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GUILHERME HENRIQUE AMENT BARBIRATO

Sandwich panel of oriented particles with unconventional and waste materials
Painel sanduíche de partículas orientadas com materiais não convencionais e residuais

Pirassununga
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“O destino é uma questão de escolha.”

Augusto Cury

ABSTRACT

BARBIRATO, G. H. A. **Sandwich panel of oriented particles with unconventional and waste materials.** 2022. 105 f. Tese de Doutorado – Faculdade de Zootecnia e Engenharia de Alimentos, Universidade de São Paulo, Pirassununga, 2022.

The development of materials using forest biomass by-products makes it possible to replace conventional materials, adds value to the raw material, and contributes to the sector's circular economy. A sustainable alternative for these residues would be to transform them into panels of reconstituted forest biomass. In this scope, the present research aimed to optimize the content of castor oil polyurethane resin (PU-Castor) for OSB (Oriented Strand Board) panels made of reforestation wood waste and bamboo and to study the mechanical performance of OSB sandwich panels with flat faces and cores. trapezoidal with application bias as a structural component. The study was designed in 3 stages, namely: 1- optimization of the content of castor oil polyurethane resin for flat OSB panels made of reforestation wood waste and bamboo; 2- development and performance evaluation of OSB sandwich panel with trapezoidal core and flat faces; 3- Analysis of critical regions and faults of OSB sandwich panel specimens. The results obtained in the first stage indicated that the bamboo OSB panels with 8% resin content reached the minimum requirements recommended by the European standard EN 300:2006, for type 1 OSB panels (general use in a dry environment). Panels with a content of 10% met the minimum requirements for type 3 (structural purposes in a humid environment) and panels with a content of 12 and 15% met the normative requirements for OSB panels of type 4 (special structural purposes in a humid environment). On the other hand, for the OSB panels made of reforestation wood waste, only the panels with contents of 10 and 12% reached the minimum normative recommendations for OSB type 2 panels (structural purposes in a dry environment). In the second stage, the OSB sandwich panel presented greater rigidity of the set and lower specific weight and, consequently, a mechanical performance that enables its application as a structural component. In accordance with the recommendations presented by APA-PS 2-10, the OSB sandwich panel can be used in structural, flooring, and ceiling applications. In the third stage, the OSB sandwich panel presented failure regions in the glue line, between the core and the external face, and also, in the external faces with propagation to the core region.

Keywords: OSB. Wood Waste. Bamboo. Castor oil polyurethane resin. Trapezoidal core. Structural Component.

RESUMO

BARBIRATO, G. H. A. **Painel sanduíche de partículas orientadas com materiais não convencionais e residuais.** 2022. 105 f. Tese de Doutorado – Faculdade de Zootecnia e Engenharia de Alimentos, Universidade de São Paulo, Pirassununga, 2022.

O desenvolvimento de materiais utilizando subprodutos da biomassa florestal possibilita a substituição de materiais convencionais, agrega valor à matéria prima e contribui com a economia circular do setor. Uma alternativa sustentável para esses resíduos seria transformá-los em painéis de biomassa florestal reconstituída. Nesse escopo, a presente pesquisa teve como objetivo otimizar o teor de resina poliuretana à base de óleo de mamona (PU-Mamona) para painéis OSB (Oriented Strand Board) de madeira residual de reflorestamento e bambu e estudar o desempenho mecânico de painéis OSB sanduíche com faces planas e núcleo trapezoidal com viés de aplicação como componente estrutural. O estudo foi delineado em 3 etapas, a saber: 1- otimização do teor de resina poliuretana à base de óleo de mamona para painéis OSB planos de madeira residual de reflorestamento e bambu; 2- desenvolvimento e avaliação de desempenho de painel OSB sanduíche com núcleo trapezoidal e faces planas; 3- Análise das regiões críticas e de falhas de corpos de prova de painel OSB sanduíche. Os resultados obtidos na primeira etapa indicaram que os painéis OSB de bambu com 8% de teor de resina atingiram os requisitos mínimos recomendados pela norma europeia EN 300:2006, para painéis OSB do tipo 1 (usos gerais em ambiente seco). Os painéis com teores de 10% atingiram os requisitos mínimos para tipo 3 (fins estruturais em ambiente úmido) e os painéis com teores de 12 e 15% atingiram os requisitos normativos para painéis OSB do tipo 4 (fins estruturais especiais em ambiente úmido). Já, para os painéis OSB de madeira residual de reflorestamento, apenas os painéis com teores de 10 e 12% atingiram as recomendações mínimas normativas para painéis OSB tipo 2 (fins estruturais em ambiente seco). Na segunda etapa, o painel sanduíche OSB apresentou maior rigidez do conjunto e menor peso específico e consequentemente, um desempenho mecânico que viabiliza sua aplicação como componente estrutural. De acordo com as recomendações apresentadas pela APA-PS 2-10, o painel OSB sanduíche pode ser utilizado em aplicações estruturais, pisos e forros. Na Terceira etapa, o painel OSB sanduíche apresentou regiões de falhas na linha de cola, entre o núcleo e a face externa, e também, nas faces externas com propagação para a região do núcleo.

Palavras-chave: OSB. Madeira residual. Bambu. Resina Poliuretana à Base de óleo de mamona. Núcleo trapezoidal. Componente estrutural.

FIGURE LIST

TABLE LIST

LIST OF PUBLICATIONS RELATED TO THE DOCTORATE THESIS

Published papers in peer-reviewed journals:

BARBIRATO, G. H. A.; GAUSS, C.; LOPES JUNIOR, W. E.; MARTINS, R.; FIORELLI, J. Optimization of castor oil polyurethane resin content of OSB panel made of Dendrocalamus asper bamboo. Ciência Florestal, Santa Maria, v. 32, n. 1, p. 187-205, 2022. DOI 10.5902/1980509846908. Available from: https://doi.org/10.5902/1980509846908.

BARBIRATO, G. H. A. *et al*. Sandwich OSB Trapezoidal Core Panel with Balsa Wood Waste. Waste Biomass Valor 13, 2183–2194 (2022). https://doi.org/10.1007/s12649-021-01660-2

BARBIRATO, G. H. A.; LOPES JUNIOR, W. E.; MARTINS, R. H. B.; SORIANO, J.; FIORELLI, J. Experimental evaluation and numerical modeling of the mechanical performance of OSB sandwich panels manufactured with trapezoidal core, Construction and Building Materials, 326, 126721, 2022.
https://doi.org/10.1016/j.conbuildmat.2022.126721.

Papers submitted/under submission for publication:

BARBIRATO, G. H. A.; LOPES JUNIOR, W. E.; MARTINS, R. H. B.; FIORELLI, J. Evaluation of OSB panels using wood waste with different contents of castor oil polyurethane resin-based.

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1 CHAPTER 1 – Introduction

1.1 Contextualization

In Brazil, Eucalyptus and Pinus wood from planted forests is currently the main source of raw material for the reconstituted wood panel industry. Although the initial purpose of the first particleboard industries in the world was the use of residual forest biomass, in the country, this practice has not yet been implemented on an industrial scale, being restricted to a few academic works carried out on a laboratory scale. However, it is known that the panel industry has the potential to use these wastes, since it is characterized by the high generation of these by-products in its production chain.

There are several categories of engineered wood panels, one of which is OSB (Oriented Strand Board) oriented particle board. Among the main possibilities of using these panels, structural applications can be highlighted, such as: horizontal and vertical sealing in civil construction and pallet components used in the storage of products. Some other structural applications are suitable for OSB panels such as walls, ceiling and floor supports, structural beam components, furniture structure and packaging.

However, commercial OSB panels are produced with polymeric matrices, such as urea-formaldehyde and phenol-formaldehyde, which release formaldehyde into the environment during production and throughout their shelf life. Formaldehyde is a colorless gas, with a strong odor, high chemical reactivity and soluble in water, which causes irritation to the eyes, skin and respiratory tract.

There is a worldwide trend that aims to preserve the environment and ecosystems, preserving these sources for future generations. In the meantime, there is the use of biodegradable, non-polluting products that also originate from residual inputs. The polyurethane resin derived from castor oil, classified as impermeable and which has the characteristic of being non-aggressive to the environment and to humans, follows this line of conduct and has been a promising alternative to replace the adhesives used commercially.

In this era of industrialization, the selection of materials is mainly based on price and the type of facility found for their production or processing, and the lack of technical information makes consumers use industrialized materials. Like Balsa wood wastes and bamboo is a fast-growing material and can play an important role in changing the current way of managing natural resources.

Most research has been based on the evaluation of flat OSB panels with particles agglomerated with organic adhesive. Recent studies have developed sandwich panels composed of a three-dimensional hollow core creating high-performance panels. This new geometry (trapezoidal core) creates a more stiffness, strength product with a lower specific weight, being the differential for products with a view to application in civil construction. The faces have the function of withstanding tensile, compression and shear stresses in bending, since the core must be rigid enough in the direction perpendicular to the faces to avoid crushing. Construction systems that use sandwich panels provide thermal and acoustic insulation and enable lighter constructions and faster execution compared to conventional masonry constructions.

1.2 Motivation

Therefore, the present research project presents as a novelty the use of unconventional raw materials (Waste from reforestation of Balsa wood and Bamboo) for the production of flat OSB panels and trapezoidal core sandwiches agglomerated with two-component polyurethane resin based on castor oil (PU – Castor Oil) and the application of this sandwich panel as a constructive element for internal sealing systems.

Within this context, the problem to be addressed in this research project refers to overcoming the inherent deficiencies of the raw material (such as selection and morphological characteristics), adaptation/optimization of processing parameters (pressure, temperature and time pressing) and final product design (mechanical properties) of trapezoidal core sandwich OSB panel bonded with organic matrix for use as a sealing component.

In order to carry out a bibliographic survey in the Scopus and Web of Science databases, to obtain information regarding the scientific advance over the last four decades on the subject of oriented particle boards (OSB panel) and from which moment they began to appear researchers with Balsa wood and Bamboo as raw material for the production of these flat and three-dimensional (3D) or corrugated core panels.

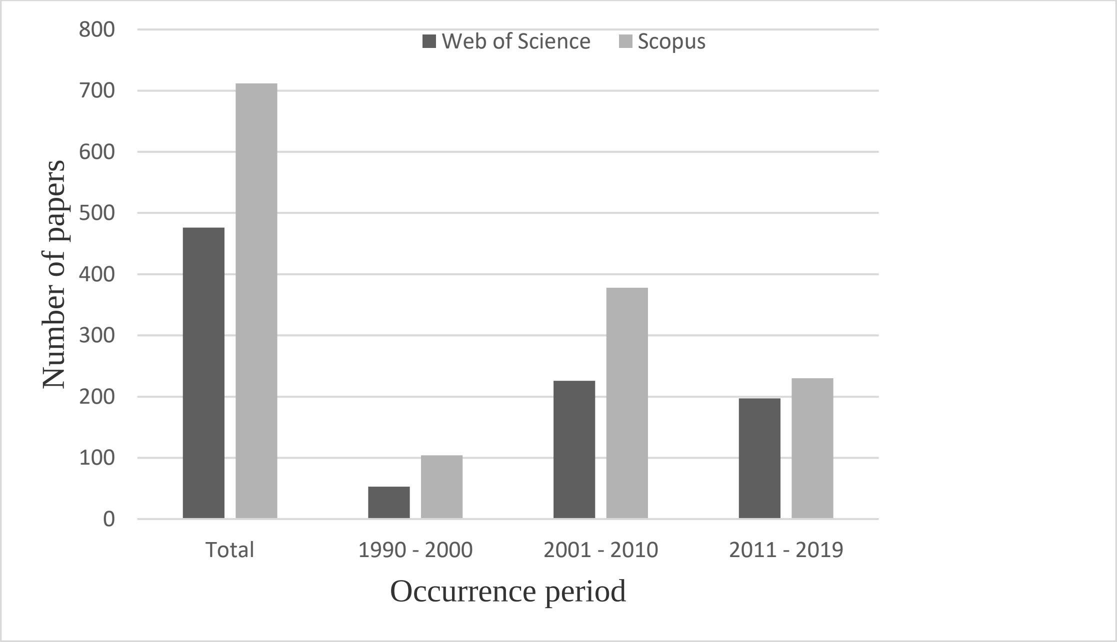
Thus, this search was divided into four stages:

1. Initially, the OSB panel descriptor was used (separate);
2. OSB panel; Balsa wood (combined);

3. OSB panel; Bamboo (combined);
4. OSB sandwich (separate).

The descriptors used in the search should be present in the title, abstract or keywords of scientific articles. It was possible to observe in this survey that scientific research addressing OSB panels began to gain prominence in the 1990s and the number of publications in this period reached 100 articles. Since the publications kept growing until 2010 (Figure 1).

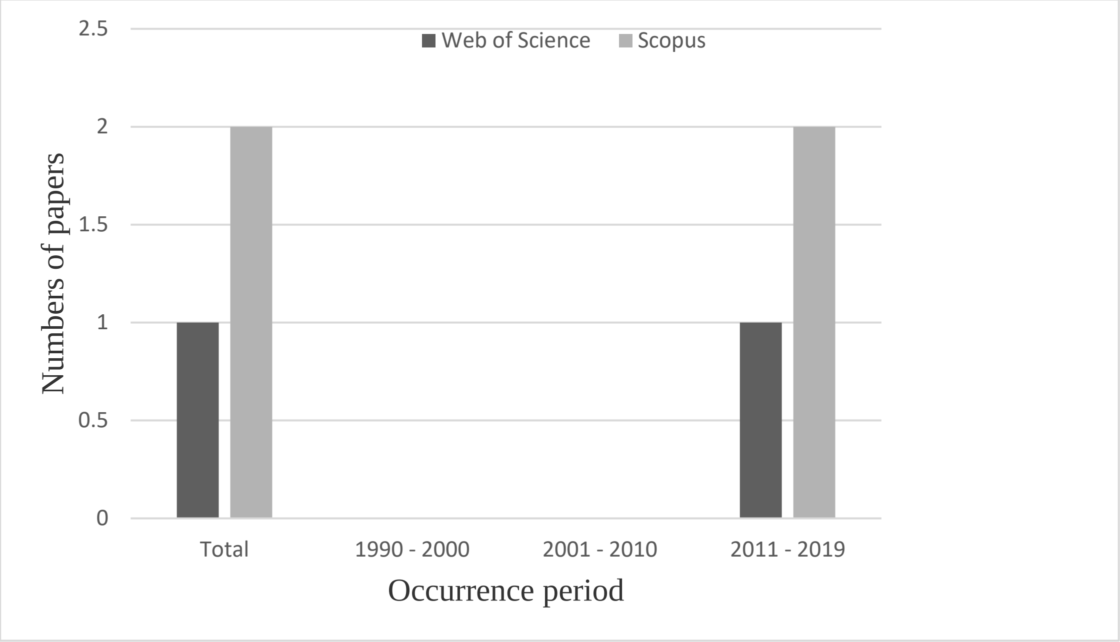
Figure 1 - Total of published papers with the "OSB panel" term



Source: Database of WEB OF SCIENCE and SCOPUS
Source: Own Author

In the second step, we refined the search to find articles dealing with the topic of oriented particleboard, using the keyword "OSB panel" combined with Balsa wood particles (*Ochroma Pyramidale*), using the keyword "Balsa wood" (Figure 2). It was possible to find only 2 articles. The first work found was by Barbirato et al. (2018), who evaluated two different densities of OSB panels with residual Balsa wood with two resin contents. The following year, Barbirato et al. (2019a) studied the mechanical performance of OSB panels with residual Balsa wood with three different densities and two resin contents, based on low impact velocity, 4-point static bending, and profilometry tests.

Figure 2 - Total of published papers with "OSB panel + Balsa wood" term

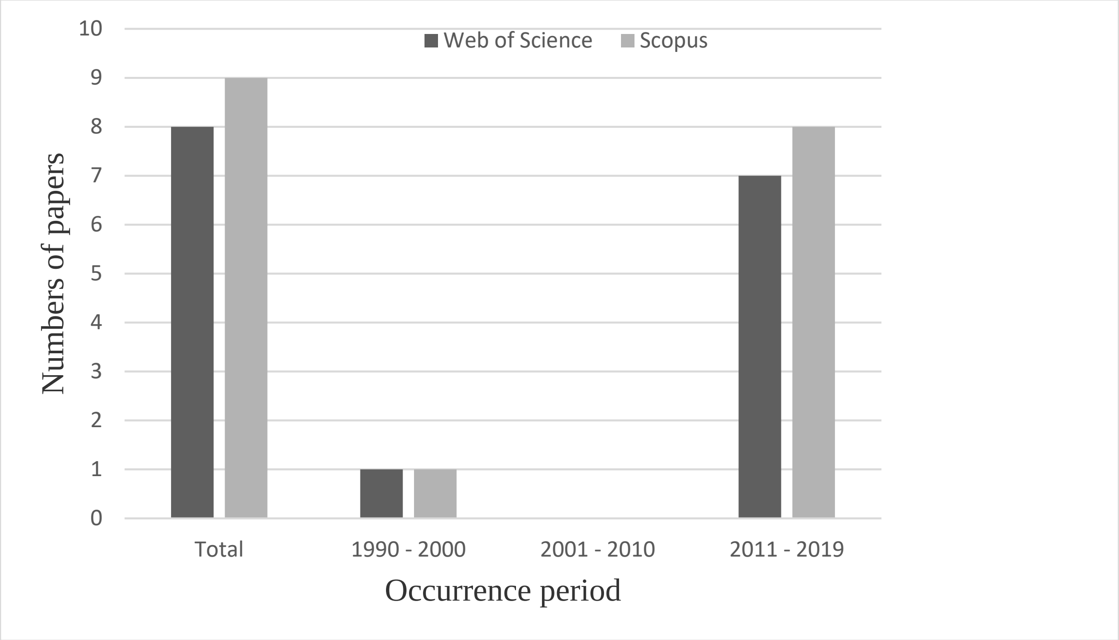


Source: Database WEB OF SCIENCE and SCOPUS
Source: Own Author

In the third step, we refined the search to find articles dealing with the topic of oriented particle panel, using the keyword “OSB panel” combined with Bamboo particles (*Dendrocalamus Asper*), using the keyword “Bamboo” (Figure 3).

A work was found in the 1997's, whose author was Ernst (1997). The author evaluated the development potential of MDF with different materials and concluded that compared to other wood-based materials, such as particleboard, the prospects of OSB for MDF for the year 2000 are considered very promising.

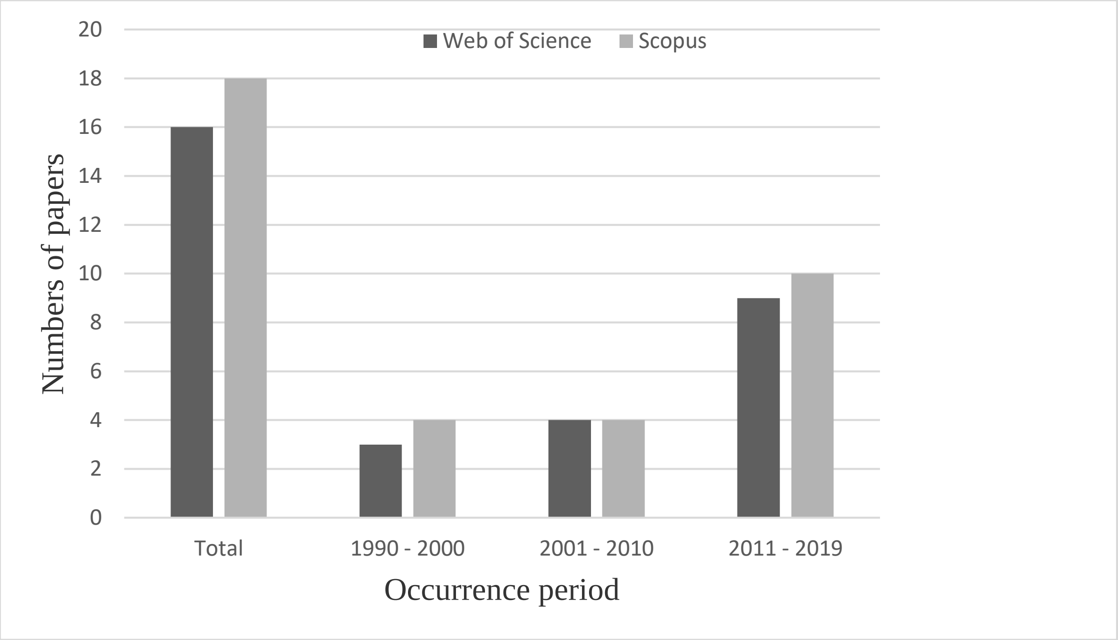
Figure 3 - Total of published papers with "OSB panel + Bamboo" term



Source: Database WEB OF SCIENCE and SCOPUS
Source: Own Author

The fourth search was about OSB sandwich panels, using the keyword "OSB sandwich" alone (Figure 4). It was possible to observe in this survey that scientific research addressing OSB sandwich panels began to gain prominence in the 1990s, but the number of publications in this period was only 2 articles. The publications continue to grow to this day.

Figure 4 - Total of published papers with "OSB sandwich" term



Source: Database WEB OF SCIENCE and SCOPUS
Source: Own Author

However, if we use the keywords “OSB sandwich” in combination with both “Balsa wood” and “Bamboo”, we do not find any reference in the literature. From this survey, the originality of the objective of this work was evidenced and the results may contribute to the field of knowledge in an incremental way.

Therefore, the hypothesis of this research permeates the statement: “It is feasible to produce OSB panels with unconventional raw materials and the application of OSB sandwich panels with flat faces and trapezoidal core as a structural component”.

1.3 Objectives

1.3.1 General Objectives

To optimize the PU-Castor resin content for OSB panels made of residual Balsa wood (*Ochroma Pyramidale*) and Bamboo (*Dendrocalamus asper*) and to study the mechanical performance of OSB sandwich panels with flat faces and trapezoidal core with application bias as a structural component.

1.3.2 Specific objectives

(i) Optimize the PU-Castor resin content for OSB panels with residual Balsa wood and Bamboo;

(ii) Evaluate the mechanical performance of OSB sandwich panels with flat faces and trapezoidal core, produced with the optimized formulation;

(iii) Develop and evaluate mechanical performance across critical regions and fault regions to increase mechanical performance for applications as a structural component.

1.4 Thesis structure

This thesis is divided into 6 chapters. Each chapter, described hereunder, is independent. Chapter 3, 4, and 5 is presented in the format of fully published/submitted or under submission papers.

Chapter 1: This chapter brings the contextualization, motivation, and objectives of this work, followed by the thesis organization and structure.

Chapter 2: This chapter presents a literature review focused on the applications and properties of the bamboo and wood waste material and presents discussions of the conventional and on-going development of treatment methods/technologies for bamboo/wood.

Chapter 3: This chapter presents a study of the optimization of castor oil polyurethane (PU) resin content for the production of Oriented Strand Boards (OSB) using bamboo (*Dendrocalamus asper*) and Balsa wood (*Ochroma Pyramidale*) waste. For this study, medium-density (650 kg/m^3) OSB panels were produced with different resin contents (8%, 10%, 12%, and 15%). The unconventional materials particles were characterized through physical, chemical and anatomical analyses, identifying the potential of this product as a raw material for OSB panels. Subsequently, the physical and mechanical properties of OSB panels were evaluated. This Chapter has the main purpose to evaluate the bamboo and wood waste particles for the production of OSB panels agglomerated with different contents of castor oil polyurethane adhesive.

Chapter 4: This chapter focuses on the development of a new geometry for OSB sandwich panel with trapezoidal core produced with Balsa Wood (*Ochroma Pyramidale)* waste agglomerated with bicomponent castor oil polyurethane resin. Mechanical properties were evaluated and significant increases in the stiffness of the panel were identify, enabling its use as structural components in civil construction.

Chapter 5: This chapter presents a study aimed to evaluate experimentally the deflections and predictions of critical regions for the failure of the panel of the mechanical performance of OSB (Oriented Strand Board) panels stiffened by the trapezoidal core according to the bending direction. By the cross-section of the panels manufactured with strands of Balsa wood waste and castor oil polyurethane resin, the influence of the core direction on the flexural stiffness and ultimate load capacity was evaluated.

Chapter 6: This chapter is dedicated to the final remarks and a summary of the main conclusions obtained throughout the development of this thesis. Future activities related to this area of research are advised.

2 CHAPTER 2 – Literature Review

This chapter is dedicated to a concise literature review and theoretical background about OSB flat panels, Balsa wood, Bamboo and constructive elements to understanding this doctorate thesis and seeks to contextualize the state of the art that permeates this field of knowledge

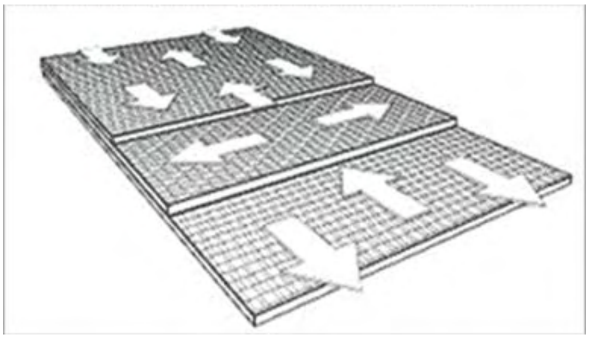
2.1 OSB flat panels

OSB (Oriented Strand Board) structural particle boards appeared in the mid-1970s in the US and Canada as a 2nd generation product of structural waferboard sheets. From the 1980s onwards, the use of OSB panels was widespread, resulting in a significant increase in new production units in all regions of the world. In North American countries, 51% of OSB applications occur in housing construction. In the United States of America, this panel is present in homes, used in internal and external walls, floors and ceilings, with highly satisfactory performance. The wide use of this panel in the USA and Europe is due to the speed and ease of installation, in addition to great energy savings compared to conventional constructions (REMADE, 2007; DOS SANTOS; AGUILAR, 2007).

In Brazil, the first OSB sheet factory started production in 2002, with an installed capacity of 350,000 m³/year in the state of Paraná (IWAKIRI et al., 2004). According to Iwakiri (1989) the great advantage in the production of OSB lies in the degree of use of the logs, given that the losses are minimal and occur in the form of fines, in the phases of generation and drying of the particles. The possibility of the OSB panel being produced from lower quality logs, as well as having a lower production cost and having sufficient properties for various uses, are factors that make OSB panels occupy market niches that were previously exclusive to plywood (JANSSENS, 1998).

OSB is a panel of long, thin, oriented wood particles (strands), consolidated by the use of resins, heat and pressure (BORTOLETTO JÚNIOR; GARCIA, 2004). Typically formed by three layers of particles (Fig. 5), in the inner layer the alignment is perpendicular to the direction of panel formation, while in the outer layers the alignment is parallel (TSOUMIS, 1991).

Figure 5 - Targeting strands by layer on the OSB panel



Source: (VIRTUHAB, 2017).

Studies on properties, as well as the production and influence of processing variables of OSB panels, from species of the genus Pinus planted in Brazil, were carried out by many authors. One of them are Bortoletto Júnior and Garcia (2004) who evaluated plywood and OSB panels from an upholstered furniture industry. The properties of resistance (modulus of rupture (MOR)) and stiffness (modulus of elasticity (MOE)) to static bending were determined in order to compare and evaluate the possibility of direct replacement of plywood, traditionally used in furniture, by OSB. The tests were carried out based on the Brazilian standard (ABNT NBR 9533, 1986). The authors concluded that the direct replacement of plywood with OSB is not recommended due to the results obtained for physical and mechanical properties. However, the authors indicated that further studies would be necessary.

Silva (2006) evaluated the technical feasibility of using long and oriented particles of sugarcane bagasse in the manufacture of OSB panels agglomerated with two different contents of polyurethane resin based on castor oil (10 and 20%). The panels achieved physical and mechanical properties that met the requirements of EN 300:2002 for OSB panels, in the different ranges suggested for the product's applications. However, it is worth adding that the sugarcane bagasse panel with 10% castor oil-based resin obtained the best performance.

Iwakiri et al. (2009) evaluated the influence of the thickness of the strand particles and the inclusion of laminar reinforcement on the physical-mechanical properties of *Pinus taeda* L OSB panels. 25:50:25. Panels with different particle thicknesses (0.4, 0.7 and 1.0 mm) were produced. The results obtained by the authors for MOR and MOE of different thicknesses (0.4, 0.7 and 1.0) were 34, 43.6 and 31.5 MPa and 5566, 5952 and

5129 MPa, respectively. For internal adherence, the authors obtained the following mean values: 0.25, 0.39 and 0.52. The authors concluded that the increase in particle thickness resulted in lower values of MOE and MOR, but higher values of internal adhesion and the inclusion of laminar reinforcement on the faces significantly improved the MOR and MOE in static bending in the perpendicular direction.

Souza (2012) produced and evaluated the performance of OSB panels made with Pinus sp. with the inclusion of metallic screens for an increase in the properties of resistance and rigidity in the static bending. A castor oil-based polyurethane resin content of 12% was used and the mass ratio for the face/core/face layers was 20:60:20. The results showed the efficiency of OSB panels when comparing their properties with the minimum values required by the standards and values found in the literature for panels of this nature.

Bufalino et al. (2014) evaluated the feasibility of using and mixing *Toona ciliata*, *Eucalyptus grandis/urophylla* and *Pinus oocarpa* woods in the production of OSB panels. The phenol-formaldehyde adhesive was used at a proportion of 9% for all treatments. A mass ratio of 25:50:25 for face:core:face was used. Most OSB panels do not fully meet the requirements specified by the EN 300:2003 standard for physical and mechanical properties. OSB panels made with *Eucalyptus grandis/urophylla* and *Pinus oocarpa* wood have the potential to be marketed as OSB type 1 (used for interiors, furniture and dry environment) and OSB type 2 (used for structural purposes and dry environment), respectively. As for the panels made with *T. ciliata* wood on the face and *Eucalyptus grandis/urophylla* wood on the core, the authors met the requirements established for OSB type 1.

Ferro et al. (2015) investigated the feasibility of producing OSB panels with Paricá wood particles (*Schizolobium amazonicum*) bonded with castor oil polyurethane resin. Three resin contents (8%, 10% and 12%) were evaluated. The panels achieved physical and mechanical properties that met national and international regulatory documents. However, it is worth mentioning that the panels manufactured with 8% resin proved to be the best solutions, as they present better performance, using less adhesive in the manufacture of the panels.

In this context, the wood used in the manufacture of commercial OSB panels comes from reforested species, mainly *Pinus spp.* and, to a lesser extent, some species of *Eucalyptus* (IWAKIRI, 2005). Considering the large volume of wood required in the panel manufacturing process and the need to seek new alternative materials, a constituent of forest biomass arouses interest in the use of other species, such as the balsa wood residue (*Ochroma pyramidale*) and bamboo (*Bambuseae*), as they are species that present accelerated growth compared to others used commercially in the production of panels and different densities.

2.2 **Balsa Wood (*Ochroma Pyramidale*)**

Balsa (*Ochroma Pyramidale)* is a low-density, lightweight wood that has been used in the restoration of degraded areas of natural forests thanks to its accelerated growth rate and good tolerance to direct sunlight. (LORENZI, 1992). According to Fernández (2010) the growth rate is high, being surpassed only by the Chinese species of bamboo (*Bambusa vulgaris Schrad*) (Fig. 6).

Figure 6 - Balsa Wood Tree (*Ochroma Pyramidale*)

Source: Own Author.

According to Daniels (2013) Balsa wood can have a density that varies from 100 kg/m^3 to 380 kg/m^3, being more common from 120 kg/m^3 to 200 kg/m^3. Because it is soft, homogeneous and has good workability, it is usually used in model airplanes, handicrafts, toys and packaging. It has high buoyancy, which qualifies it as a good material for frequent use by the nautical and aeronautical industries (LOUREIRO; SILVA; ALENCAR, 1979).

The soil and climate of the place where the tree comes from, the botanical classification, its physiology, the anatomy of the woody tissue and the chemical variation, are preponderant factors that influence the physical characteristics of the wood. The chemical constitution of wood directly influences its behavior in compression, tension, bending, shear, shrinkage, swelling, among other properties (HELLMEISTER, 1982). Despite its great potential, balsa wood still seeks to consolidate and expand its market in Brazil. According to studies carried out by Borrega et al. (2015) the mechanical properties of Balsa wood can reach values of up to 8 GPa for modulus of elasticity and 70 MPa for modulus of rupture at the highest densities. These relatively high mechanical properties of Balsa wood make it attractive for use as constituent particles of OSB panels.

In recent years, some academic research has proposed the use of by-products for the production of particle board and demonstrates feasibility. Hellmeister (2017) evaluated 10 mm thick flat OSB (Oriented Strand Board) panels consisting of Balsa wood waste (*Ochroma Pyramidale*) from reforestation, agglomerated with urea-formaldehyde (UF), phenol-formaldehyde (FF) and castor oil polyurethane adhesive (PU-Castor). The author evaluated low (350 and 500 kg/m^3) and medium density (650 kg/m^3) panels, using resin content in particle mass of 8% for UF and FF and 12% for PU-Castor resin. The results obtained by the author showed that the residual Balsa wood OSB panels agglomerated with PU-Castor resin reached the recommendations for type 1 OSB panels, for internal and non-structural use, of the European standard EN 300: 2006 - Oriented Strand Boards (OSB) – Definitions, classification and specifications.

Barbirato et al. (2018) evaluated low density OSB panels (300 and 400 kg/m^3), 10 mm thick and consisting of Balsa wood waste (*Ochroma Pyramidale*) from reforestation, agglomerated with PU-Castor resin at levels of 11 and 15%. The results obtained by the authors showed that the residual Balsa wood presented potential for the production of OSB panels and the treatment with a density of 400 kg/m^3 and resin content of 15% presented better physical and mechanical performance. Barbirato et al. (2019a) studied the mechanical performance of OSB panels with residual Balsa wood with three different densities (300, 400 and 650 kg/m^3) and two resin contents (11 and 15%). Low impact velocity, 4-point static bending and profilometry tests were performed. The results showed that the panels with higher density supported a greater amount of load in terms of peak force and perforation energy. Both properties clearly influenced by the better compaction of the particles.

2.3 Bamboo (*Dendrocalamus Asper*)

Bamboo is a fast-growing plant that is endemic in several parts of the world, mainly in the southern hemisphere, and this grass is a species with potential for use in these territories (Fig. 7).

Figure 7 - Bamboo clump (*Dendrocalamus Asper*)

Source: Own Author.

Bamboo is a great example of a material available in nature that has an enviable versatility compared to other manufactured materials. Throughout history, humans have been using bamboo as food, shelter, tools, household items and as many other items. Today, around one billion people in the world benefit from its use. In relation to industrial use, bamboo also extends to applications in the energy, chemical and civil construction sectors. (SASTRY, 1999 apud PEREIRA, 2012). In environmental terms, as bamboo is an undemanding rustic plant and is a perennial source for raw material extraction, it contributes to the protection and recovery of degraded soils as well as being used as an excellent tool to contain erosion. In addition, the use of bamboo fibers as reinforcement in cementitious composites and also in polymer matrix composites instead of synthetic fibers means a decrease in the use of non-renewable materials (ABDUL KHALIL et al., 2012; CORREIA; et al., 2015; HUANG; NETRAVALI, 2009).

This plant presents an accelerated growth, approximately 30 m in a year. Afterwards, the culms continuously acquire mechanical strength until they become mature after 3 to 5 years, reaching adequate structural strength (LIESE; WEINER, 1996; PEREIRA; BERALDO, 2007). Knowing that only mature culms should be used in civil construction or for the production of composites, especially due to their greater mechanical strength, dimensional stability and durability.

According to Liese (1987) bamboo is chemically composed of 50-70% holocellulose, 30% pentosans and 20-25% lignin, depending on the species and age of the stem. The author also describes the anatomical point of view of bamboo, formed by fibers (40%), parenchyma cells (50%) and vessels (10%).

The mechanical properties of bamboo are directly related to the species, age, moisture content, soil, harvest time, stem geometry, among other factors (GHAVAMI; MARINHO, 2005). In general, the following values regarding the mechanical properties of bamboo can be considered (BERALDO; ZOULALIAN, 1995 apud PEREIRA, 2012; BERALDO et al., 2003): Compressive strength: 50 to 90 MPa, Modulus of elasticity: 2.6 to 20 GPa, Tensile strength: 2.5 to 3.5 times its compressive strength. Flexural strength: 70 to 150 MPa.

Lima et al. (2012) found that, when studying two species of bamboos that are common in the Western Amazon, they found basic density values of 570 kg/m^3, 550 kg/m^3 and 590 kg/m^3 for *Bambusa vulgaris* and values of 400 kg/m^3, 510 kg/m^3 and 550 kg/m^3 for *Guadua sp.* in the base, middle and top positions, respectively.

Nurhazwani et al. (2016) investigated the mechanical properties of hybrid particle boards made of bamboo (*Dendrocalamus asper*) and rubber tree (*Hevea brasilienses*) with a density of 700 kg/m^3, varying the proportions of 100% bamboo, 70% bamboo and 30% rubber tree, 50% bamboo and 50% Rubber Tree, 30% Bamboo and 70% Rubber Tree and 100% Rubber Tree, agglomerates with 12% urea-formaldehyde resin content. The results concluded that the panels with 100% Bamboo had the highest values of MOR and MOE, being 15.30 MPa and 2650 MPa, respectively.

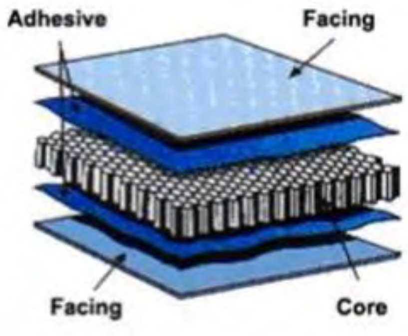
Almeida et al. (2017) evaluated the mechanical characteristics of wood-bamboo particleboards, with proportions of 100% wood and 0% bamboo, 75% wood and 25% bamboo, 50% wood and 50% bamboo. The authors used *Eucalyptus urophylla* x *grandis*, Bamboo (*Dendrocalamus asper*) and castor oil-based polyurethane resin. The results obtained by the authors for the panels with 100% bamboo were 1.68 MPa for bending test, 15.2 MPa for MOR, 2466 MPa for MOE, 1256 MPa for the withdrawal test at the top of specimen and 1392 MPa for the face withdrawal test.

2.4 OSB sandwich with trapezoidal core

Looking for new alternatives for the panel market, new geometries are currently being studied, such as three-dimensional panels, with flat external faces and corrugated core, thus having a more rigid, resistant product with a lower specific weight.

A sandwich structure consists of two cladding faces connected to a core, the faces are generally thin in relation to the total thickness of the composite and sheets of higher density and stronger than the core material are used (CARLSSON; KARDOMATEAS, 2011) (Fig. 8).

Figure 8 - Typical structure of a sandwich composite

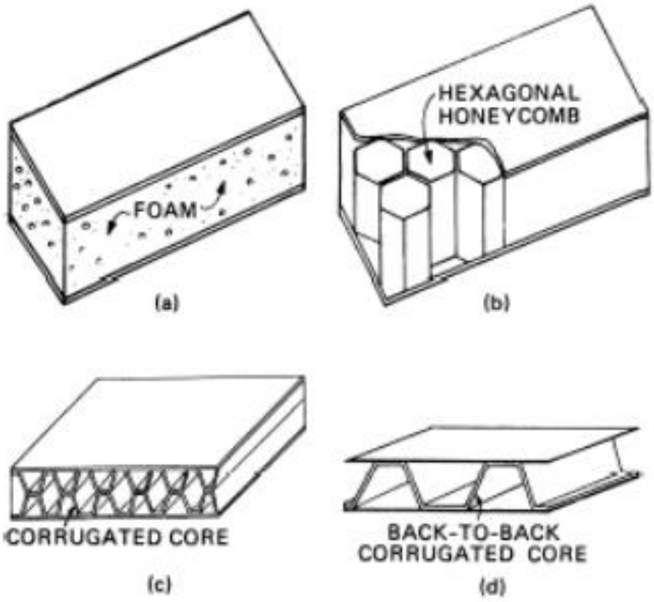


Source: (WAY, 2015).

The sandwich panel configuration is advantageous as it combines high bending stiffness and low weight (GAGLIARDO; MASCIA, 2011). According to Tita (2007) the faces have the function of withstanding tensile, compression and shear stresses in bending, and the core must be rigid enough in the direction perpendicular to the faces to avoid crushing.

According to Carlsson and Kardomateas (2011), the core sandwich panels are classified into two broad categories: “Cellular” and “Structural”. The “cellular” nuclei have empty spaces closed by walls, such as foam and hexagonal (honeycomb). "Structural" cores consist of a continuous web made of a solid material, such as the corrugations found in cardboard packaging. These cores are generally called wavy or corrugated (trapezoidal shape) (Fig. 9).

Figure 9 - Different types of core materials: (a) foam; (b) honeycomb; (c) corrugated; (d) back-to-back

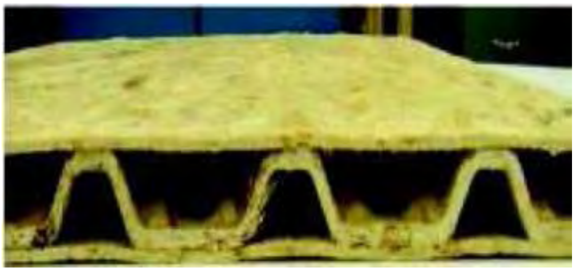


Source: (NALLAGULA, 2006).

Voth (2009) developed an OSB panel with wood particles and a three-dimensional (3D) format for the core and flat edges. This panel was produced in a mold designed to form a thin-walled core composed of wooden (strands). The core had a biaxial wavy geometry, with continuous ribs on the X axis and segmented on the Y axis. The panels were molded with a density of 312 kg/m^3 and 8% phenol-formaldehyde (FF) resin. After manufacturing the 3D core, two flat panels were glued on top and bottom with modified diisocyanate (MDI) adhesive (Fig. 10).

According to Voth (2009) this corrugated core shape has significant benefits for the construction industry because the hollow core cavities allow the passage of electrical conductors and plumbing. Also, according to the author, this type of panel has potential for applications such as floors, ceilings, walls, industrial shelves, furniture and building systems.

Figure 10 - Tridimensional Panel (3D)



Source: Voth (2009).

White et al. (2015) evaluated the flexural stiffness of 3D OSB panels developed by Voth (2009). The results indicated that the specific stiffness of these panels was 71% higher than that measured for flat plywood panels and 88% higher for flat OSB panels. As a complement, the authors claim that there is a 40% reduction in the amount of raw material, when compared to the amounts needed to manufacture an equivalent flat OSB panel.

Way et al. (2016) produced a prototype corrugated core sandwich panels made from oriented chips (OSB). The objective of the work was to study the structural performance of the product, validate the design and provide suggestions for future developments. The results validated that the three-dimensional design promotes high strength and stiffness in relation to specific weight. They also concluded that panels with a three-dimensional design showed better bending efficiency when compared to flat panels (Fig. 11).

Figure 11 - (a) Cross-section of the sandwich panel; b) bottom view of the corrugated core

Source: Way et al. (2016).

Pozzer and Fiorelli (2018) evaluated the mechanical performance of a sandwich panel with a corrugated core made of sugarcane bagasse particles agglomerated with two-component polyurethane resin based on castor oil (PU-castor). The flat OSB panels that make up the external face were produced with a thickness of 10 mm and a nominal density of 750 kg/m^3. The corrugated core was produced with the same density and thickness of 15 mm. The junction of the external face with the core was with the PU-castor adhesive, distributed homogeneously on each contact surface of the corrugated core with the flat panels. The results obtained by the authors were 3646.94 N.m/m for the flexural strength of the panel, 697.45 kgf/m^2 for uniform load based on the allowable deflection and 464.86 kgf/m^2 for the total load based on the permissible deflection.

2.5 Adhesives

With the second world war, other resins were developed, such as resorcinol formaldehyde and the first polyurethane resins, when Dr. Otto Bayer, a scientist who headed the research department of the BAYER company for more than 1930 years, discovered the polyaddition process of polyisocyanates, the basic principle in the manufacture of these products (BAYER, 1947).

Later, with the evolution of the chemistry of macromolecules, a great variety of polymeric resins, with better characteristics in terms of their adhesion aspect, was developed, allowing great expansion of the industries of resins based on vinyl, polyester, polyurethane, etc (MANTILLA CARASCO, 1984).

According to Jesus (2000) in the early 1980s, an important national contribution was made to the study of polyurethane-based resins, by the Department of Chemistry and Molecular Physics, of the current Institute of Chemistry at USP in São Carlos. The researchers of the Analytical Chemistry and Polymer Technology Group have developed a polyurethane resin that has several advantages, such as: handling at room temperature, great resistance to the action of water and ultraviolet rays, great mechanical resistance and being derived from renewable natural resources, whose raw material (castor beans) of easy climatic adaptation is found throughout the national territory.

There is a worldwide trend towards the use of biodegradable, non-polluting and natural materials. According to Araújo and Chierice (1992), this trend advanced research in the area of polyurethane resin, with the discovery of polyurethane derived from castor oil, thus expanding new perspectives for its application. Known internationally as "Castor Oil" and, in Brazil, as Caturra, castor bean (Ricinus communis) is a plant of the euphorbiaceous family, from which ricinolein oil is extracted, as a by-product of castor oil, also popularly called castor oil. The plant that originates this oil is found in abundance throughout the national territory and, mainly, in the tropical and subtropical regions of Brazil. From castor oil it is possible to synthesize polyols and pre-polymers with different characteristics that, when mixed, give rise to a polyurethane.

The polyurethane resin based on castor oil is a two-component type, composed of polyol B1640 and prepolymer A249, cold curing. After mixing the components, its viscosity increases and its applicability time is close to 20 minutes.

2.6 Standard parameters for OSB flat panels

The European standard EN 300:2002 – Oriented Strand Boards (OSB) – Definitions, classification and specifications defines four types of OSB according to their mechanical strength and physical properties:

- OSB/1 – General purpose boards and boards for interior components (including furniture), used in a dry environment;
- OSB/2 – Boards for structural purposes, used in a dry environment;
- OSB/3 – Boards for structural purposes, used in a humid environment;
- OSB/4 – Plates for special structural purposes, used in wet environment.

The European standard (EN 300) also determines threshold value requirements for the mechanical properties (Table 1) of transverse and longitudinal MOR and MOE moduli, internal bond, internal bond in boiling water and swelling in thickness after 24 hours. Therefore, there is interest in developing a material that meets the qualities of OSB panels required by standard.

Table 1 - Requirements for specified mechanical and physical properties

Property	**Test Method**	**Type**	**Requirement**
			Board Thickness (mm, nominal)
			6 - 10
Thickness Swelling (%) (24 hours)	EN 317	OSB Type 1	25
		OSB Type 2	20
		OSB Type 3	15
		OSB Type 4	12
MOR Longitudinal (MPa)	EN 310	OSB Type 1	20
		OSB Type 2	22
		OSB Type 3	22
		OSB Type 4	30
MOR Transverse (MPa)	EN 310	OSB Type 1	10
		OSB Type 2	11

		OSB Type 3	11
		OSB Type 4	16
MOE Longitudinal (MPa)	EN 310	OSB Type 1	2500
		OSB Type 2	3500
		OSB Type 3	3500
		OSB Type 4	4800
MOE Transverse (MPa)	EN 310	OSB Type 1	1200
		OSB Type 2	1400
		OSB Type 3	1400
		OSB Type 4	1800
Internal Bond (MPa)	EN 319	OSB Type 1	0.3
		OSB Type 2	0.34
		OSB Type 3	0.34
		OSB Type 4	0.5

Source: Own Author.

2.7 Review Considerations

Based on the information in the literature, it is possible to conclude that OSB panels have been gaining ground in the furniture and construction industries. These panels have a better use of the log than other panels, such as plywood, and generate less waste during their production.

It is also important to point out that concern for the environment has grown a lot around the world, aiming at the production of sustainable materials that reduce environmental impact. The use of castor oil-based polyurethane resin is a major advance in panel production, as it does not emit formaldehyde, is not harmful to the environment, when compared to commercial resins (urea and phenolic) and enables the production of panels of particles with different physical and mechanical properties compared to those produced with formaldehyde-based resins.

Another great initiative to reduce the impact on the environment is the use of forest residues, encouraging the use of reforestation species and those that contribute to the protection and recovery of degraded soils. In this case, residual Balsa wood and bamboo stand out.

With this global trend, where the authorities' concern with sustainable development has been growing, the civil construction sector has sought to meet sustainability concepts, with this, new technologies, systems and construction components have been gaining ground. In this context, OSB sandwich panels with flat faces and trapezoidal core produced with alternative raw material agglomerated with castor oil-based polyurethane resin is a niche that must be researched, to contribute to the social and economic development of the country.

3 CHAPTER 3 – Optimization of OSB nonconvenctional materials flat panels with PU-Castor oil resin

In this chapter presents a study of the optimization of castor oil polyurethane (PU) resin content for the production of Oriented Strand Boards (OSB) using bamboo (*Dendrocalamus asper*) and Balsa wood (*Ochroma Pyramidale*) waste. For this study, medium-density (650 kg/m^3) OSB panels were produced with different resin contents (8%, 10%, 12%, and 15%). The unconventional materials particles were characterized through physical, chemical and anatomical analyses, identifying the potential of this product as a raw material for OSB panels. Subsequently, the physical and mechanical properties of OSB panels were evaluated. This Chapter has the main purpose to evaluate the bamboo and Wood waste particles for the production of OSB panels agglomerated with different contents of organic resin.

The following published/submitted papers are related to this Chapter:

BARBIRATO, G. H. A.; GAUSS, C.; LOPES JUNIOR, W. E.; MARTINS, R.; FIORELLI, J. Optimization of castor oil polyurethane resin content of OSB panel made of Dendrocalamus asper bamboo. Ciência Florestal, Santa Maria, v. 32, n. 1, p. 187-205, 2022. DOI 10.5902/1980509846908. Available from: https://doi.org/10.5902/1980509846908.

BARBIRATO, G. H. A.; LOPES JUNIOR, W. E.; MARTINS, R. H. B.; FIORELLI, J. Evaluation of OSB panels using wood waste with different contents of castor oil polyurethane resin-based.

3.1 Optimization of castor oil polyurethane resin content of OSB panel made of *Dendrocalamus asper* bamboo

3.1.1 Introduction

Bamboo is an excellent example of an abundant material available in nature with outstanding properties and versatility. It is a plant with a high growth rate that is industrially used for several applications in the energy, chemical, and civil construction sectors (SASTRY, 1999 apud PEREIRA, 2012). There is a growing global market for bamboo, mainly due to the high demands of sustainable products in Europe and in the United States. The International Network for Bamboo and Rattan (INBAR) evaluated the global economy of bamboo in US$ 60 billion with a high potential for additional income for rural communities. In this context, several researchers have been studying and developing bamboo-based products as building materials (non-structural and structural), in their natural form (full-culm) or as engineered materials such as Laminated Bamboo Lumber, Particleboards, OSB, and cement-reinforced composites (ALMEIDA *et al*., 2013; ARRUDA *et al*., 2011; CORREIA *et al*., 2015; ESPELHO; BERALDO, 2008; GAUSS; KADIVAR; SAVASTANO, 2019; GHAVAMI, 2005; GHAVAMI; TOLEDO FILHO; BARBOSA, 1999; HARRIES; SHARMA; RICHARD, 2012; MATTONE, 2005; PAPADOPOULOS *et al*., 2004; SHARMA; HARRIES; GHAVAMI, 2013; SHARMA *et al*., 2015a, 2015b; YU *et al*., 2015).

One such application is oriented strand board (OSB). These panels consist of thin, oriented chips that are shaped by resin, heat and pressure (BORTOLETTO JÚNIOR; GARCIA, 2004). The use of OSB panels has grown significantly and occupied the previously exclusive space of plywood, as the plywood panels require logs of higher quality for their manufacture and, therefore, they are of relatively higher cost (BORTOLETTO JÚNIOR; GARCIA, 2004). Surdi (2012), highlights some applications of OSB panels, such as the use in walls, furniture, packaging, floor supports, and even the use of constructive elements.

Febrianto et al. (2012) demonstrated the effects of strand length and pre-treatment techniques on the physical, mechanical and durability properties of OSB panels made from Betung bamboo (*Dendrocalamus asper* (Schultes.f) Backer ex Heyne). The panels were produced with different strand lengths (50, 60, and 70 mm), with a nominal density of 700 kg/m^3 and a 5% content of commercial methylene diphenyl diisocyanate (MDI) adhesive. The results obtained by the authors indicated that the values of modulus of elasticity (MOE) and modulus of rupture (MOR) in the perpendicular direction were significantly affected by strand length. OSB prepared from strands with 70 mm strand length had better values compared to 60- and 50-mm strand lengths.

Sun et al. (2018) evaluated the effects of culm age, height, and node on the properties of OSB made from bamboo and the effect of adhesive loading on the board durability. The strands of bamboo were classified into different types, for example, bamboo age, height, and node or internode. The panels were produced with a nominal density of 800 kg/m^3 and a resin content of 6% of commercial MDI and phenol-formaldehyde (PF). The bamboo age was not significant for both mechanical properties (MOR and MOE), and physical properties (thickness swelling), but had an influence on the internal bond (IB) strength.

The Brazilian and the international literature have no studies related to the OSB panels with the use of *Dendrocalamus asper* bamboo agglomerated with castor oil polyurethane resin. However, promising results have been reported using this resin for the production of particleboards (CRAVO et al., 2015; FIORELLI et al., 2012; ZAIA et al., 2015). Therefore, this study aimed to analyze a new potential for bamboo in the production of medium-density (650 kg/m^3) OSB particleboards and evaluate different castor oil PU resin contents on the physical and mechanical performance of the final material.

3.1.2 Material and methods

3.1.2.1 Bamboo material

Mature culms (more than three years old) of *D. asper* bamboo (SisGen ID 002) were harvested at an experimental field in the USP campus, Pirassununga, Brazil, and stored in a protected environment. Samples extracted from the middle section of different culms (more uniform region) were used to prepare the strand particles for the OSB panels. Only internodes were used.

3.1.2.2 Real density and pH

The real density of the bamboo was determined using a helium pycnometer following the methodology established by Moura and Figueiredo (2002). The bamboo particles were dried at 60°C for 48 h before the measurement. For the pH measurement, a modification was made in the methodology proposed by Vital (1973) and described by Barbirato et al. (2018).

3.1.2.3 Apparent density

The apparent density of the bamboo was measured by the water immersion method at 27 °C (water density = 0.9965 g/cm3), as described in ASTM Standard D2395 – 17.

3.1.2.4 Chemical composition

The determination of the chemical constituents (lipids, nitrogen, fats, and soluble compounds) and contents of the cell wall (protein, hemicellulose, cellulose, and lignin) of the bamboo particles was carried out following the methodology proposed by Van Soest (1994) described by Barbirato et al. (2018).

3.1.2.5 Anatomy of the bamboo

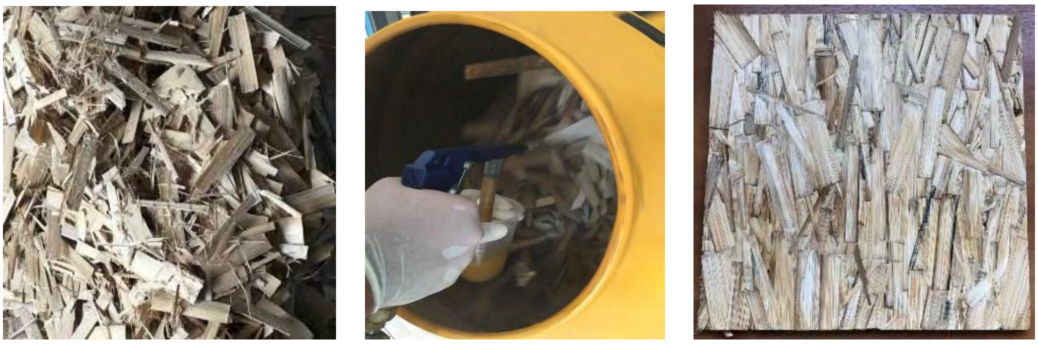
The anatomy of the bamboo (fiber bundle, parenchyma, vessels, and phloem) was evaluated in a Scanning Electron Microscope (SEM), Hitachi microscope model TM300. The samples were analyzed using a backscattered electron detector at an acceleration voltage of 15 kV.

3.1.2.6 Production of the OSB panels with bamboo and PU resin

The OSB panels were produced with bamboo particles as follows: small samples of bamboo (9 cm for width and 3 cm for length) were processed in a Marconi electric motor chip mill, generating strands with 9 cm in length, 2.5 cm in width and 0.1 cm thick (Fig. 12a). These particles were then dried at 65°C for 48 hours to obtain a material with a moisture content of 8% and then sieved to remove the fines.

The castor oil polyurethane resin was prepared with a prepolymer/isocyanate ratio of 1:1, sprayed onto the particles and mixed in a rotary drum blender. Different resin contents were used based on the dry weight of the particles. The material was then placed on a forming pad (60 x 60 x 1 cm) with a ratio of 30:40:30 for each orientation layer (face:core:face). The obtained mattress was manually pre-pressed, inserted into a thermo-hydraulic press (Fig. 12b) and pressed for 10 minutes at 100°C with a pressure of 50 kg/m^2. Two panels for each treatment (Fig. 12c) of medium-density (650 kg/m^3), based on the dry weight of the particles and different resin contents (8%, 10%, 12% and 15%) were produced, according to Table 2.

Figure 12 - Production process of OSB panels. A) Strands of Bamboo. B) Spraying the resin. C) OSB bamboo panel



(a) (b) (c)

Source: Own Author.

Table 2 Parameters of treatments

Treatments	Panels by Treatment	Density (kg/m^3)	Dimension (cm)	Thickness (mm)	Resin content (%)
T1	2	650	60 x 60	10	8
T2	2				10
T3	2				12
T4	2				15

Source: Own Author.

3.1.2.7 Characterization of the OSB bamboo panels

The physical and mechanical characterization of the medium-density OSB panels were carried out following the procedures established by the European Committee for Standardization (2002). It was determined the bulk density, thickness swelling (TS), longitudinal and transverse modulus of rupture (MOR), longitudinal and transverse modulus of elasticity (MOE), and internal bond strength (IB) of the panels.

The descriptive statistics evaluated the values obtained for the physical-mechanical properties to organize the results. Arithmetic means were used as a measure of central tendency and coefficients of variation as a measure of dispersion. Subsequently, the data were inserted into an inferential analysis to check a significant difference between the treatments studied. A completely randomized design was used, and the data compared by the Tukey test when the ANOVA was significant, both of which were tested at $p < 0.05$.

The results obtained were compared with the requirements indicated by the European standard EN 300 (2002) - Oriented Strand Board (OSB) – *Definitions, classification and specifications*.

3.1.3 Results and discussion

This section presents the results of the physical-chemical characterization of the bamboo particles, the physical and mechanical characterization of the panels, and the microstructural analysis of the particles.

3.1.3.1 Physical, chemical and anatomical properties of the bamboo

Table 3 presents the average values obtained for the physical and chemical properties of the bamboo used in this work.

Table 3 - Mean values of physical and chemical properties of bamboo particles

Sample	**Apparent density (kg/m^3)**	**Real density (kg/m^3)**	**Holocellulose (%)**	**Lignin (%)**	**Source**
Bamboo (*Dendrocalamus asper*)	**690**	**1303**	**68.50**	**20.2**	**This study**
	-	-	53.00	25.0	Dransfield and Wijaya (1995)
	-	-	65.8	30.4	Laemsak and Kungsuwan (2000)
	-	-	74.00	28.5	Kamthai (2003)

Source: Own Author.

The apparent density of bamboo is high compared to different species of *Eucalyptus* and *Pinus spp*. woods used in the production of commercial OSB panels, e.g., 510 kg/m^3 to *Eucalyptus urophylla* and 620 kg/m^3 to *Eucalyptus grandis* according to Brito and Barrichelo (1977), and 527 kg/m^3 to *Pinus taeda* according to *Trianoski et al.* (2014). This characteristic will imply less volume of particles to make the panels and consequently require less resin content to ensure an adequate agglomeration of the particles.

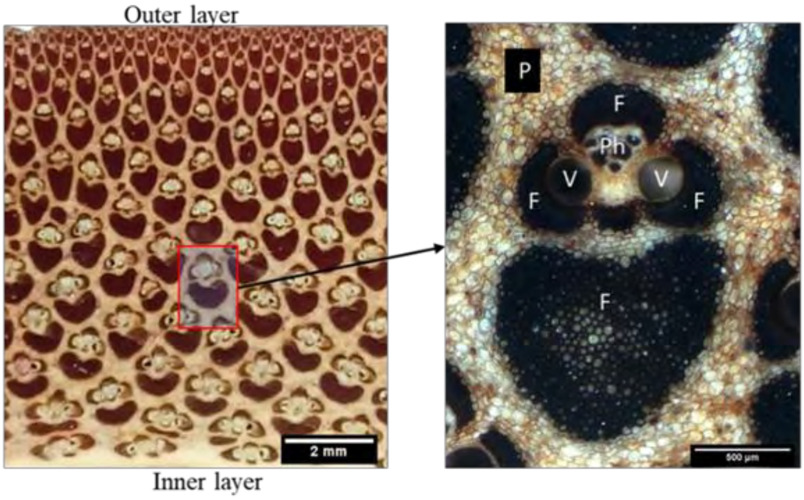
The real density of bamboo proved to be very close compared to other lignocellulosic fibers and wood species, e.g., 1240 kg/m^3 to *Pinus spp.*, 1400 kg/m^3 to Sugarcane bagasse, 1370 kg/m^3 to Peanut shell and 1300kg/m^3 to Coconut shell fiber according to Fiorelli et al. (2014).

In terms of chemical composition, the bamboo particles used in this work presented higher levels of holocellulose and lower levels of lignin contents compared to other studies. Kamthai (2003), investigated the chemical composition at different locations along the culm length of three years old *D. asper* bamboo. The results indicated that the chemical compositions show relatively small differences among different locations. In general, the composition of the bamboo used in this study is within the range reported for different species of bamboo, holocellulose between 54-82% and lignin between 20-34% (DEPUYDT et al., 2019; LI et al., 2015; LIESE; TANG, 2015). Compared to the other wood species (FENGEL; WEGENER, 1984), the chemical compositions of *D. asper* are similar to those of hardwoods and softwoods.

3.1.3.2 Anatomical characteristics of bamboo under SEM

Figure 13 shows the transverse cross-section of a sample of bulk bamboo used in this work. The main anatomical constituents, e.g., fiber bundle, parenchyma, vessels, and phloem, are presented. The fiber bundles/vessels combined are also called vascular bundles.

Figure 13 - Optical microscopy of the transverse cross-section of bulk bamboo used in this work showing the main anatomical constituents: F (Fiber bundle), P (Parenchyma), V (Vessels), and Ph (Phloem) (GAUSS, 2020)

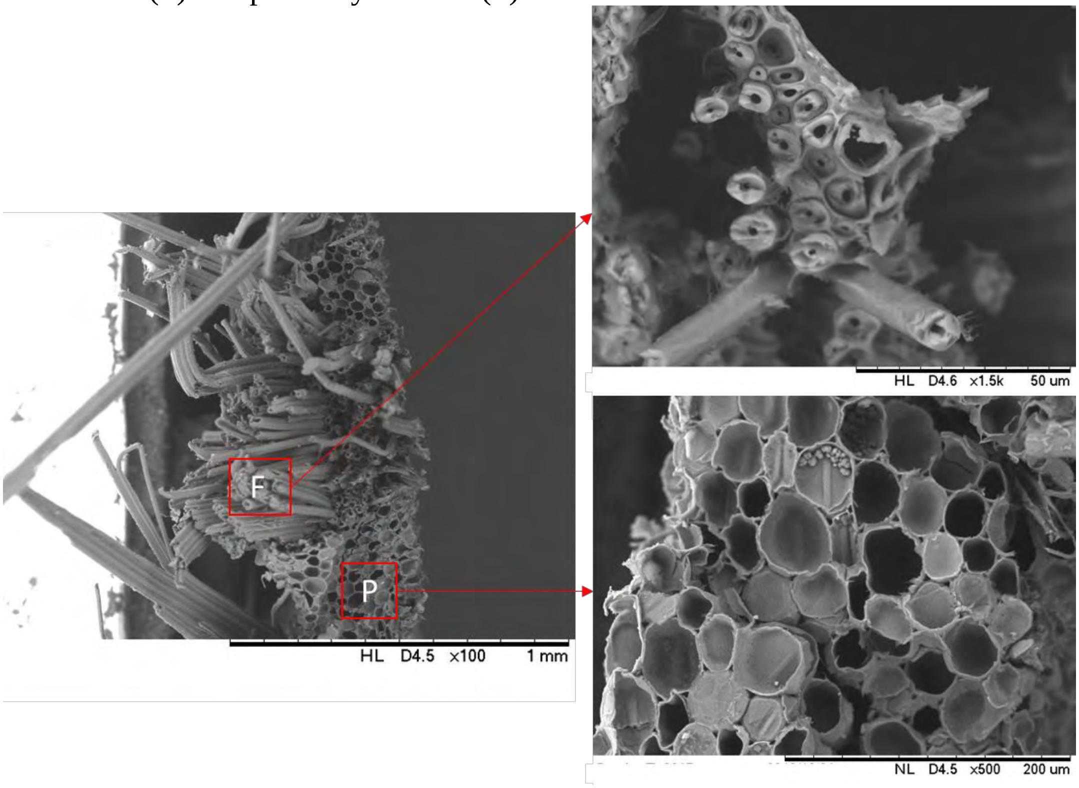


Source: Own Author.

According to Grosser and Liese (1971) the vascular bundle shape, size, arrangement, and number in the transverse section of the internode part can be used to classify the bamboo anatomical structure; for example, *D. asper* bamboo is classified under anatomical group D for having type IV vascular bundles (GROSSER; LIESE, 1971b). Additionally, although there is no correlation of the vascular bundles' fraction with age, the fraction of fiber bundles changes along the culm height, with higher fractions towards the top region (GROSSER; LIESE, 1971b; LIESE; WEINER, 1996).

Figure 14 presents the transverse section of a fractured bamboo strand analyzed through SEM. The fiber bundle is the main component responsible for the bamboo strength, especially in tensile loading. Its presence is clearly identified in the fractured strand, and it works as a reinforcement phase in a weaker matrix (parenchyma). The parenchyma cells have a more uniform and isotropic shape (see the bottom image of Figure 14), which reflects in a "sponge" like behavior. It also acts as an energy reservoir (mainly starch) for the bamboo plant. This unique configuration as a natural composite gives the bamboo an advantage in terms of failure mode over other common wood strands (LIESE; TANG, 2015).

Figure 14 - Transverse section of the bamboo strand highlighting its main constituents: fiber bundles (F) and parenchyma cells (P)



Source: Own Author.

3.1.3.3 Physical and mechanical properties of OSB panels

Table 4 presents the mean values, and the respective coefficients of variation (COV) of the physical (bulk density, water absorption, and thickness swelling) properties and Table 5 gives the mean values and the respective COV of the mechanical (MOR, MOE and IB) properties of the OSB panels (T1 to T4 treatments). For all the tests (physical and mechanical), 10 specimens per condition were evaluated. Besides, values of those properties recommended by the European normative document EN 300 (2002) for OSB panels type 1 to 4 are presented.

Table 4 - Average values obtained from the physical properties and values recommended by the European Standard EN 300 (2002) for OSB panels type 1 to 4

Treatment	**Bulk density kg/m^3**	**Water Absorption (%)**	**Thickness Swelling (%)**
		24 h	**24 h**
T1	**653.77^{a}**	**49.07^{a}**	**20.43^{a}**
(CV)	(6.00)	(10.66)	(12.49)
T2	**638.28^{a}**	**28.81^{b}**	**13.00^{b}**
(CV)	(4.46)	(6.45)	(16.73)
T3	**650.60^{a}**	**28.94^{b}**	**9.70^{c}**
(CV)	(4.65)	(6.55)	(14.22)
T4	**643.46^{a}**	**23.51^{c}**	**8.45^{c}**
(CV)	(4.69)	(8.75)	(17.9)
EN 300 (2002) Type 1	----	----	25
EN 300 (2002) Type 2	----	----	20
EN 300 (2002) Type 3	----	----	15
EN 300 (2002) Type 4	----	----	12

Means followed by different lowercase letters in the column differ significantly at 5% by the Tukey Test.

Source: Own Author

Table 5 - Average values obtained from the mechanical properties and values recommended by the European Standard EN 300 (2002) for OSB panels type 1 to 4

Treatment	**MOR (MPa)**		**MOE (MPa)**		**IB (MPa)**
	Long.	**Trans.**	**Long.**	**Trans.**	
T1	**27.73^{a}**	**25.47^{a}**	**5804^{a}**	**2121^{a}**	**0.73^{a}**
(CV)	(19.54)	(13.19)	(19,16)	(11.22)	(8.10)
T2	**40.09^{b}**	**30,37^{a}**	**6955^{a}**	**2643^{b}**	**0.96^{b}**
(CV)	(13.54)	(17.43)	(18.91)	(14.35)	(11.89)
T3	**49.75^{c}**	**30.85^{a}**	**8393^{b}**	**2302^{ab}**	**1.38^{c}**
(CV)	(9.76)	(17.80)	(13.36)	(19.23)	(11.50)
T4	**42.63^{bc}**	**25.33^{a}**	**6579^{a}**	**1845^{a}**	**1.32^{c}**
(CV)	(17.16)	(24.51)	(14.96)	(19.43)	(8.14)
EN 300 (2002) Type 1	20	10	2500	1.200	0.30
EN 300 (2002) Type 2	22	11	3500	1.400	0.34
EN 300 (2002) Type 3	22	11	3500	1.400	0.34
EN 300 (2002) Type 4	30	16	4800	1.900	0.50

Means followed by different lowercase letters in the column differ significantly at 5% by the Tukey Test.

Source: Own Author

For the water absorption (24 hours), the T1 treatment showed a significant difference ($p<0.05$) in relation to T2 treatment. However, although T2 is not significantly different from T3, both showed a significant difference ($p<0.05$) in comparison with treatment T4. For the thickness swelling (24 hours), T1, T2, and T3 are statistically different ($p<0.05$), while T3 presented similar value to T4, which showed the lowest TS among the analyzed conditions. When compared to the EN 300 (2002) Standard, the T1 treatment could be classified as OSB type 1 (general-purpose, non-load-bearing panels, and panels for interior fitments for use in dry conditions), presenting values close to OSB type 2 panels. The T2 treatment was classified as OSB type 3 (load-bearing panels for use in humid conditions), while the T3 and T4 treatments achieved OSB type 4 panels (heavy-duty load-bearing panels for use in humid conditions). It is also important to emphasize that, as expected, as the resin content increases, the average values of physical properties (water absorption and thickness swelling) decreases, proving a direct relationship between the resin and the physical properties.

Along with the results obtained for the mechanical properties, it was observed that for the longitudinal MOR, treatment T1 showed a significant difference ($p<0.05$) in comparison with the other treatments, presenting the lowest value. Although with considerably different resin contents, T2 and T4 did not present a significant difference. T3 showed the highest longitudinal MOR, statistically equivalent to T4 but different from T2. For the transverse MOR, interestingly, no significant difference was noted among the different treatments.

In terms of longitudinal MOE, although treatments T1, T2 and T4 showed no significant difference, their values are statistically lower than T3. For the transverse MOE, similar values were obtained for all the conditions, with the highest values (and statistically different) observed for the T2 and T3 conditions.

For internal bond strength, the lowest value was observed on the T1 treatment, significantly different from the other conditions. T3 and T4 presented the highest values of IB, with no statistical difference between them. Comparing the treatments, in terms of mechanical properties with EN 300 (2002) - Oriented Strand Board (OSB) - Definitions, classification and specifications, all conditions achieved OSB type 3 panels. Treatments T2 and T3 were the only ones to achieve OSB type 4 panels.

Papadopoulos et al. (2004) validated the technical feasibility of producing one layer of experimental particleboard from bamboo chips bonded with UF resin. Bamboo chips were characterized by having higher length to thickness and length to width ratios and lower bulk density than industrial wood chip particles. The panels were produced with a density of 750 kg/m^3 and differents resin contents (10, 12 and 14%). The results obtained in this study showed that bamboo strands can be successfully used, as an alternative lignocellulosic raw material, to manufacture boards type 3 for interior applications using a relatively low resin dosage (10% UF). Similarly to the results presented in our work, satisfying physical and mechanical properties can be achieved (complying with EN300 (2002) requirements) using bamboo strands even when lower contents of resin are used. The castor oil-based polyurethane resin can be successfully applied for bamboo OSB boards, presenting a promising option for formaldehyde-free engineered bamboo materials.

Febrianto et al. (2015) evaluated the effect of bamboo species and resin content on the physical and mechanical properties of OSB prepared from steam-treated bamboo strands of three species of Indonesian bamboo, namely Andong (*Gigantochloa verticillata*), Betung (*Dendrocalamus asper*), and Ampel (*Bambusa Vulgaris*). The OSB panels were prepared by bonding the strands with 3 to 5% of methylene diphenyldiisocyanate (MDI) resin and 1% paraffin. The mean values of water absorption and thickness swelling varied from 19.3% to 36.9% and from 8.6% to 14.1%, respectively. The mean values of longitudinal and transverse MOR in the dry-state ranged between 21 and 65 MPa and between 11 and 43 MPa, respectively, whereas in the wet-state, the mean values of MOR ranged from 9 to 51 MPa and 11 to 32 MPa, respectively. The longitudinal and transverse MOE, in the dry-state, ranged from 4828 to 10215 MPa and 1267 to 3496 MPa, respectively whereas in the wet-state, MOE values were 1701 to 6222 MPa and 1012 to 2612 MPa, respectively. In conclusion, higher resin content in resulted in better physical and mechanical properties.

3.1.4 Conclusions

Bamboo (*Dendrocalamus asper*) demonstrates high potential for the production of Oriented Strand Boards (OSB) panels based on physical, chemical and microstructural characterizations.

The evaluated treatments (T1 to T4) met the minimum requirements of the European standard EN 300 (2002) - Oriented Strand Board (OSB) – *Definitions, classification and specifications,* for OSB type 1. In particular, panels with 10%, 12% and 15% resin contents comply with the minimum recommendations for applications as structural panels.

The different resin contents show a direct relationship with the physical and mechanical properties of the OSB panels. It can be concluded that for this study, the optimum resin content for the production of medium-density (650 kg/m^3) OSB panels with *D. asper* bamboo was 12%, which presented the best physical and mechanical performance.

The results presented in this study show the potential of using castor oil-based polyurethane resin in combination with bamboo strands for the production of formaldehyde-free engineered bamboo materials for structural applications.

3.2 Evaluation of OSB panels using wood waste with different contents of castor oil-based polyurethane resin

3.2.1 Introduction

Aiming at reducing the pressure on the environment and contributing to the promotion of sustainability in industrial processes, particle boards (among them, OSB panels – Oriented Strand Board) with residual forest biomass agglomerated with organic resin are being consolidated in the market as alternatives to various applications, such as linings and partitions for the furniture industry (SURDI, 2015), as well as being used in construction, in applications such as floorings and sealing.

The residual balsa wood from reforestation regions has a rapid growth rate, ready for use within 4 to 5 years, whereas the commercial trees (Pine and Eucalyptus), which are used by the plywood industry, demand approximately 8 to 12 years. Moreover, Balsa wood has a low apparent density, around 200 kg/m^3, compared to Pine and Eucalyptus, which reach values of 600 to 800 kg/m^3. This low density is essential for its easy handling, allowing it to be engineered into panels of specific density.

Some recent studies have investigated OSB panels produced with balsa wood residue from reforestation, agglomerated with organic resin (BARBIRATO et al., 2019a, 2018; EDUARDO et al., 2021; HELLMEISTER et al., 2021; LOPES JUNIOR et al., 2021; SORIANO et al., 2021). All these studies, however, used resin contents higher than 11%. The wood panel industry often uses urea-formaldehyde and phenol-formaldehyde resins, the reported resin contents are less than 10%. The main objective is to achieve a lower resin content while still meeting with the normative recommendations. Notably, the wood panel industries in countries with wood supply use only the trunk of trees. To produce OSB panels, however, it is possible to use residues, such as chips, logs with imperfections (nodes and bark), and low-quality wood. This practice allows for a sustainable destination for this material, adds value to this new product, contributes to the reduction of the environmental impact caused by the disposal or burning of this raw material, and incorporates the product into the circular economy of the timber sector.

The novelty of this study is in the reduction of castor oil-based polyurethane resin contents in the production of OSB panels of residual balsa wood to approximate to the contents used commercially, presenting the physical and mechanical performance as well as the anatomical characteristics of this new product. This reduction in resin content seeks a more sustainable alternative, since the wood comes from reforestation, and presents a more economical alternative, since the amount of resin used is lower when compared with percentages greater than 12%. Therefore, this study aims to investigate the influence of the variation of castor oil-based polyurethane resin content on the physical and mechanical properties of OSB particle panels made of residual balsa wood from reforestation areas, with density of 650 kg/m^3 (density used commercially for OSB panels), agglomerates with different contents (8, 10, and 12%) of castor oil-based polyurethane resin (phenol-free). The mechanical characterization of these flat OSB panels, for possible applications in both the furniture and construction business, follows the minimum recommendations of the EN 300:2002 – Oriented Strand Board (OSB) – Definitions, classification, and specifications (EUROPEAN COMMITTEE, 2002).

3.2.2 - Material and Methods

3.2.2.1 - Production of OSB Panels of Residual Balsa Wood

OSB panels were produced from balsa wood waste from reforestation regions (SisGen A4206B8), i.e.: 1- Balsa wood waste (woodchips) was processed in a wood chipper (Marconi brand, model MA685), and chips with length of 9 cm, width of 2.5 cm, and thickness of 1 mm were produced (Fig. 15A); 2- after the production of the chips, they were sent to a warmhouse with a temperature of 65°C, for 48 hours, to obtain a material with 8% moisture content; 3- After drying, the chips were sieved to remove the finer grains 4- An estimation was performed of the quantity of particles for the targeted density of 650 kg/m^3 panel and for the variation of the contents (8, 10, and 12%) of castor oil-based polyurethane resin (castor-PU) to be used by panel. Subsequently, the particles were inserted into a concrete mixer machine and the resin was applied by spraying to obtain a homogeneous distribution of the resin along the particles; 5- the material was inserted into a mattress mold (600 mm × 600 mm × 10 mm), considering the face-core-face mass ratio of 30:40:30 (Fig. 15B), and then transferred to the thermohydraulic press (pressure 50 kgf/cm^2, temperature of 100°C, and pressing time of 10 minutes) (Fig. 15C). At the end of the pressing process, the panels were stored at room temperature for 72 h, a period marked by the continuation of the resin curing process. After this period, the panels were cut in its final dimensions (580 mm × 580 mm) from which specimens were extracted for physical, mechanical, and anatomical characterization tests. Thus, OSB panels of residual balsa wood (Fig. 15D) were manufactured according to the experimental plan presented in Table 6, totaling 8 panels (two for each treatment). The OSB panels of balsa residual wood of this study were referenced with the following abbreviations: RBOSB-T1, RBOSB-T2, and RBOSB-T3.

Figure 15 - Production process: (A) Balsa wood chips; (B) particle forming and guiding mold; (C) Mattress pressing; (D) Balsa wooden OSB panel

Source: Own Author.

Table 6 - Treatments studied and resin contents

Treatments	Density	Thickness	Resin Contents
RBOSB-T1	650 kg/m^3	10 mm	8%
RBOSB-T2			10%
RBOSB-T3			12%

Source: Own Author

3.2.2.2 Physical and Mechanical Characterization of OSB Panels of Residual Balsa Wood

The physical (water absorption, thickness swelling, and apparent density) and mechanical (static bending, internal adhesion, and screw pullout for face and top) characterization of residual balsa wood OSB panels (RBOSB panels) followed the recommendations of normative documents EN 310 (EUROPEAN COMMITTEE, 1993a), EN 317 (EUROPEAN COMMITTEE, 1993b), EN 319 (EUROPEAN COMMITTEE, 1993c), EN 320 (EUROPEAN COMMITTEE, 2011), and EN 323 (EUROPEAN COMMITTEE, 1993d). Table 7 shows the description of each test, the standards used, dimensions, and the total quantity of samples per test. The physical tests performed were done to prove the efficiency of the resin in relation to impermeability when in contact with water, the mechanical tests were made to evaluate the characteristics of the wood and its potential for applications in the furniture industry or in construction.

Table 7 - Experimental plan of physical and mechanical tests

Assays	Normative	Length (mm)	Width (mm)	Samples	
Apparent Density	EN 323	50	50	10	
Water Absorption	EN 317	50	50	10	
Thickness Swelling				10	
Bending Test	EN 310	250	50	Transv. 15	Long. 15
Internal Bond	EN 319	50	50	8	
Screw Withdrawal	EN 320	50	50	Face 10	Top 10

Source: Own Author.

The results obtained were compared with the minimum requirements of the European standard EN 300: 2002 – Oriented Strand Board (OSB) – definitions, classification, and specifications (EUROPEAN COMMITTEE, 2002) that defines four types of uses for OSB panels, regarding their use in the furniture and construction industry.

For the statistical analysis of the data, an inferential analysis was performed to diagnose the existence of a significant difference between the treatments studied (RBOSB-T1 to RBOSB-T3). The completely random design (CRD) was used, and the data were compared by the Tukey's test when the ANOVA was significant, both were tested with $p<0.05$.

3.2.2.3 Anatomical Characterization of Residual Balsa Wood OSB Panels

The images of the OSB panels of residual balsa wood were obtained by means of a Scanning Electron Microscope (SEM), Hitachi TM300 model. For the acquisition of the images, the electron backscattering technique was used, amplified by 50×, 100×, and 200×, which allowed for the identification of the dispersion of the resin inside the panels according to the variation of the contents used. This analysis is also important to understand the efficiency of panel compaction, an extremely important characteristic since it directly reflects on the physical and mechanical properties of the panels.

3.2.3 Results and Discussion

The results obtained from the physical, mechanical, and anatomical characterizations from RBOSB-T1 to RBOSB-T3 panels agglomerates with different levels of castor oiled-based polyurethane resin (Castor-PU) are presented in the next items.

3.2.3.1 Physical and Mechanical Characterization of Residual Balsa Wood OSB Panels

Table 8 shows the physical properties of RBOSB panels, such as apparent density, water absorption (2 hours and 24 hours), and thickness swelling (2 hours and 24 hours), compared to the specifications of the European standard EN 300:2002, which are presented by the mean and respective coefficient of variation (CV). This regulation presents four types of OSB panels up to 10 mm thick (Types 1 to 4), which are indicated according to the application of the panel as structural or non-structural, in dry or humid environments, and in external or internal use of the construction.

Table 8 - Mean values for the physical properties of OSB panels of residual balsa wood

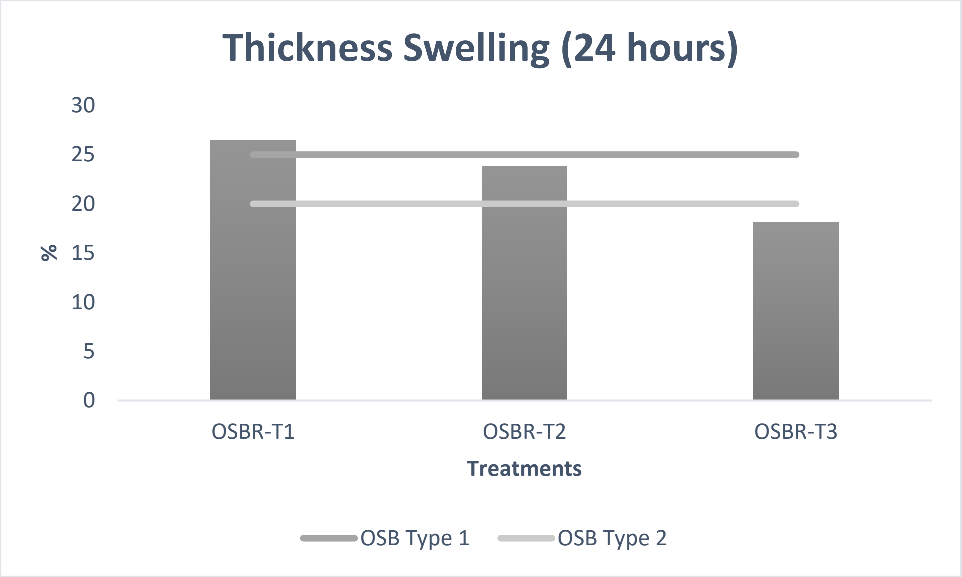
TREATMENTS	**APPARENT DENSITY**	**WATER ABSORPTION (WA)**		**THICKNESS SWELLING (TS)**	
		2 H	**24 H**	**2 H**	**24 H**
RBOSB-T1 - 8%	635.11^a	31.60^a	67.67^a	12.02^a	26.49^a

(CV)	(5.25)	(14.60)	(8.78)	(11.40)	(11.52)
RBOSB-T2 – 10%	621.56^{a}	29.58^{a}	68.71^{a}	12.65^{a}	23.83^{ab}
(CV)	(3.71)	(10.56)	(6.57)	(9.74)	(15.00)
RBOSB-T3 – 12%	633.80^{a}	19.28^{b}	49.43^{b}	10.94^{a}	18.09^{b}
(CV)	(4.28)	(13.51)	(9.59)	(8.29)	(13.27)
EN 300 – OSB 1	-	-	-	-	25
EN 300 – OSB 2	-	-	-	-	20

* Mean values followed by different lowercase letters in the column differ significantly to 5% ($p<0.05$) by the Tukey's Test.
Source: Own Author.

With the results obtained for the physical properties, it was observed that for water absorption (WA) (2 hours and 24 hours) the treatments RBOSB-T1 and RBOSB-T2 showed no statistically significant difference between them but showed a statistically significant difference ($p<0.05$) in relation to the RBOSB-T3 treatment. For the values obtained from thickness swelling (TS) (2 hours), all treatments showed no statistical difference amongst themselves. For The TS (24 hours) the treatments RBOSB-T1 and RBOSB-T2 did not present significant difference ($p<0.05$) among themselves, but the RBOSB-T1 treatment showed a significant difference for the RBOSB-T3 treatment, which showed no statistical difference for the RBOSB-T2 treatment. When compared with EN 300:2002 – Oriented Strand Board (OSB) – Definitions, classification and specifications, the T1 treatment did not reach values for TYPE 1 OSB panels, the T2 treatment reached for OSB type 1 panels, and the T3 treatment reached minimum requirements recommended by the regulatory for type 2 OSB panels (Fig. 16).

Figure 16 - Comparison of treatments results with the standard (EN 300). Thickness Swelling 24 hours



Source: Own Author.

It is important to highlight that as the resin content increases there is a tendency of less water absorption, this also happens for thickness swelling, proving a direct relationship between the resin content and the physical properties of the panels. The RBOSB-T2 treatment showed results for TS (24 h) close to Lopes Junior et al. (2021), which obtained TS (24 h) value equal to 23.26% for OSB panels of residual balsa wood of 650 kg/m³ and castor-PU resin content of 13%. Barbirato et al.(2019a) obtained results for WA (24h) of 134 % and 106 % considering OSB panels of residual balsa wood of 650 kg/m³ and castor-PU resin contents of 11 % and 15 %, respectively.

Overall, there was no statistical difference between the mean values obtained for apparent density and they are within the range of 621.56 to 643.57 kg/m³, this proves that the production process of the residual balsa wood OSB panels were successfully performed and reached the intended target density of 650 kg/m³.

3.2.3.2 - Mechanical Characterization of Residual Balsa Wood OSB Panels (RBOSB)

Table 9 shows the mechanical properties of RBOSB panels obtained by static bending tests (MOR and MOE), internal adhesion (IA), and screw pullout (face and top) compared to the specifications of the European standard EN 300:2002, are presented by the mean and respective coefficient of variation (CV).

Table 9 - Mean values for the mechanical properties of OSB panels of residual balsa wood

Treatments	**MOR (MPa)**		**MOE (MPa)**		**IB (MPa)**	**SCREW WITHDRAWAL (N)**	
	Long.	**Transv.**	**Long.**	**Transv.**		**Face**	**Top**
RBOSB-T1 - 8%	27.11^{a}	17.54^{a}	4194^{a}	1462^{a}	0.43^{a}	1032.35^{a}	826.71^{a}
(CV)	(10.45)	(9.79)	(10.80)	(9.57)	(4.88)	(8.40)	(6.30)
RBOSB-T2 – 10%	27.86^{a}	16.74^{a}	3882^{a}	1427^{a}	0.61^{b}	1177.98^{b}	919.16^{ab}
(CV)	(12.94)	(15.82)	(9.18)	(13.39)	(8.13)	(6.90)	(5.31)
RBOSB-T3 – 12%	24.84^{a}	17.34^{a}	3750^{a}	1404^{a}	0.54^{b}	1234.59^{b}	1156.32^{b}
(CV)	(9.01)	(14.68)	(15.52)	(10.33)	(13.22)	(8.67)	(13.06)
EN 300 – OSB 1	20	10	2500	1200	0.30	-	-
EN 300 – OSB 2	22	11	3500	1400	0.34	-	-

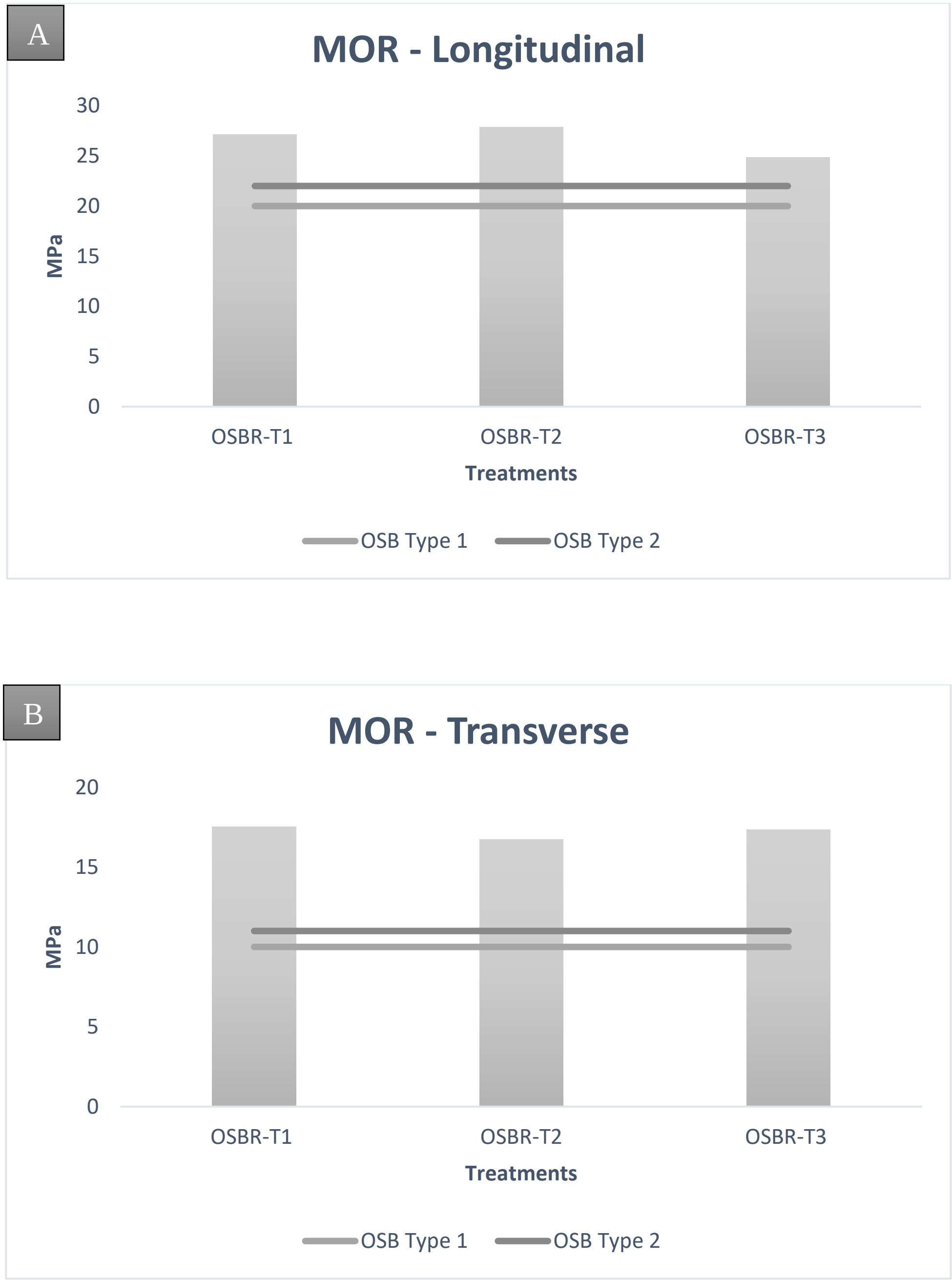
* Mean values followed by different lowercase letters in the column differ significantly to 5% ($p<0.05$) by the Tukey's Test.

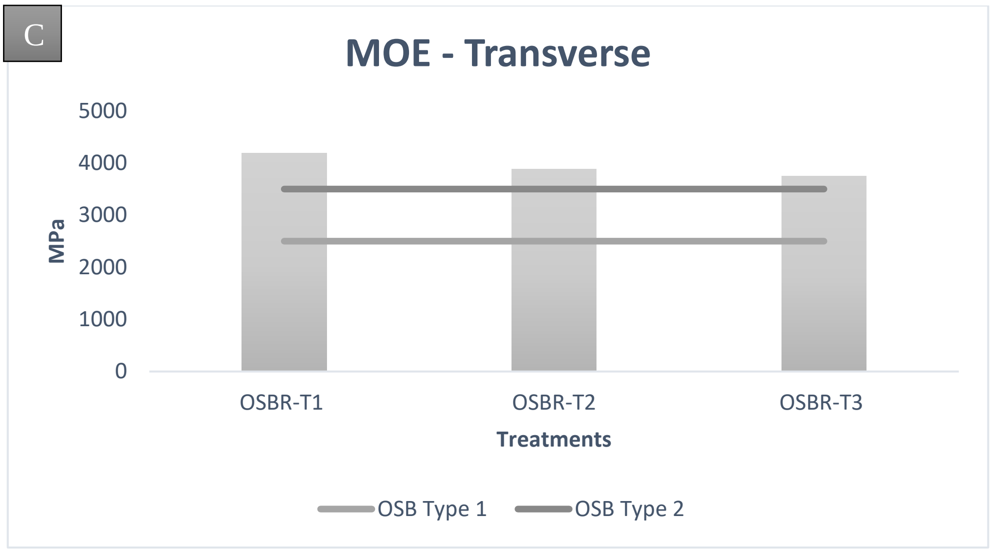
Source: Own Author.

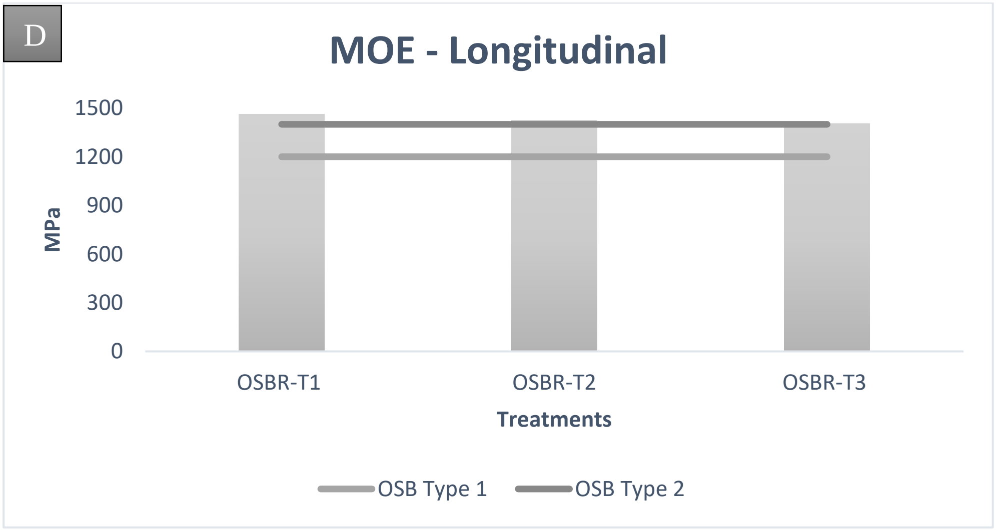
With the results obtained for the mechanical properties, it was observed that, for the longitudinal and transverse rupture modulus (MOR) and for the longitudinal modulus of elasticity (MOE), the treatments RBOSB-T1, RBOSB-T2, and RBOSB-T3 did not present significant difference ($p<0.05$) between them. For the transverse modulus of elasticity, however, the RBOSB-T1 treatment showed no significant difference ($p<0.05$) compared to the RBOSB-T2 treatment but presented statistical difference to the RBOSB-T3 treatment, which, in turn, did not present a statistically significant difference compared to the RBOSB-T2 treatment. For internal bond (IB), the RBOSB-T2 and RBOSB-T3 treatments showed no statistically significant difference between them, while the RBOSB-T1 treatment showed a significant difference compared to the other treatments studied. Comparing the results of the treatments with the EN 300:2002 - Oriented Strand

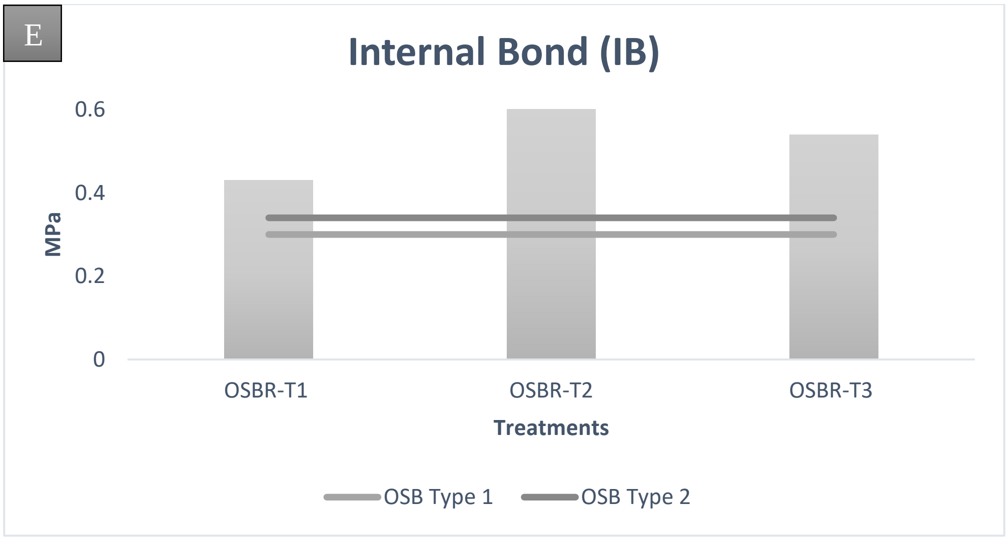
Board (OSB) – Definitions, classification, and specifications, they all achieved sufficient results to be classified as type 2 OSB panels (Fig. 17).

Figure 17 - Comparison of treatments results with the standard (EN 300). (A and B) Modulus of rupture longitudinal and transverse. (C and D) Modulus of elasticity longitudinal and transverse. (E) Internal Bond









Source: Own Author.

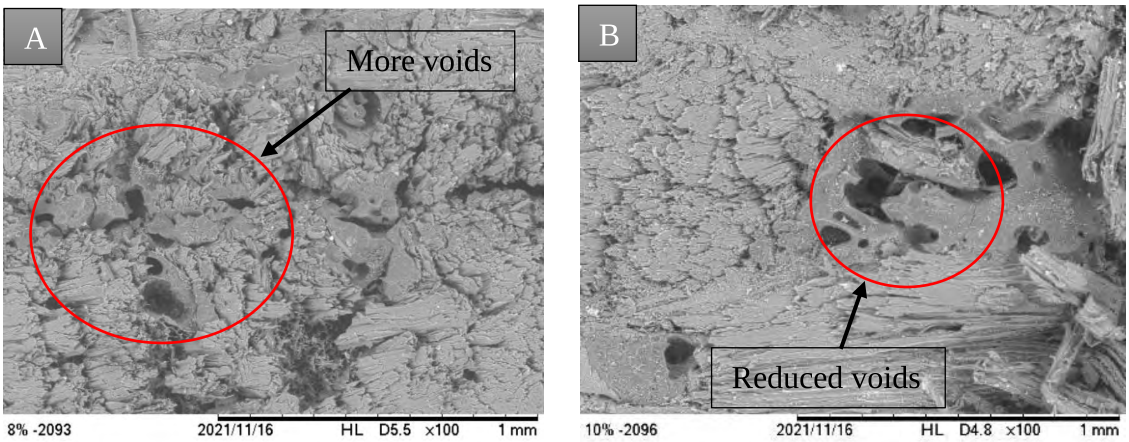
Lopes Junior et al. (2021) and Campos Filho et al. (2021) worked with OSB panels of residual balsa wood with density 650 kg/m³ and castor oil resin content of 13%. Considering the treatments RBOSB-T1 and RBOSB-T2, our study obtained values for transv. MOR, long. MOE, and IA higher than those obtained by the aforementioned authors, using lower resin contents.

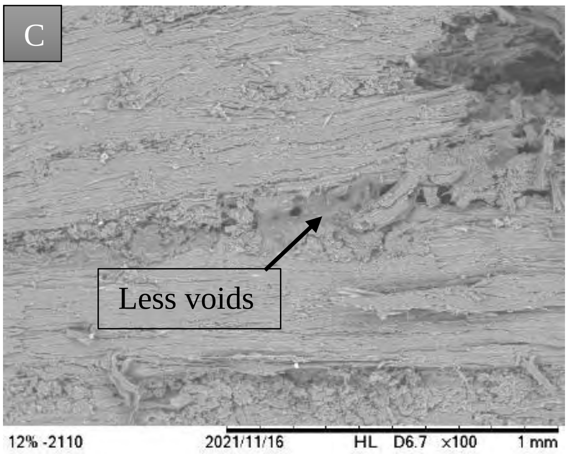
For the withdrawal test, the analysis of the mean values obtained allowed us to observe that the increase in density and resin content, from RBOSB-T1 to RBOSB-T3, resulted in a better performance. Thus, it is important to emphasize that the optimization of the resin content with the density used is extremely valuable for the physical and mechanical properties of the OSB panel of residual balsa wood.

3.2.3.3 - Anatomical Characterization of OSB Panels of Residual Balsa Wood under SEM

Figure 18 shows the scanning electron microscope (SEM) images of the cross-section of the RBOSB panels amplified by 100×. There is an adequate compaction of the particles; however, Figure 4A, with resin content of 8%, shows a greater number of voids compared to the other treatments, a characteristic that directly influences the physical and mechanical properties of the panels. Figure 18B, with a resin content of 10%, presents a smaller number of voids compared to Figure 18A, and these voids are reduced with the increase of the resin content (Figures 18C).

Figure 18 - Cross section - SEM (Zoom 100x): (A) 8%; (B) 10%; (C) 12%





Source: Own Author.

3.2.4 Conclusion

The study of the resin content for residual Balsa wood OSB panels from reforestation regions showed that panels with more than 10% castor-PU resin meet the normative recommendations. This content is justified by the characteristics of the wood (porous), to achieve minimum requirements of the European standard for structural OSB panels type 2. Studies have also shown that it is possible to produce panels with resin levels below 10% for non-structural applications such as furniture, linings, and partitions, reaching the minimum requirements for type 1 OSB panels.

4 CHAPTER 4 – Development of a new geometry for OSB sandwich panel with trapezoidal core

This chapter focuses on the development of a new geometry for OSB sandwich panel with trapezoidal core produced with Balsa Wood (*Ochroma Pyramidale)* waste agglomerated with bicomponent castor oil polyurethane resin (phenol free). Mechanical properties were evaluated. This modification guarantees significant increases in the stiffness of the panel, enabling its use as structural components in civil construction.

The following published paper is related to this Chapter:

BARBIRATO, G. H. A. *et al*. Sandwich OSB Trapezoidal Core Panel with Balsa Wood Waste. Waste Biomass Valor 13, 2183–2194 (2022). https://doi.org/10.1007/s12649-021-01660-2.

4.1 Sandwich OSB Trapezoidal Core Panel with Balsa Wood Waste

4.1.1 Introduction

Strand-based wood composites have gained popularity in the construction industry. These panels have several advantages, including the ease and speed of construction, thermal and acoustic insulation capacity, and low manufacturing costs. Currently, there are specific panels for each type of application, be it acoustic, thermal, or structural. Oriented strand boards (OSB) have gained immense market share since their inception, especially by replacing plywood. Several studies (e.g.(BORTOLETTO JÚNIOR; GARCIA, 2004; BUFALINO et al., 2014; DA ROSA et al., 2017; FERRO et al., 2015; IWAKIRI et al., 2009; MACEDO, 2014; NASCIMENTO et al., 2015; IWAKIRI; MENDES; SALDANHA; SANTOS, 2004)) have evaluated the physical and mechanical properties of OSB panels manufactured with different wood species and different resin content. Comprehensive property characterization and greater confidence in the material helped expand the applications of OSB in the construction industry.

Due to the increased exploitation of natural resources and associated environmental impact concerns, there has been a great demand for alternative materials that use renewable raw materials and reduce energy expenditure in the production process. One of these alternatives is Balsa wood (*Ochroma Pyramidale*), which is known for being an extremely light wood (low density) and has an accelerated growth profile, which helps in the reforestation of planted forests. Balsa has been used by companies in the nautical and aeronautical sectors for its light weight and high mechanical properties for low-density wood. Recent studies (BARBIRATO et al., 2019a, 2018, 2019b; CABRAL et al., 2018) have investigated this type of wood for the production of OSB panels.

Search for new alternatives within the panel market has led to studies involving new geometries, such as a sandwich or three-dimensional panels, with flat external faces (flat panels) and corrugated core (CARLSSON; KARDOMATEAS, 2011). The sandwich design results in a stiffer, more resistant product with a lower specific weight (GAGLIARDO; MASCIA, 2011). The use of sandwich construction systems can provide increased thermal and acoustic performance and enable the structures to be built faster (GAGLIARDO; MASCIA, 2011). Currently, there is limited literature available on OSB sandwich panels.

Voth et al. (2015) evaluated the flexural rigidity of the OSB 3D panels. The results indicated that the specific rigidity of these panels was 71% higher than that measured for conventional plywood panels and 88% higher for OSB panels. Additionally, there was a 40% of reduction in the amount of raw material used, when comparing to the quantities needed to manufacture equivalent conventional panels.

Way et al. (2016) produced a prototype of corrugated core sandwich panels made of oriented strand boards (OSB). The objective of this work was to study the structural performance of the product and provide suggestions for future developments. The results validated the geometry of molded core panels and provided better flexural efficiency than flat panels. Similarly, Pozzer et al. (2020) evaluated the mechanical performance of a sandwich panel with a corrugated core consisting of sugarcane bagasse particles agglomerated with two-component polyurethane resin based on castor oil (PU-castor). The flat OSB panels that made up the external face were produced with a thickness of 10 mm and a nominal density of 750 kg/m^3. The corrugated core had the same density but a thickness of 15 mm and was bonded to the face using PU-castor adhesive, homogeneously distributed on each contact surface of the corrugated core with the flat panels. The authors reported 2.1×10^6 $N\text{-}mm^2/m$ for longitudinal axis and 0.73×10^6 $N\text{-}mm^2/m$ for transverse axis bending stiffness (EI), and 1199 N-mm/m and 819 N-mm/m for longitudinal axis and transverse axis maximum moment (F_bS), respectively. To date, Balsa wood or wood waste has not been used to construct such a panel. Therefore, an opportunity exists in developing and characterizing such a product for engineering end-use.

This study investigated a new geometry for OSB sandwich panel with trapezoidal core, using Balsa wood waste agglomerated with castor oil polyurethane resin. The motivation for this project was to develop a sandwich panel using wood waste with mechanical properties that might be utilized for structural applications, seeking a new alternative for wood composite panels found in the current market. Specifically, the objective of this study was to fabricate a prototype of OSB sandwich panels with a trapezoidal core and perform a robust mechanical property characterization to validate the technical efficiency of these sandwich panels for application as a structural component.

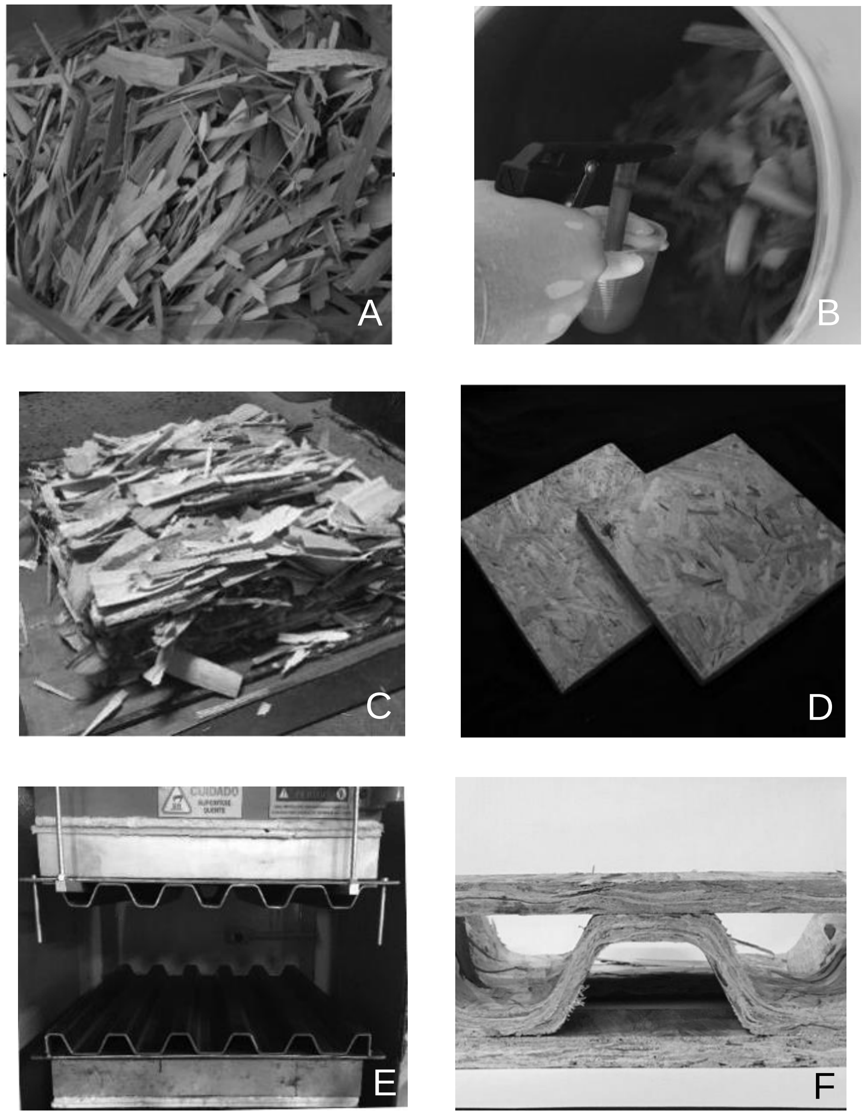
4.1.2 Methodology

4.1.2.1 Production process of OSB flat and sandwich trapezoidal core panels

The production process for the OSB panels included three stages. The first step was the treatment of the residual Balsa wood. After collection of the raw materials, the material was stranded to obtain 9 cm long, 2.5 cm wide, and 0.1 cm thick strands (Fig. 19a). The strands were then oven-dried for 48 hours at 65 ºC to reach 8% moisture approximately. The second stage is the production process of the OSB panels, with a 30:40:30 layer distribution (face: core: face) of strands. The strands were inserted in a rotating mixer and the resin was sprayed to achieve a target resin content of 12% (Fig. 19b). This ensured greater homogenization of the resin in the particles. Subsequently, the strands were oriented and the mats were formed (600 x 600 mm) (Fig. 19c) and finally, pressed for 10 min at 100 ºC with a pressure of 50 kg/m^2 in a thermo-hydraulic press. Medium-density panels (650 kg/m^3) were produced with 10 mm thickness (Fig. 19d). The third stage was the production of the trapezoidal panel, followed by bonding of the flat external faces with the trapezoidal core, constituting the OSB sandwich panel with the trapezoidal core (OSBTC) (Fig. 20). For molding of the panels in the trapezoidal format (400 x 400 x 65 mm), a metal mold with the trapezoidal format was fabricated, which consists of two parts (lower and upper) (Fig. 19e). This metallic mold was attached to the press. The mats were inserted and pressed with similar parameters as the OSB flat panels.

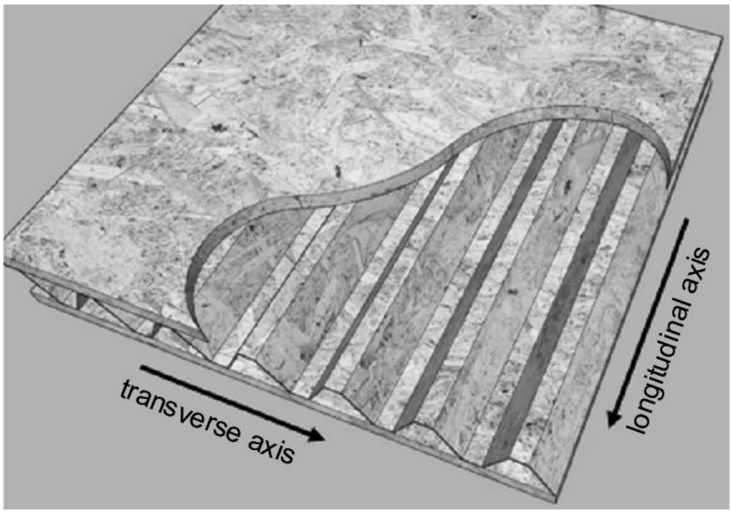
The bonding of the flat faces to the trapezoidal core was performed using Poly Urethane (PU)-Castor oil resin (Fig. 19f). Seven grams of resin was divided on each contact surface with the corrugated panel and applied homogeneously, totaling forty-nine grams (POZZER et al., 2020). Subsequently, a manual press was used, with six (6) pressure points and a pressure of 2.85 kgf was applied to each point. The pressing time was 48 hours at room temperature to cure the resin.

Figure 19 - Production process of OSB flat and sandwich panels: (A) Strands of Balsa wood waste; (B) Resin spraying; (C) Oriented particle mattress; (D) OSB flat panel; (E) Trapezoidal mold; (F) Cross-section of OSB sandwich panel



Source: Own Author.

Figure 20 - Top view of OSB Sandwich Trapezoidal core with axis directions



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4.1.3 Mechanical characterization of OSB sandwich panels

A comprehensive mechanical testing program was designed to characterize the mechanical properties of the OSBTC. A brief description of the standards used and the dimensions of the specimens is presented in Table 10.

Table 10 - Test matrix of OSB sandwich panels

Test	Standard	Length (mm)	Width (mm)	Samples
Bending-longitudinal axis	ASTM D3043 ASTM C393	360	120	3
Bending-transverse axis				3
Flatwise compression	ASTM D143	120	120	9
Dowel bearing	ASTM D5764	75	120	12
Withdrawal	ASTM 1761	75	120	12
Lateral connections		230	120	6
Small-scale shear walls	ASTM E564	360	360	3

Source: Own Author.

4.1.3.1 Bending test

Bending properties were characterized using a three-point bending test following the recommendation of (ASTM D3043, 2017) while the failure types were compared as per (ASTM C393, 2016). It was necessary to adjust the dimensions of the specimens according to the geometry of the trapezoidal core such that each longitudinal sample represented a section that was repeated on the transverse axis. The standard geometry of the specimens is 75 mm x 200 mm (ASTM D3043, 2017). However, if this configuration is used the specimens would not cover an entire cell of the nucleus (of the trapezoidal core). Therefore, the geometry was adjusted following the recommendations of the standard for the use of non-standard samples. For non-standard geometries, the length of the specimen must be equal to the length of the support (span) plus 50 mm. The test was conducted in a Universal Testing Machine (UTM) as shown in Figure 21 A1 and Figure 21 A2. The load was applied via displacement of the actuator crosshead at a rate of 6 mm/min so that failure is reached between 3 to 6 minutes after the start of testing. Bending stiffness per millimeter (*BS*) (Eq. 1) and maximum moment per millimeter of panel width (*MM*) (Eq. 2) are shown below:

$$\mathbf{BS} = \frac{\mathbf{P} * \mathbf{S}^3}{\Delta * \mathbf{48} * \mathbf{W}} \tag{1}$$

$$\mathbf{MM} = \frac{\boldsymbol{P} * \boldsymbol{S}}{\mathbf{4} * \mathbf{W}} \tag{2}$$

where:

(P/Δ) = slope of the linear region on the displacement-load curve (N)

S = span length (mm)

W = sample width (mm)

4.1.3.2 Flatwise Compression

Flatwise compression tests were performed following (ASTM D143, 2014) on a UTM (Fig. 21 B). The load was applied at a rate of 1 mm/min and the tests were stopped after a compressive deformation of 2.5 mm. A 25-mm-thick steel plate (300 mm in length) was attached to a spherical seat which was attached to the crosshead, while a circular 50-

mm-thick steel plate (125 mm in diameter) rested on a base equipped as the specimen support. Load and crosshead deflection data were used to calculate compressive stress:

$$\mathbf{CS} = \frac{\boldsymbol{F_{2,5}}}{\boldsymbol{A}} \tag{2}$$

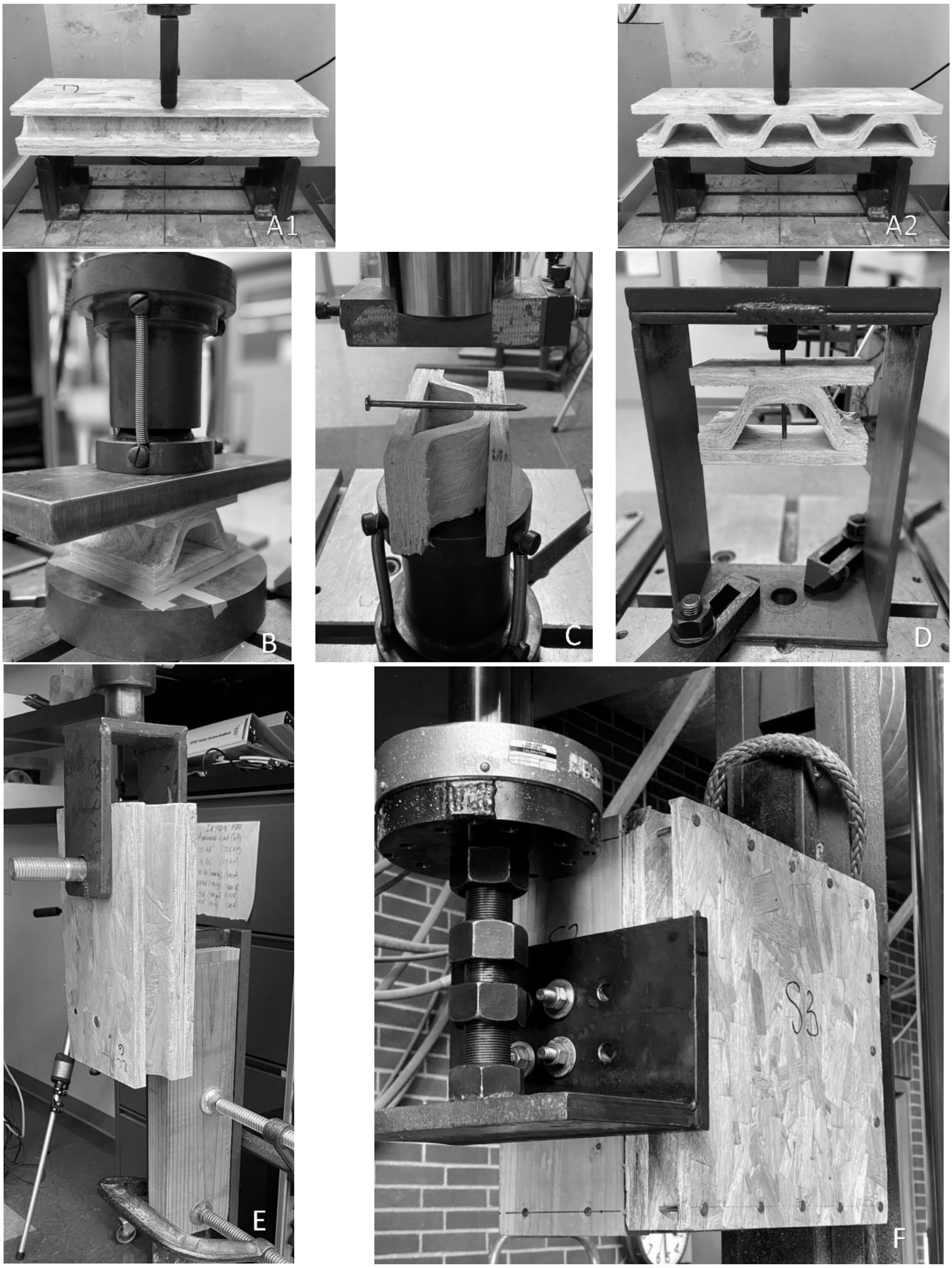
where:

CS = compressive stress (MPa)

$F_{2,5}$ = load at the compressive displacement of 2.5mm (N)

A = total cross-sectional area of the facing (mm^2)

Figure 21 - Apparatus of mechanical tests with the samples: (A1) bending longitudinal (left) and (A2) transverse (right) axis; (B) flatwise compression; (C) dowel bearing top and rib; (D) withdrawal; (E) lateral connection; and (F) small-scale shear wall

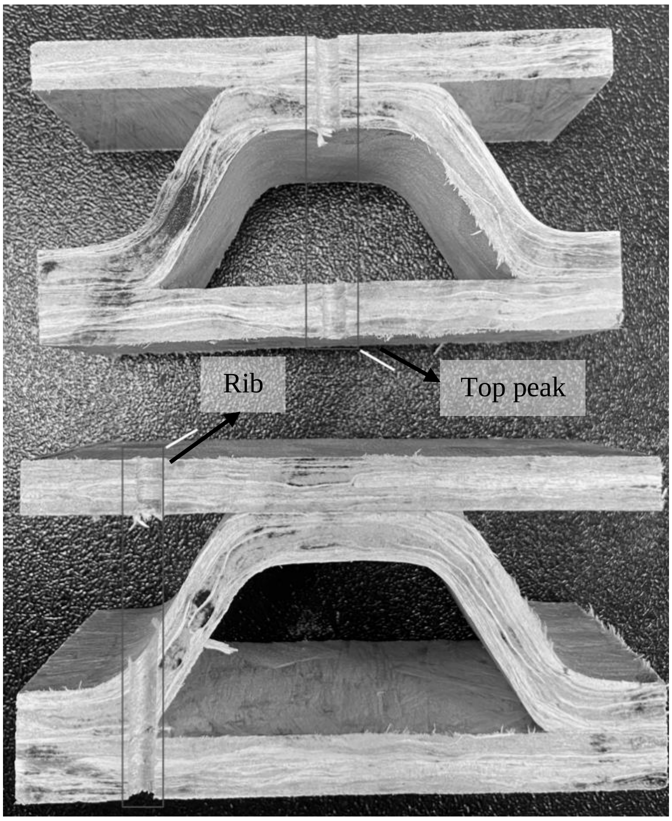


Source: Own Author.

4.1.3.3 Dowel Bearing

Dowel bearing strength was tested following the (ASTM D5764, 2013). Two types of samples were prepared corresponding to trapezoidal core peak and trapezoidal core middle (Fig. 22). Nails (10d penny size, 3.8 mm diameter, and 75 mm length) were embedded by a steel-loading block at a rate of 1.5 mm/min. The calculation for dowel-bearing strength was using the 5% offset method (AFPA-NDS, 2012) for determining yield load and dividing that load by the total bearing area of the nail.

Figure 22 - Dowel bearing samples and different core regions (Top and Rib)



Source: Own Author.

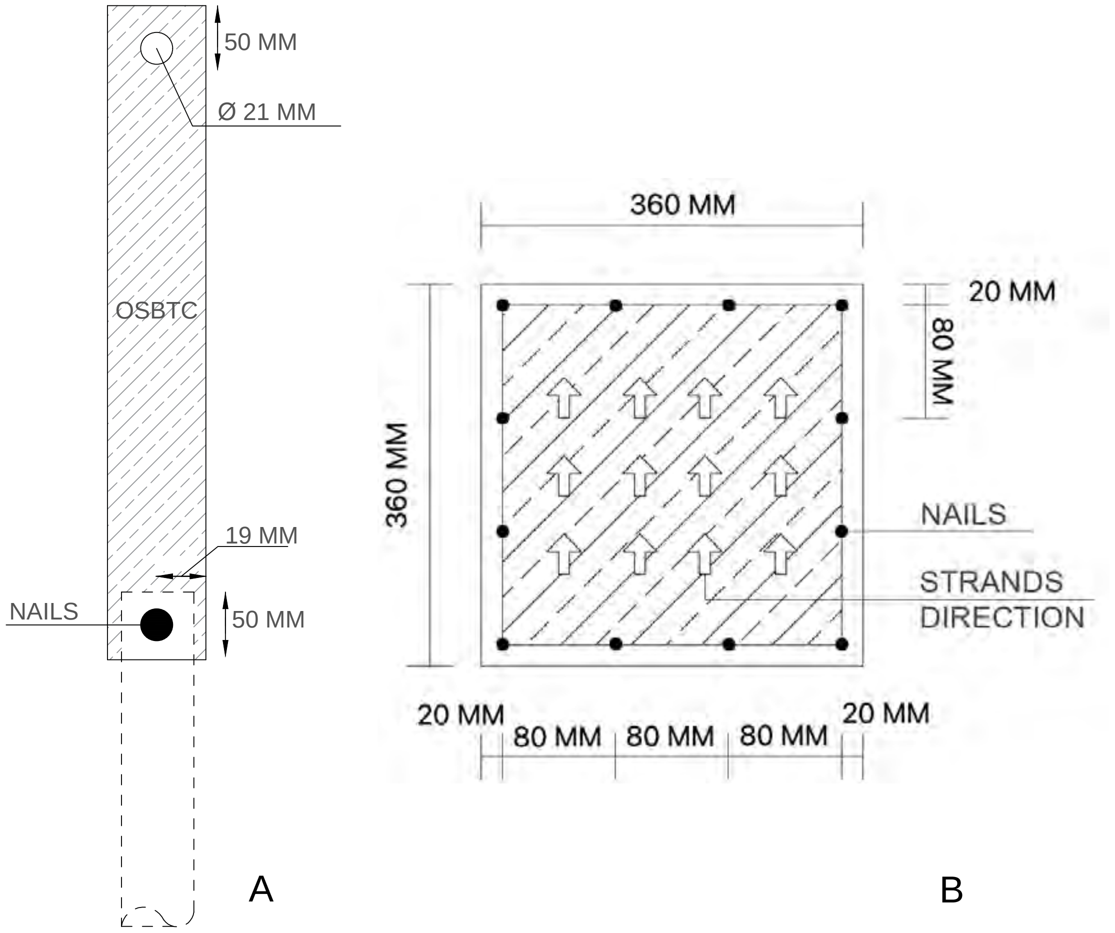
4.1.3.4 Withdrawal capacity

Withdrawal capacity was investigated following the (ASTM D1761, 2012). Nails (10d penny size, 3.8 mm diameter, and 75 mm length) were hand-driven, leaving approximately 13 mm in length towards the head. The withdrawal equipment was equipped with a pivoting joint to eliminate all eccentricities during the test. A tensile force was applied at a rate of 0.75 mm/min to reach a peak force in 90 seconds. Withdrawal capacity was calculated as the maximum load per millimeter of penetration depth (BREYER et al., 2015; WAY et al., 2016).

4.1.3.5 Lateral Connections

The lateral capacity was characterized by clamping the framing member (i.e., main member) and pulling on the sheathing member (i.e., side member) at a constant displacement of 2.54 mm/min (Fig. 21 E). The main member was nominal 2×6 (38×140 mm) Douglas-fir lumber which was 305 mm long. The specific gravity of main member was 0.49 (AFPA ADS/LRFD) (2012b). The side member was an OSB sandwich panel which was connected to the framing member with a single nail (20d penny size, 4.9 mm diameter, 101 mm length) (Fig. 23 A and Fig. 23 B). Nail-bending yield strength (F_{yb}) was 750 MPa. Yield load was determined using the 5% offset method and the mode of yielding was characterized as one of the six possible yield modes defined in the (AFPA ADS/LRFD) (2012b).

Figure 23 - (A) Lateral connection geometry; (B) Small-scale shear walls configuration



Source: Own Author.

4.1.3.6 Small-Scale shear walls

Small-scale shear wall tests were constructed following the (ASTM E564, 2018), and modified for a reduced specimen size (360 mm x 360 mm). A shear wall specimen consisted of framing members and a sheathing member. The framing consisted of top and bottom chords and two vertical studs of Douglas-fir (No. 3 grade), with a cross-section of 38 mm x 140 mm was used for framing lumber. The top and bottom chords were 360 mm long and the studs were 286 mm long. The sheathing was an OSB sandwich panel that was attached to the frame with the nails (4.9 mm diameter and 101 mm length) and spaced 80 mm around the wall and 20 mm from the edge of the framing members (Figure 23 B). For the ease of testing the walls were rotated 90 degrees and attached to a metal frame, which was clamped on a UTM. The top plate of the wall was attached to the actuator with a custom-designed metal rail. A displacement rate of 6.35 mm/min was used to load the walls. Load and cross arm deflection was continuously monitored.

4.1.4 Results and Discussion

4.1.4.1. Bending tests

Average bending properties determined from the testing program along with their associated variation are presented in Table 11. For comparison, data from other studies are also presented (Table 11).

Table 11 - Mean values of bending tests and other studies

Panel Type	**Bending stiffness (BS) (N-mm^2 / mm) (x10^6)**		**Maximum moment (MM) (N-mm / mm)**		**Source**
	Long.	**Transv.**	**Long.**	**Transv.**	
OSB Trapezoidal core with Balsa wood waste	**12.8 (25.5)**	**7.68 (2.08)**	**6496 (13.7)**	**3675 (4.88)**	**This Study**
Molded Core Panel (MCP)	19.1 (5.0)	12.1 (7.5)	3950 (12.3)	3353 (14.6)	(WAY et al., 2016)
Trapezoidal core Sugarcane Bagasse	2.1 (27.5)	0.73 (10.5)	1199 (29.9)	819 (19)	(POZZER et al., 2020)
Class APA PS 2-10 - Structural	1.8	0.7	920	650	(ASSOCIATION, 2011a)
Class APA PS 2-10 – Single Floor	8.7	2.1	2080	820	(ASSOCIATION, 2011a)

*Values in parentheses represent the coefficient of variation (%)
Source: Own Author.

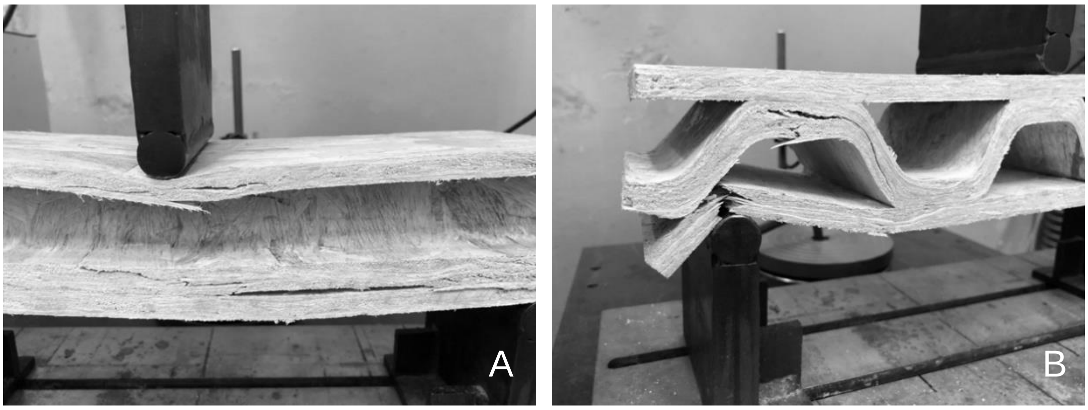
OSBTC had a high performance for both directions (longitudinal and transverse axis) compared with the trapezoidal core sugarcane bagasse. When compared to the Molded Core Panel (MCP), the properties of OSBTC were lower. This can be explained by the species used for both the products – Balsa vs. mixed hardwoods. It is important to mention that MCP and OSBTC presented different dimensions (total height and thickness of each layer), that contributed to the different values of EI and maximum moment.

Two major types of failure were observed - flexural failure located on the outer face (Fig. 24 A) and core shear failure (Fig. 24 B). The flexural failure occurred at the bottom fiber of the mid-span cross-section and developed to the end of the sample (Fig. 24 A). This failure was presented in the sample tested in the longitudinal direction. The shear failure in the core (Fig. 24 B) occurred for the samples tested in transversal direction until the total rupture of the external face and subsequent detachment of the core and face interface.

A minor failure that was observed in the sample tested in the longitudinal direction is local compression on the top surface of the OSBTC beam, where the load was applied. In addition, although the predominant failure mode was the flexural failure located on the outer face (Fig. 24 A), the OSB sandwich with trapezoidal core panels showed little failure in the connection interface between the core and the outer faces. This was also observed by (WAY et al., 2016) with a molded core panel. This proves that the junction between the core and the outer faces using castor oil polyurethane resin showed sufficient adhesive capacity for this sandwich panel configuration.

The failure is always initiated on the external faces since the OSB is relatively weak when the span is oriented perpendicularly to the direction of alignment of the strands in the external layer (WAY et al., 2016).

Figure 24 - Typical failures for OSBTC: (A) Localized flexural failure in the top and in the bottom (Longitudinal); (B) Core shear failure (Transverse)



Source: Own Author.

4.1.4.2 Flatwise compression

Table 12 presents mean values of flatwise compression of OSB sandwich panels with trapezoidal core and the values reported in other studies.

Table 12 - Mean values of flatwise compression in compare with another study

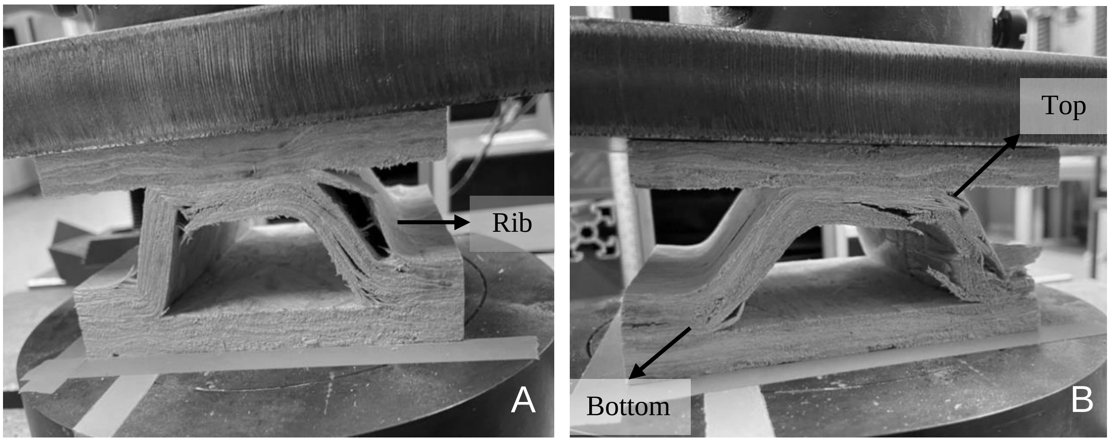
Type of panel	Load at 2.5 mm (kN)	Compression Strength (MPa)	Source
OSBTC (COV)	**10.0 (23.8)**	**0.77 (22.8)**	**This Study**
MCP (COV)	9.57 (28.5)	0.92 (28.9)	(WAY et al., 2016)

Source: Own Author.

The flatwise compression test showed a high variability (COV of 23.8%) as reported in (Table 12). This variability is an artifact of the panel design and testing configuration. The compressive strength is directly related to the part of the panel the sample was taken from. Way et al. (2016) reported even higher COVs than observed in this study. The specimen size was determined concerning the core geometry and this produced two different failure modes. The core had two regions, the top and bottom flange that had direct contact with the external faces and the rib that are the angular part of the trapezoid shown in the geometry of the core, these ribs connect the upper flange to the lower flange (Fig. 25 A). The first failure mode was rib buckling (Fig. 25 A). This failure occurred due to the rib not resisting the compression load. The second failure mode observed was the flexure failure in the top flange region (Fig. 25 B), this failure was also observed by Voth (2009).

Way et al. (2016) observed 65% of the studied samples presented failure as rib buckling and that the failure in flexure in the top flange was responsible for 22% of the samples. Other types of failures were also observed by the author, such as delamination between the core and facing (2%), shear failure in the core (8%), and finally, shear failure in the facings (3%).

Figure 25 - (A) Buckling failure of the rib portion; (B) Flexural failure in the top and bottom region



Source: Own Author.

4.1.4.3 Connection tests

Table 13 presents mean values of mechanical connections of OSB sandwich panels with trapezoidal core flat panels and the values of those properties according to another study found in the literature.

Table 13 - Mean values of mechanical connections and mean values of another study

Property	**Withdrawal (N/mm)**	**Dowel Bearing (MPa)**		**Lateral Connections (N)**	**Shear Walls**	**Source**
		Top	**Rib**		**Elastic Slope (N/mm)**	
OSB Trapezoidal core (COV)	**25.5 (17.6)**	**32.4 (22.2)**	**35.9 (19.4)**	**1549.6 (10.6)**	**319.3 (4.6)**	**This Study**
MCP	31.5 (31.4)	40.9 (19.4)	38.2 (18.4)	1034 (22.2)	453.9 (5.5)	Way et al. (2016)

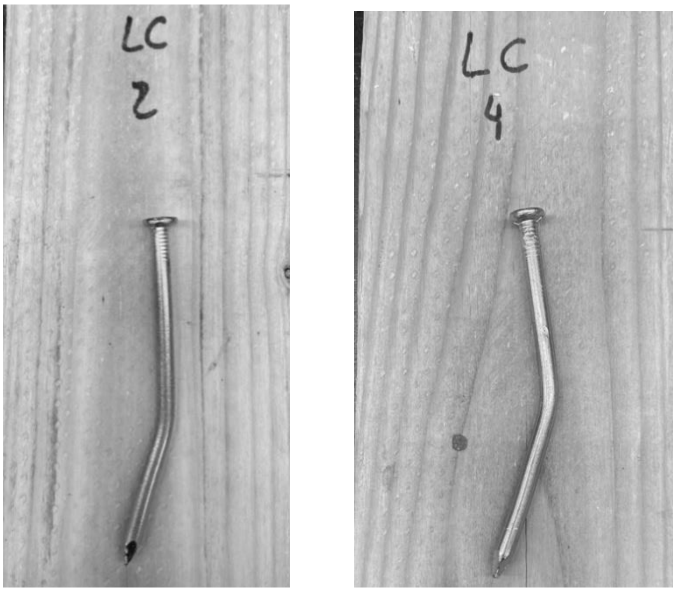
Source: Own Author.

The mean value obtained for withdrawal for the OSBTC sandwich showed a result slightly inferior to the molded core panel studied by (WAY et al., 2016). The variability of the OSB panels was also shown to be lower, which demonstrates the better homogeneity of the samples. The OSBTC panels did not show a load-slip before reaching the maximum load, whereas the MCPs presented a typical load-slip behavior. This behavior can probably be attributed to the addition of the adhesive in the sandwich panel production process and the ability of the core to compress during the test (WAY et al., 2016).

For the dowel bearing test, as the two cores present different geometries (MCP and OSBTC), it was not possible to make a comparison between them. The values both at the flange of the core and in the middle of the rib were similar indicating that the embedding region had no discernable effect on the dowel bearing strength of OSBTC. The results demonstrate that the trapezoidal core structure does not influence the dowel bearing strength; however, this resistance remains a function of the density (AFPA NDS (2012a)).

The edge connections for OSBTC when tested for lateral resistance exhibited a mode III_m yielding (AFPA NDS (2012a)) of the fastener (Fig. 26). This was the predominant mode of yielding for the connections, with the fastener bending within the confines of the framing member (Fig. 26) and slight crushing of wood in the OSBTC.

Figure 26 - Samples with the nail bended after the test



Source: Own Author.

4.1.4.4 Small-Scale Shear Walls

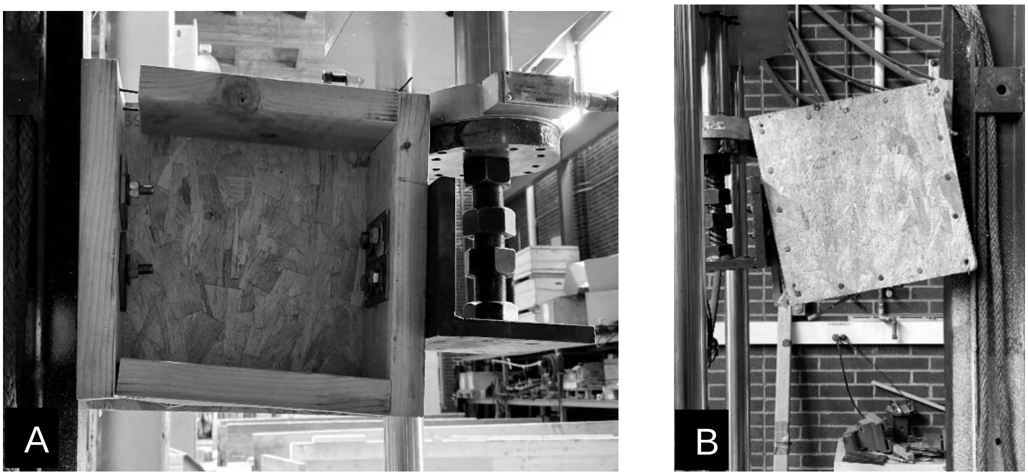
The shear wall values exhibited a low COV within the three samples tested (Table 13). Due to differences in the geometry of the samples and nail types used in this test, a direct comparison with (WAY et al., 2016) is not warranted.

The failure progress of three specimens during the test was relatively similar. The pull-out of nails in the connection between the bottom chord and vertical stud initiated in the early stage (Fig. 27 A). After these nails were completely pulled out, the rotation of OSBTC was observed. The rotation degree increased with the cylinder displacement. The failure at either corner of OSBTC or top and bottom chords of the frame developed because the two chords were fixed to the steel frame and the custom-designed metal rail. As a result, the nails in the connection between OSBTC and the frame caused the tear-out at the OSBTC corners (as observed in Specimen 1, Fig. 28 A) and the split on the chords (as observed in Specimen 2, Fig. 28 B). In the first two specimens, the nails showed little to no deformation. However, the nail deformation and nail pull-out occurred at the connection of OSBTC and the frame in the test of specimen 3 (Fig. 28 C)

It is worth mentioning that this separation between the OSBTC plate and the nail shown in the upper and lower corner because fasteners are not used, means that the nails which make this junction of the panel with the framing member were strongly tensioned, limiting the wall´s the ability to support the bottom plate of the OSBTC panel (WAY et al., 2016).

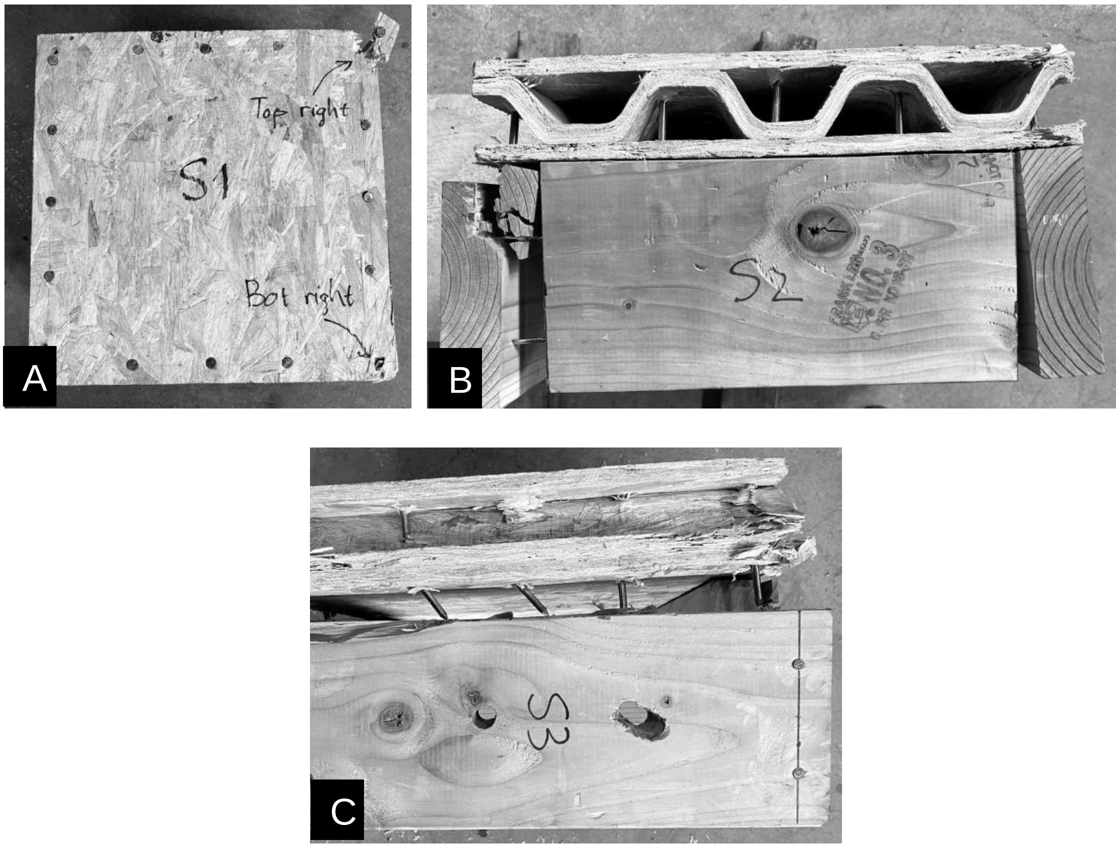
The third sample (S3) showed the failure also occurred in the upper right corner, although it had a failure much later in the test compared to the other two, the failure was also found in the upper right region with the pullout of the nail. It was also possible to observe in Figure 26, that the nails showed a slight deformation.

Figure 27 - Failure progress of small-scale shear wall specimens: (A) Nail pull-out at the connection of bottom chord and vertical stud, (B) Rotation of OSBTC followed by failures in OSBTC and chords



Source: Own Author.

Figure 28 - Failures of samples: (A) Sample 1: Tear-out at corners of OSBTC; (B) Sample 2: Split at chords of the frame; (C) Sample 3: Pullout and deformation of the nail



Source: Own Author.

4.1.5 Conclusion

The Balsa wood waste showed potential for forming the OSB sandwich with trapezoidal core panel. The adhesively bonded faces and trapezoidal core performed well during mechanical characterizations, proving that castor oil polyurethane has potential for application as an adhesive.

The trapezoidal geometry of the core proved to be a viable solution. The OSBTC had better flexural performance than many of its counterparts and comparable properties to molded core panels. The compression properties were similar to other sandwich panels previously studied. This validates the trapezoidal core design, which promotes the high stiffness of the sandwich panel.

To effectively design a connection with OSBTC, its withdrawal, dowel bearing, and lateral resistance information is needed. The testing program characterized these properties. For the dowel bearing, the values presented both in the flange and in the middle part of the rib in the core were similar, indicating that the region chosen for the inlay did not affect the dowel bearing strength. For lateral connections, the results were surprising and presented good performance. The small-scale shear wall samples performed as expected, in comparison to other studies in the literature. In summary, these results provide an insight into the connection performance of OSBTC.

In conclusion, the results suggest that this OSB sandwich with trapezoidal core panel, using Balsa wood waste agglomerated with organic resin, is a viable material. The OSBTC was more efficient when used in the longitudinal direction. These results are from small-scale panels. Therefore, characterizing performance of these panel types in full-scale sizes which represent real-world applications is recommended for future studies.

5 CHAPTER 5 – Analysis the deflections and predictions of critical and failures regions for OSB sandwich panels with trapezoidal core

This chapter presents a study aimed to evaluate experimentally the deflections and predictions of critical regions for the failure of the panel of the mechanical performance of OSB (Oriented Strand Board) panels stiffened by the trapezoidal core according to the bending direction. By the cross-section of the panels manufactured with strands of Balsa wood waste and castor oil polyurethane resin, the influence of the core direction on the flexural stiffness and ultimate load capacity was evaluated.

The following published paper is related to this Chapter:

BARBIRATO, G. H. A.; LOPES JUNIOR, W. E.; MARTINS, R. H. B.; SORIANO, J.; FIORELLI, J. Experimental evaluation and numerical modeling of the mechanical performance of OSB sandwich panels manufactured with trapezoidal core, Construction and Building Materials, 326, 126721, 2022.
https://doi.org/10.1016/j.conbuildmat.2022.126721.

5.1 Experimental evaluation of the mechanical performance of OSB sandwich panels manufactured with trapezoidal core

5.1.1 Introduction

The main reasons for studies on the production of sandwich panels with the various possible shapes for the core topology are due to the efficiency of this type of flexural structure (CASTANIE; BOUVET; GINOT, 2020; JIN; HU; WANG, 2015; KLÍMEK et al., 2016; SMARDZEWSKI; WOJCIECHOWSKI, 2019; SUSAINATHAN et al., 2017; TAUHIDUZZAMAN; CARLSSON, 2021; YANG et al., 2020; ZHANG; CHENG; LIU, 2014), which can be designed with low weight when considering the stiffness and strength. In this regard, the design for optimization of a hollow core sandwich panel requires the consideration of three main factors: (1) the use of non-planar structural sheets, e.g. with the core drawn based on a sinusoidal or trapezoidal line (ZHANG; KIM, 2019), or drawn as honeycomb arrangement (CHENG; LIU, 2012); (2) the use of a lattice system formed by dowels with variable cross-section (LI et al., 2019a; MENG et al., 2020); (3) the use of a lattice system with dowels made of material more strength than the applied to the top and base plates of the panel (LI et al., 2020; ZHANG et al., 2013; ZHENG et al., 2020). When deciding on the shape and material that will constitute the core of the panel, in addition to the material properties and the efforts due to loading, the production process of the parts and/or the entire panel must also be considered.

Agglomerated particleboards (MDP) were created in Germany in the early 1940s, to make the use of wood waste feasible given the difficulty of obtaining quality raw material for the production of plywood panels, due to the insulation trade imposed by the Second World War. In the mid-1970s, the process of developing OSB (Oriented Strand Board) type structural flat panels was initiated (IWAKIRI, 2005). These panels use almost all the logs, as they add thin and crooked logs, branches, and in some cases, the bark. The only neglected parts of the trees are the leaves and the root (SILVA, 2006). The world capacity for OSB rose from less than 2 million m^3 (1996) to approximately 44 million m^3 in 2017 (WOOD BASED PANELS INTERNATIONAL, 2019). Production of OSB continues to increase, reaching record production numbers in Europe with approximately 8.4 million m^3 in 2016 (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2018). The OSB has achieved an important stage for its applications in various industrial sectors, among which civil construction and furniture production should be highlighted. Due to its manufacturing process and the characteristics of an engineered timber product structural, OSB can be employed in the production of prefabricated wall panels, web of prefabricated wood I-joist, side reinforcements for wood trusses, roofing, and sheets of flooring panels (ASDRUBALI et al., 2017; COLLINS; COSGROVE; MELLAD, 2017; ORLOWSKI et al., 2019; SHMULSKY; JONES, 2011; YANG et al., 2020).

Based on the context presented that portrays the growing increase in consumption of wood-based panels combined with the need for technologies for the use of inputs considered as by-products, avoiding pressure on natural ecosystems, they have raised interest in academic and industrial scope for the development of non-conventional materials (NOCMAT) that use forest biomass by-products as raw material, aiming at the development of ecologically favorable materials and with competitive mechanical properties, compared with those of other commercial materials, thus being able to contribute to sustainable development. Several types of research developed in the last decade have evaluated the application of fibrous raw material of agro-industrial by-products or forest biomass, for the manufacture of flat particleboards agglomerated with organic or inorganic resin, in different world regions, and these studies have shown satisfactory results (BARBIRATO et al., 2018; BUFALINO et al., 2014; FERRO et al., 2015; FIORELLI et al., 2012). Fibers of natural origin have promoted an excellent alternative for the production of reinforced composites and their valorization is highlighted by (LI et al., 2019b; NGAOWTHONG et al., 2019), because of the possibilities of exploring its good mechanical properties of tensile strength and modulus, while contributing to the reduction of environmental pollution.

With the advancement of technology and the study of geometries to increase panel stiffness, recent studies have developed sandwich panels composed of a corrugated core creating new high-performance panels (KAVERMANN; BHATTACHARYYA, 2019; POZZER et al., 2020; VOTH et al., 2015; WAY et al., 2016). The advantage of the geometry of these sandwich panels is an increase in the rigidity of the assembly associated with a lower specific weight, consequently, the ease of handling and installation. These panels also feature good thermal and acoustic insulation, a good ability to absorb energy and distribute stresses across the core, and combinations of different materials can be made (DAVIES, 1998; PETERS, 1998; ZENKERT, 2005). The importance of the use of balsa wood in the production of different types of sandwich panels is highlighted (SAYAHLATIFI; RAHIMI; BOKAEI, 2021, 2020; SHIR MOHAMMADI; NAIRN, 2017), due to its fast-growing and high specific mechanical properties.

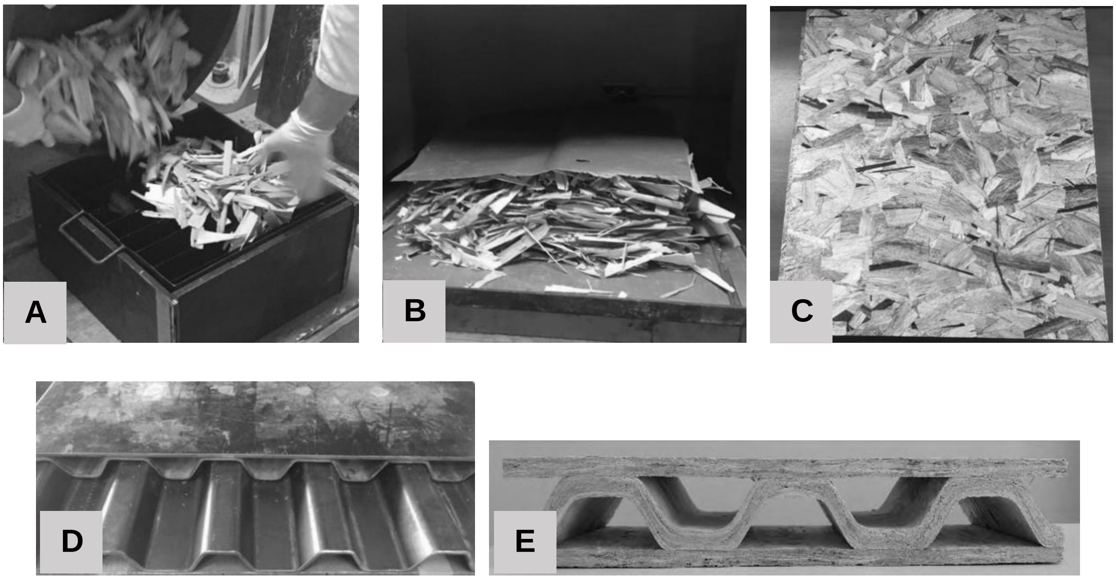
In this context of technology contribution with wood-based compounds, for this research, OSB sandwich panels were manufactured, with faces and a trapezoidal core produced from balsa wood waste and castor oil polyurethane resin, therefore being an unconventional and green material. The trapezoidal geometry was adjusted for the feasibility of its shape given by the arrangement and agreement of the strands, as well as to provide a good surface for contact and bonding with the flat plates of the panel. With this, the objective of this study was to evaluate experimentally the mechanical performance of the manufactured panels, in the context of the stiffness efficiency, as well as under the aspects of failure prediction, according to the longitudinal and transversal directions to the main axis of the trapezoidal core.

5.1.2 Material and Methods

5.1.2.1 Production of flat and sándwich OSB panels

The OSB flat panels of the faces were produced with a density of 650 kg/m^3 and two-component castor oil polyurethane (PU) resin, following the recommendations established by Barbirato et al. (BARBIRATO et al., 2018). After obtaining and drying the particles (strands) of balsa wood waste, with a length of 90 mm, the material was taken to a gluing machine where it received the PU-castor oil resin in a proportion of 12%, of the dry weight of the raw material. After mixing, the material was introduced into a flat panel forming mold, respecting the face-core-face mass ratio of 30:40:30. Subsequently, the material was inserted in a thermo-hydraulic press at an average temperature of 100 ºC for 10 min., with an average pressure of 5 MPa, and then kept in an air-conditioned environment for 72 h for the curing of the resin to occur. The products were trimmed to final dimensions (400 x 400 mm). The thickness of the panels assessed was 10 mm. The three-dimensional panel of the core was produced in a forming mold, with trapezoidal geometry. The raw material was inserted, and the pressure parameters were the same used to produce the flat panel. The junction of the external faces with the trapezoidal core was made by bonding with PU-Castor oil resin, which was applied to all contact surfaces of these parts. The amount of resin applied was 49 g, following the recommendations established by Pozzer et al. (2020). Figure 29 illustrates the production process described.

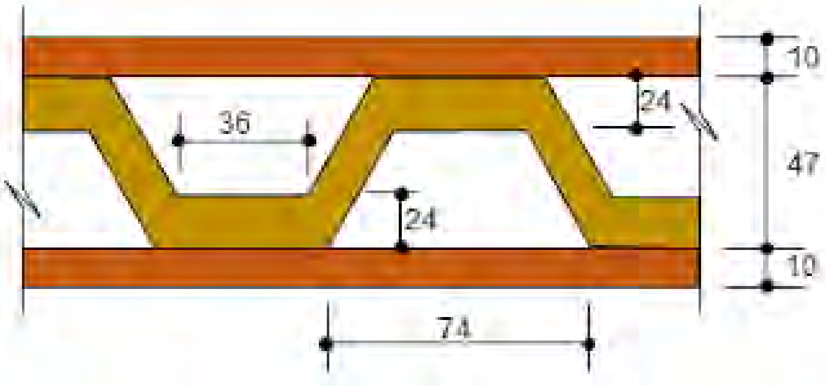
Figure 29 - Flat and sandwich panel production process: (A) strands orientation; (B) strands mattress; (C) flat panel; (D) trapezoidal mold; (E) sandwich panel with a trapezoidal core



Source: Own Author.

The finished sandwich panels for the bending tests presented in their cross-sections the average values of the dimensions of their faces and trapezoidal core elements represented in Figure 30.

Figure 30 - Shape and dimensions (mm) of the sandwich panel cross-section



Source: Own Author.

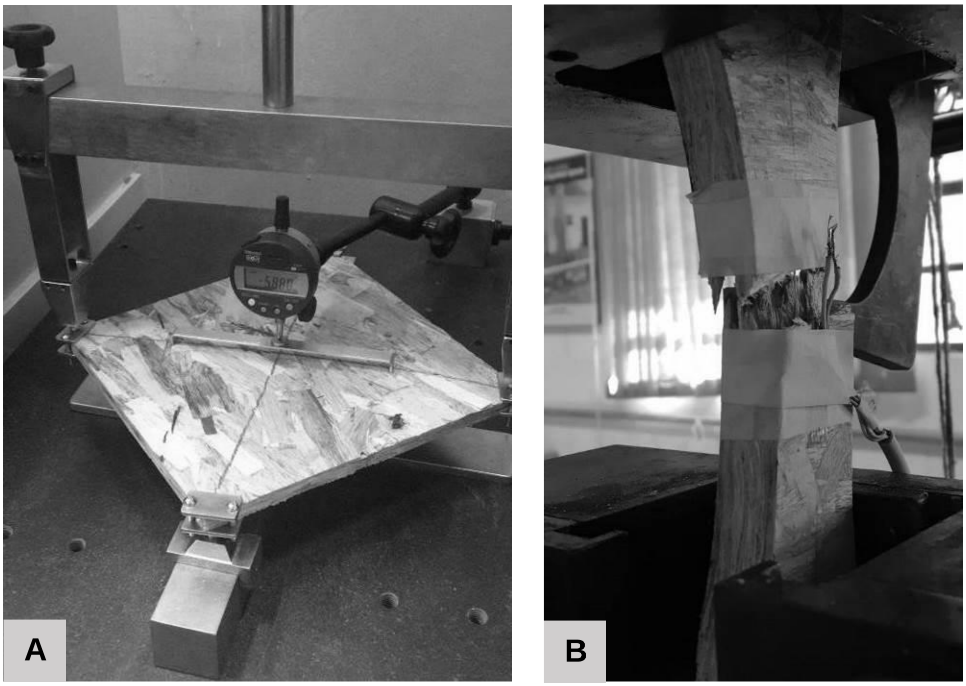
5.1.3 Mechanical characterization

5.1.3.1 Parameters and constitutive models for the panels modeling

The models for the behavior of the material were established based on the results obtained in tests of specimens extracted from flat plates according to the longitudinal and transversal directions, according to the standards ASTM D1037 (2016) and ASTM D3044 (2016). From these tests, tension and compression elasticity module (E), Poisson's ratios (υ), and shear modulus (G) were obtained (Table 14). To obtain the properties of Table 13, the tests were carried out on specimens in the longitudinal and transverse directions, and for the thickness direction, as a simplification, the property obtained experimentally in the transverse direction was considered for the orthotropic model.

Figure 31 shows the tests setup used to obtain the shear modulus, and the tension test to obtain the elasticity modulus and Poisson's ratio.

Figure 31- Setup for (A) Shear modulus test; (B) tension test to obtain the elasticity modulus and the Poisson's ratio



Source: Own Author.

Table 14 - Parameters for the material's behavior

Volume of sandwich panel	**X-axis**			**Y axis** [a]		
	E (N/mm^2)	υ	G (N/mm^2)	E (N/mm^2)	υ	G (N/mm^2)
Upper face	792.2	0.31	418	505	0.13	418
Trapezoidal core	505	0.13		792.2	0.31	
Bottom face	3983	0.31		2539	0.13	

[a] Were adopted equal to the values for the Y-axis obtained in the tests.
Source: Own Author.

5.1.3.2 Quasi-static bending tests of the sandwich panels

The characterization of the optimized OSB sandwich panels was carried out using quasi-static bending tests, according to the specifications of the (ASTM D3043, 2017). The test was conducted in a Universal Testing Machine (EMIC DL 30.000) and the static schema as shown in Figure 32A. Three specimens were made in the longitudinal direction (named SL panels) of 120 × 360 mm (Fig. 32 B) and three in the transverse direction (named ST panels) of 120 × 360 mm (Figure 32 C). The dimensions of the specimens were adjusted according to the geometry of the trapezoidal core so that each SL panel represented a section that was repeated to the ST panels. The standardized dimensions of the specimens are 75 × 200 mm ASTM D3043 (2017), however, this configuration of the specimens does not cover an entire cell of the core, so we chose to adjust the geometry, following the recommendations of the standard for the use of non-standard samples (ASTM C393, 2016). For non-standard geometries, the length of the specimen must be equal to the length of the support (span) plus 50 mm. As an example, the application of this configuration for non-standard geometries, Orlowski et al. (2019) evaluated pre-fabricated timber floor which the ratio between the span and the depth were too small (e.g. 8 times).

The test speed is set so that the specimen should fail within 3 to 6 min. The suggested standard crosshead speed of the machine is 6 mm/min. The load cell was used at the center span which has an axial force capacity of 300 kN. The load on the load cell and the displacement in the actuator head were obtained automatically by the data logger of the testing machine.

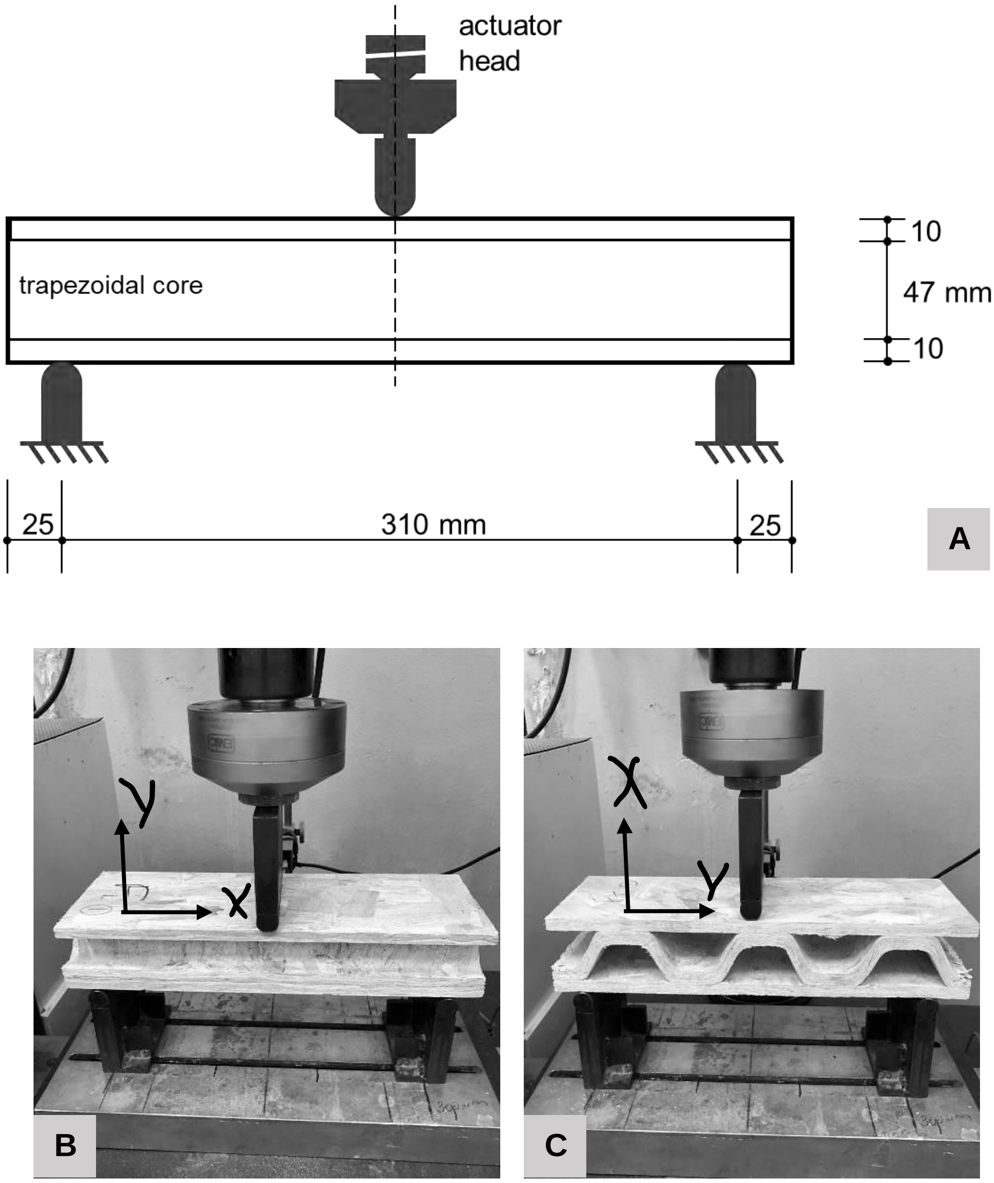
To determine the panel bending stiffness (E × I), Equation 3 was used and, Equation 4 was used to calculate the maximum bending moment (FbS) per millimeter of the specimen width.

$$\mathbf{E} \times \mathbf{I} = \frac{\mathbf{P} \times \mathbf{Ls}^{3}}{\Delta \times \mathbf{48} \times \mathbf{b}} \tag{3}$$

$$\mathbf{FbS} = \frac{\mathbf{P} \times \mathbf{Ls}}{\mathbf{4} \times \mathbf{b}} \tag{4}$$

Where P is the load applied (N), Δ is the deflection (mm), Ls is the span length (mm) and b is the specimen width (mm)

Figure 32 - Three-point bending test: (A) Static schema side view, (B) SL orientation sample, (C) ST orientation sample



Source: Own Author.

5.1.3 Results and Discussion

5.1.3.1 Bending behavior of the sandwich panels

The panels evaluated for quasi-static bending test at three points (Fig. 32 A), following ASTM D3043 (2017), have the values of maximum loads and their corresponding maximum moment shown in Table 15. To bending stiffness, the experimental results show a greater efficiency of 56% for the SL panels group to the ST panels group, for which the mean values resulted equal to 11.33 and 7.25 (×10^6 N mm^2 / mm), respectively. For the SL group, the mean value of the ultimate load (9448.7 N) resulted from 68% higher than the mean value for the ST group (5613.0 N). These results show the strong influence of the direction of the trapezoidal core concerning the bending direction of the sandwich panel.

Table 15 - Bending tests of the sandwich panels[a]

Sandwich panel	**Bending stiffness E × I (N mm^2 / mm) (× 10^6)**	**Maximum moment FbS (N mm / mm)**	**Ultimate load (N)**	**Source**
SL1	8.40	5314	8227.8	**This study**
SL2	15.10	7126	11033.0	
SL3	10.48	5868	9085.3	
SL **CV (%)**	**11.33** **30.28**	**6107** **15.21**	**9448.7** **15.21**	
ST1	7.80	3801	5886.1	
ST2	6.35	3526	5459.8	
ST3	7.60	3548	5493.2	
ST **CV (%)**	**7.25** **10.84**	**3625** **4.22**	**5613.0** **4.22**	
Class APA PS 2-10 - Structural	Longitudinal 1.80 Transversal 0.70	Longitudinal 920 Transversal 650	-	APA PS 2-10 (ASSOCIATION, 2011b)

[a] SL and ST is the average value for each panel group and CV is the corresponding coefficient of variation

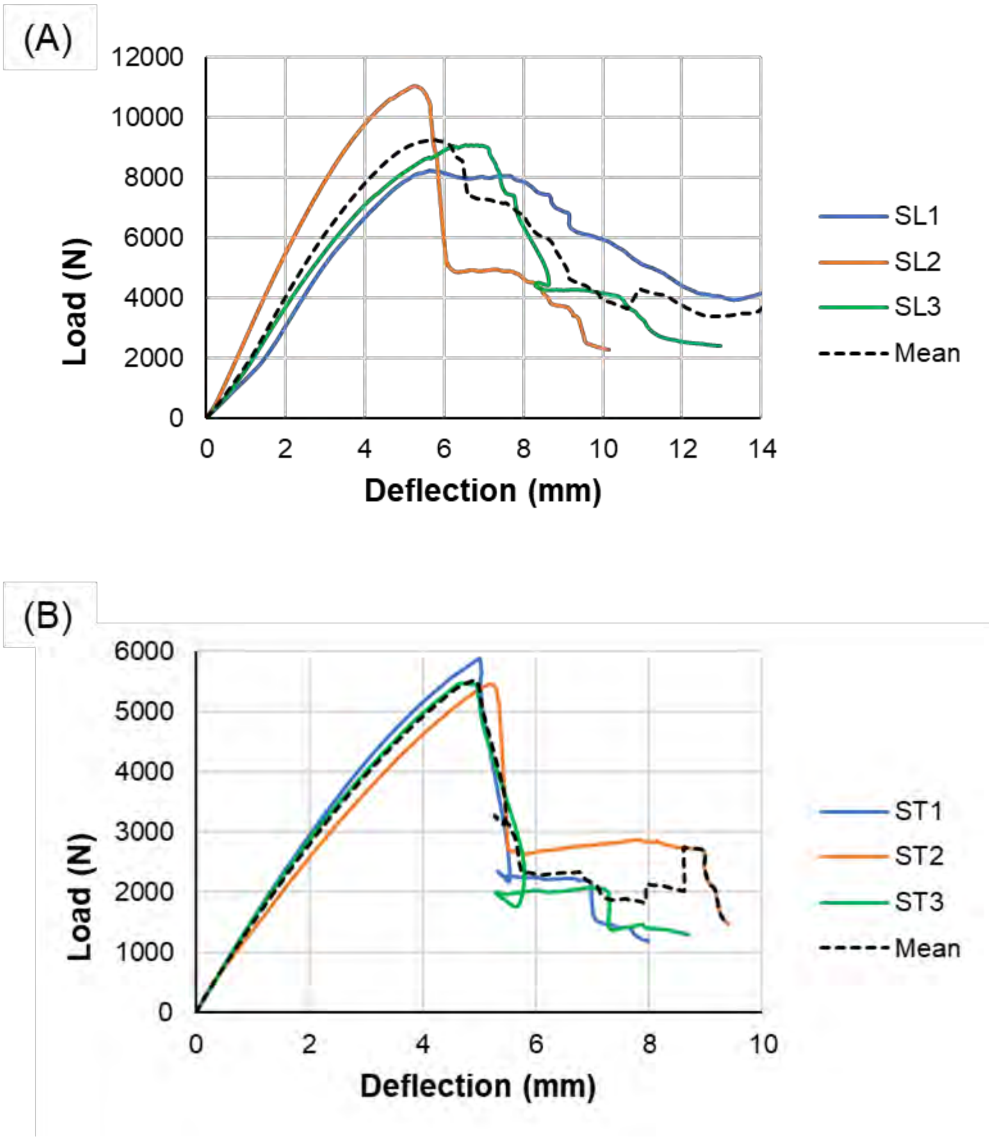
Source: Own Author.

The SL sandwich panels showed high performance both in the bending stiffness (E×I) and at the maximum bending moment when compared to the ST sandwich panels, this is due to the orientation of the trapezoidal core, for which a better stress distribution occurs in the case of the SL panels.

In comparison with the APA PS 2-10 (ASSOCIATION, 2011b), this classification indicated by the standard are requirements for classes of OSB panels with structural applications, such as on floors and walls, and as panels for the lining.

The load *versus* deflection curves recorded in the quasi-static bending tests of the SL and ST sandwich panel groups (Fig. 33) demonstrate the stiffness elastic-linear behavior for a wide range of the incremental loading, with the effect of non-linearity intensifying for the load levels closest to the respective maximum values. For each panels group, we note the similarity in the shapes of the load *versus* deflection curves. However, for the SL panels group (Fig. 33 A), the SL2 stands out for greater stiffness and greater intensity of the ultimate load. The three ST panels group (Fig. 33 B) show a more uniform bending behavior, both for stiffness and the ultimate load reached in the test.

Figure 33 - Load versus deflection curves assembled from bending tests, (A) SL panels, (B) ST panels



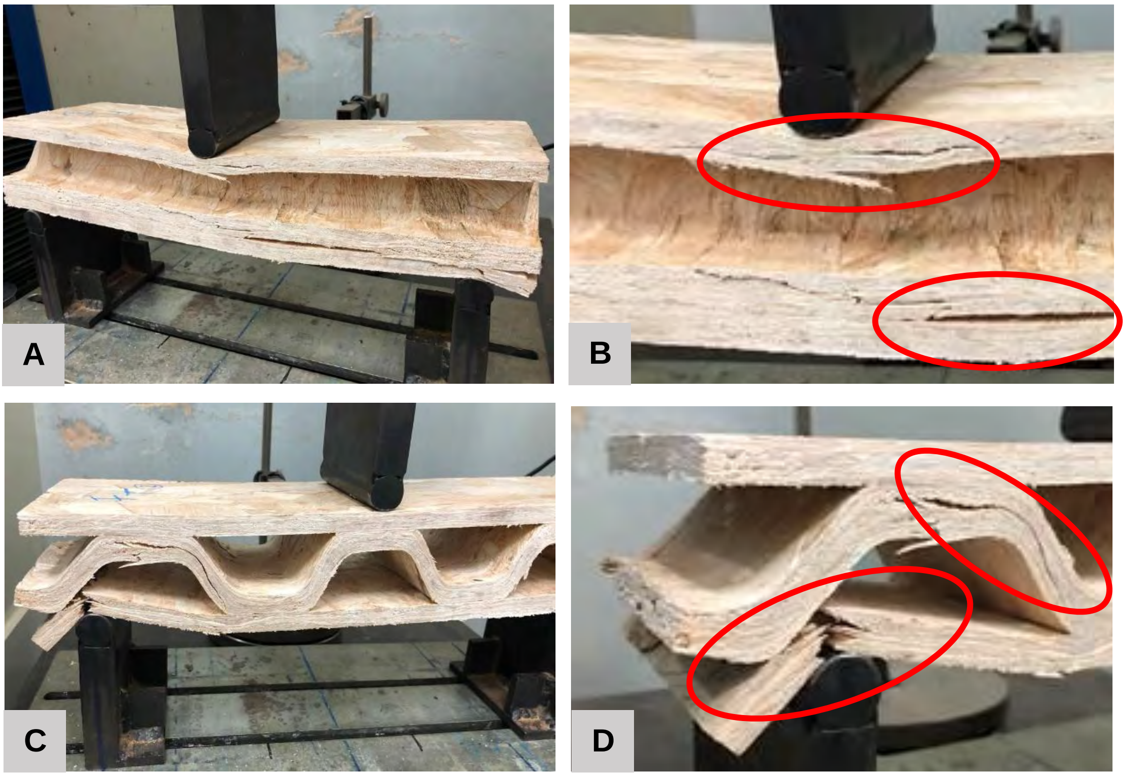
Source: Own Author.

5.1.3.2 Failure mechanisms of the sandwich panels

For this group, the failure started with compression of the upper external face (Figure 34 A and Fig. 34 B), then followed by the failure by tension and horizontal shear of the bottom face. For the ST panels, some points are more sensitive to failures, as in the regions of the bottom face with the supports used in the test. For this group, the failure started by the debonding of the core interface with the bottom plate as noted in the left support region (Figure 34 C and Fig. 34 D) and followed by shear and tension failure of the upper core region. These specific failures only compromised the test performance for the final loading step, then associated with the maximum bending loads of each panel (Table 15). Pozzer et al. (2020) evaluated sandwich panels of sugarcane bagasse particles with a trapezoidal core and found the same types of failures. Still, the authors mention that the detachment of the connection interface and the shearing of the core are acceptable failures according to the ASTM C393 (2016). The evaluation of sandwich panels produced with plywood sheets (KAVERMANN; BHATTACHARYYA, 2019), showed that the failure behavior of the panels under bending is governed according to the orientation of the corrugated core. For bending in the core direction, the failure by embedding in the load application point is followed by shear cracking, while in the bending transversal to the core axis the buckling of unsupported parts of the face was observed as a failure.

In comparison with the APA PS 2-10 (ASSOCIATION, 2011b), this classification indicated by the standard are requirements for classes of OSB panels with structural applications, such as on floors and walls, and as panels for the lining.

Figure 34 - Bending test and failure details, (A) and (B) SL panel, (C) and (D) ST panel



Source: Own Author.

5.1.4 Conclusions

The OSB sandwich panels with the trapezoidal core using Balsa wood residual agglomerates with polyurethane resin based on castor oil heat a high strength to quasi-static bending in both the longitudinal and transverse directions, surpassing the internal requirements required by the APA-PS-2 (ASSOCIATION, 2011b) in the application class for panels. The tests showed that the flexural stiffness of the panel in the longitudinal direction was 56% greater than in the transverse direction.

Feasibility consolidated the benefits of using the trapezoidal core to stiffen the sandwich panel manufactured with the technology of the OSB material, with the core oriented in the longitudinal direction of the panel, providing greater flexural rigidity and loading capacity. Thus, OSB sandwich panels with trapezoidal core have great potential for use as constructive elements.

6 CHAPTER 6 – Conclusions and final remarks

In a general context, and according to all the information presented throughout this thesis, bamboo is indeed an interesting and promising material. It showed potential for the production of oriented particle boards, using organic resin and presented an excellent physical and mechanical performance.

Also, Balsa wood waste has great potential for the production of OSB panels in applications in the field of construction components. Balsa wood presented a good physical and mechanical performance in both OSB flat panels and OSB sandwich with trapezoidal core panels.

However, the unconventional raw materials presented potential for production of flat OSB panels. The PU-Castor oil resin content was optimized in both the Balsa wood waste OSB panels and the bamboo OSB panels.

The mechanical characterization of OSB sandwich panels with trapezoidal core and flat faces presented an excellent performance, reaching all normative documents for applications as a structural component and the analysis of the critical regions and the regions of failure of this OSB sandwich panel showed that the longitudinal direction was superior to the transverse direction.

6.1 Proposals for future activities

Flat Panels

- Studies to optimize both the panel layers and the resin content, approaching commercial levels, presenting a new product alternative;
- Studies for a coating (micro or nano particles) on these panels, improving physical properties such as absorption and thickness swelling;
- Application and testing of new resins, such as synthetic resins, improving mechanical properties, especially internal bond.

OSB Sandwich panels

- Studies of new sandwich panel geometries;
- Studies to characterize the physical and thermal properties;
- Studies for waterproofing of these panels, increasing their durability when exposed to weather conditions.

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