the distribution of adhesives in both materials could be observed in more detail, where the wood-based panel obtained a better distribution of resin without excessive concentrations and in the form of drops, unlike the adhesive (Hidropul), which tended to agglutinate in great quantities on the irregularities of the cell walls of the husk. Therefore, a large mass of glue was observed, due to the large amount of adhesive used. Additionally, a greater number of voids and porosities causes a greater consumption of adhesive, which consequently restricts adequate contact between particles with lower IB (internal bond) (Klímek *et al.,* 2017). It is worth noting that water-based adhesives such as Hidropul 400 decrease wettability by interacting with the thin waxy layer, thus influencing the quality of the bond (Kwon *et al.,* 2013). According to Li *et al.,* 2010, oil-based adhesives such as diphenylmethane diisocyanate (MDI) or polymeric diphenylmethane diisocyanate (PMDI) are generally used to make high-quality straw-based particleboards.

As discussed above, the low properties of the board are evident judging from the homogenization and SEM structural analyses, which is complemented by the values found in the main mechanical tests of each material listed in the technical sheets (Tables 1 and 2), when comparing the rice husk boards with the traditional wood boards. Regarding their MOE (moudulus of elasticity), values of

2.141 and 2.400 N/mm^2 were obtained. In the same way, when comparing their MOR (modulus of rupture), resistances of 28 and 15,67 N/mm^2 were obtained, respectively. The low resistance to rupture of the husk board was made evident, which is why it is not recommended for use as construction material that supports structural compression loads. The porous structure present within the particleboard presents sound absorbing characteristics. Uses for this material could be valued in wall cladding, ceiling panels, or other settings that require sound absorption properties, but do not require robust mechanical properties, as well as other non-structural applications such as furniture and interior accessories (Kang *et al.,* 2012).

Regarding the improvement of the studied rice husk board, and based on previous research, husk pretreatments are said to decrease the amount of silica and eliminate the wax layer. These include heat treatment, steam explosion (Ndazi *et al.,* 2007), acid or alkali treatment (Ajiwe *et al.,* 1998), and the combination of alkaline treatments with hydrogen peroxide or bleaching (Salam *et al.,* 2007, Wójciak *et al.,* 2007). However, in these studies, although the properties of rice husk increased, they did not reach the potential of wood-based boards after treatment. Additionally, there is still a high adhesive addition (Li *et al.,* 2013, Zhang & Hu, 2014). It is also possible to improve the material by combining it with more woody fibers such as wood, bamboo, coconut fiber, and other residues (Hiziroglu & Suzuki, 2007, Yang *et al.,* 2003, Zhang & Hu, 2014). All of these works concluded that they could be used as structural materials when they acquire the same capacities as commercial panels, since few amounts of resin are required. Another recent study suggests the manufacture of panels without binders by hot pressing, where the silica trichomes were removed by a very fine grinding, and the wax was removed by extraction with organic solvents. However, these panels did not meet the technical specifications of MDF (Kurokochi & Sato, 2015b). In light of the above, for future research, it is suggested that several of these techniques be combined for the improvement of the studied material.

Conclusions

The board made from rice husk particles and Hidropul 400 HTR showed a low resistance in comparison with wood-fiber boards. This is due to its porous structure and its low bonding strength between particles, as well as to the silica and waxy layer present in the material.

The large amount of porosities influenced the low density of the rice husk board and, therefore, its low properties.

The rice husk particleboard used a higher amount of water-based adhesive compared to the commercial fiberboard, thus clumping mostly in its irregularities. However, this was not enough, as it did not completely cover the holes.

The packing and distribution of particles was better in the wood-based panel than in the husk one, due to the shape of its lengthier and thinner fibers, which formed well-established networks. Furthermore, its higher content of cellulose and lignin gives the fiber strength and rigidity to withstand greater pressure during the hot pressing procedure and avoid the collapse of its cell walls. The rice husk panel lacked these properties.

The use of a water-based adhesives such as Hidropul 400 HTR prevents penetration by interacting with the waxy layer of the rice husk, which is why, to improve the material, the use of an oil-based binder for the manufacturing of agglomerated rice husk panels is recommended for future research.

Although the studied rice husk board did not achieve adequate resistance properties for working as a structural material, it has great applications for interior design, due to its acoustic absorption and its low weight. Furthermore, because it was manufactured from small particles in a specialized plant, it has a great surface finish.

For the improvement of the studied rice husk panel, some of the different techniques evaluated for the pretreatment of rice husk can be implemented to eliminate the silica grains and wax, in combination with other types of natural fibers that contain larger amounts of lignin and cellulose such as bamboo, coconut fiber, and other residues, in addition to the use of equipment for the manufacturing of MDF in specialized plants, thus acquiring the properties of traditional fiberboards.

These results were obtained by performing homogenization analysis by means of SEM micrographs in combination with information from the literature. They are consistent with the properties found quantitatively in the different mechanical tests, which makes these types of analysis helpful when observing the structural behavior of any material.

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