Non-conventional Building Materials based on agro-industrial wastes

Francisco Antonio Rocco Lahr
Holmer Savastano Junior
Juliano Fiorelli
ORGANIZERS

Non-conventional Building Materials based on agro-industrial wastes

Non-conventional Building Materials based on agro-industrial wastes

Francisco Antonio Rocco Lahr
Holmer Savastano Junior
Juliano Fiorelli
ORGANIZERS

GRUPO Tiliform
Comunicação Gráfica Integrada

1st Edition 2015
Bauru, SP

Cataloging-in-Publication
Librarian Janaina Ramos – CRB-8/9166

N812 Non-conventional building materials based on agro-industrial wastes / Francisco Antonio Rocco Lahr, Holmer Savastano Junior and Juliano Fiorelli (Orgs.) – Bauru, SP: Tiliform, 2015.
328 p. ; 23 cm.

ISBN 978-85-69233-00-8

1. Unconventional materials. 2. Agroindustrial residues. 2. Organic Wastes. 4. Reuse (leftovers, bagasses, etc). I. Lahr, Francisco Antonio Rocco (Org.) II. Savastano Junior, Holmer (Org.). III. Fiorelli, Juliano (Org.). IV. Title.

CDD: 628.746

SUMMARY

7 PREFACE

9 BAMBOO PARTICULATE WASTE – PRODUCTION OF HIGH PERFORMANCE STRUCTURAL PANELS
Juliana Cortez-Barbosa, Elen Aparecida Martines Morales, Francisco Antonio Rocco Lahr, Maria Fátima do Nascimento, Victor Almeida De Araujo, Ulysses José Zaia

49 COMPOSITES OF EUCALYPT AND SUGARCANE BAGASSE: TECHNOLOGICAL CHARACTERISTICS
Ugo Leandro Belini, Juliano Fiorelli, Holmer Savastano Junior, Ângela do Valle, Poliana Dias de Moraes, Mario Tomazello Filho

75 DEVELOPMENT OF INNOVATIVE SUSTAINABLE WALLS COMPOSED OF BY-PRODUCTS OF RICE
João António Soares de Almeida, Maria Inês Vitória dos Santos, António José Barreto Tadeu, Nuno Albino Vieira Simões, João Pedro Faria Rama

103 GRANULOMETRIC CLASSIFICATION OF BAMBOO CHIPS FOR THE PRODUCTION OF PANELS FOR CIVIL CONSTRUCTION
Maximiliano dos Anjos Azambuja, Gabriela Perseguin Remedio, Rosane Aparecida Gomes Battistelle, Sérgio Augusto Mello da Silva, Ivaldo De Demenico Valarelli, Francisco Antonio Rocco Lahr

125 INFLUENCE OF ALKALINE MERCERIZATION OF TREATMENT IN THE TENSILE STRENGTH OF AÇAÍ FIBER
Antonio Mesquita de Lima, André Luis Christoforo, Lênio José Guerreiro de Faria, Tulio Hallak Panzera, Nubia Garzón Barrero

143 LIFE CYCLE ASSESSMENT OF WOOD-BASED COMPOSITES: STATE-OF-THE-ART AND OPPORTUNITIES FOR REDUCING ENVIRONMENTAL IMPACTS
Diogo Aparecido Lopes Silva, Aldo Roberto Ometto, Rita Pinheiro Garcia, Fausto Miguel Cereja Seixas Freire, Luciano Donizeti Varanda, André Luis Christoforo

179 NON-CONVENTIONAL PANELS PRODUCTS BASED ON AGRO-WASTES
Bwire Sturmius Ndazi, Wilson Otieno Ogola, Joseph Varelian Tesha, Elifas Tozo Bisanda

219 PARTICLEBOARDS BASED ON AGROINDUSTRIAL WASTE
Sergio Luis de Castro Junior, Diogo de Lucca Sartori, Mariana Pilar Gatani, Francisco Antonio Rocco Lahr, Valdemir dos Santos, Juliano Fiorelli

233 BABASSU HUSK FIBER PARTICLEBOARD
Nítalo André Farias Machado, Celso Yoji Kawabata, Juliano Fiorelli, Holmer Savastano Júnior

249 PARTICLEBOARDS PRODUCED WITH AGROINDUSTRIAL WASTES OAT HULLS (*AVENA SATIVA*) AND REFORESTATION WOOD
Luciano Donizeti Varanda, Amós Magalhães de Souza, Sabrina Fernanda Sartório Poleto, Diogo Aparecido Lopes Silva, Túlio Hallak Panzera, André Luis Christoforo, Francisco Antonio Rocco Lahr

277 PARTICLEBOARDS WITH PEANUT HUSKS AND CASTOR OIL POLYURETHANE ADHESIVE
Mariana Pilar Gatani, Victoria Granero, Juliano Fiorelli, Holmer Savastano Junior

297 RESIDUES OF SUGARCANE BAGASSE AND POLYPROPYLENE WITHOUT ADDITIVES FOR PARTICLEBOARD PRODUCTION
Rosane Aparecida Gomes Battistelle, Barbara Stolte Bezerra, Ivaldo De Domenico Valarelli, Francisco Antonio Rocco Lahr

313 USE OF AMAZON VEGETABLE FIBERS' WASTE AND WOODS FOR THE PRODUCTION OF POLYMERIC COMPOSITES
Raimundo Pereira de Vasconcelos, João de Almeida Melo Filho, Flávia Regina Silva dos Santos, Magnólia Grangero Quirino, Maria Gorett dos Santos Marques

PREFACE

In recent years, researches focusing on the development of non-conventional building materials, based on agro-industrial waste, have been gaining attention in the academic and scientific circles. In 2013 researchers of the University of São Paulo created, in the Faculty of Animal Science and Food Engineering (Pirassununga-São Paulo-Brazil), the NAP-BioSMat (Agriculture Biosysten Materials) and the Post-Graduation course on Materials Science and Engineering, with the concentration area "Development, characterization and application of materials applied to the agro industry". Aiming to bring together results of this work in University of São Paulo and in other relevant international research institutes, we organized a publication "***Non-conventional Building Materials based on agro-industrial wastes***" which has financial resource provided by Brazilian government agency CAPES.

This publication present scientific research developed by researchers of the University of São Paulo, São Paulo State University, Federal University of Santa Catarina, Federal University of Maranhão, Federal University of Amazon, University of the Amazon State, Federal University of Pará, Federal University of São João del Rei, Federal University of São Carlos (*Brazil*); Consejo Nacional de Investigaciones Cientificas y Tecnológicas (CONICET) and Centro Experimental de Vivienda Economica (CEVE) (*Argentina*); University of Coimbra (*Portugal*); University of Dar es Salaam, Kenya Polytechnic University and The Open University of Tanzania (*Tanzania*).

This book presents results of the research carried out with polymer based composites of some agro-industrial wastes: sugar cane bagasse, straw and husk left over from rice, açaí fiber, coffee husks, babassu husk fiber, wastes of oat hulls, wastes of reforestation wood, peanut husks, wastes generated in the production of Amazon vegetable fibers, bamboo particulate waste and life cycle of wood-based composites.

We express our thanks to the authors that provided their contributions and to the Post-Graduation course on Materials Science and Engineering of FZEA-USP, Brazil.

Prof. Francisco Antonio Rocco Lahr
EESC/USP/Brazil

Prof. Holmer Savastano Junior
Prof. Juliano Fiorelli
FZEA/USP/Brazil

BAMBOO PARTICULATE WASTE – PRODUCTION OF HIGH PERFORMANCE STRUCTURAL PANELS

Juliana Cortez-Barbosa and Elen Aparecida Martines Morales
São Paulo State University, Wood Industrial Engineering, Itapeva, SP.
E-mail: jucortez@itapeva.unesp.br and elen@itapeva.unesp.br

Francisco Antonio Rocco Lahr and Maria Fátima do Nascimento
University of São Paulo, Department of Civil Engineering, São Carlos, SP.
E-mail: frocco@sc.usp.br and fati@sc.usp.br

Victor Almeida De Araujo
Research Group LIGNO, Itapeva-SP, and University of São Paulo, Deparment of Forest Sciences, Piracicaba-SP.
E-mail: engim.victor@yahoo.de

Ulysses José Zaia
Fundição Brasileira de Alumínio, Tatuí, SP.
E-mail: uzaia@hotmail.com

ABSTRACT: The production of the high performance structural panel of bamboo particulates emerged with the need to obtain better utilization of this material in manufacturing of Glued Laminated Bamboo (Glubam). It was still intended to use other waste from bamboo chain from its primary processing, such as: tops, bases and small-diameter stems. The advantage of these panels is that the raw material supply is abundant, because it is a fast growing grass of easy levels of maintenance and harvest. The bamboo has been considered an excellent alternative to replace the wood in the market. Its use in the production of particleboards is well-accepted, because they behaved similarly those produced exclusively with wood. This is a preliminary work about a new bamboo-based composite, and it aims to evaluate the improvements in the utilization of reinforcements in particleboards, both made from bamboo species of *Dendrocalamus asper*. So, it was necessary to produce panels with and without reinforcement, aiming to have evaluation parameters. Castor oil-based polyurethane resin was used as the binder in view of materials with lower toxicity. The results of physical and mechanical properties presented are: specific gravity, moisture content, thickness swelling, water absorption, modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending, internal adhesion and screw pullout strength. The tests were performed according to standard documents EN 310/2000 and NBR 14810/2002, obtaining results superior to those stipulated by them. Therefore, it is shown that this panel is economically viable and environmentally friendly alternative for the utilization of the waste generated in bamboo processing of the species of *Dendrocalamus asper* species, combined with the castor oil-based polyurethane resin, favoring the used in structures, floorings, furniture, etc.

Keywords: Glued Laminated Bamboo. Waste. Particleboards. Structural reinforcement.

1. INTRODUCTION

Particleboard, among other lignocellulosic-based products emerged with the need to improve the utilization of raw material, applications of new product in specific situations, profitability, costs and market growth. Many lignocellulosic materials with their different species can be used to manufacture boards from small-diameter logs, chips, branches and sawmill waste.

These new products have applications in many industrial segments, especially in furniture, construction and for packaging. Many studies focus on the development of new examples of particleboards, and some of them can reach values of mechanical properties for structural purposes.

In this sense, the bamboo can be a good alternative for the particle production, considering the high mechanical strength of its fibers. Its application is ancient and is widely used in the eastern countries, while the western region it is still seen as a lower quality material, since only in last decade the industries started to develop products of this raw material.

In practice, it serves as food for humans and animals, biomass for renewable and clean energy, construction materials and raw material for many industrial sectors, as well as it can be identified as an element to contain erosion, and for the excellent values of strength and stiffness in parallel tension to grain.

It is a grass that offers many economic advantages, such as fast-growing, perennial, high adaptability, ease of maintenance and harvesting; because it does not require techniques with complexity for its establishment as planting, minimizing the pressure on indiscriminate use of wood species in extinction risk.

In Brazil, the lack of adequate processes of mechanization and automation of the bamboo generates large waste amounts, which can become environmental pollutants if it is not used. Besides this waste, bamboo laminas have been studied for their application as reinforcement in timber or in wooden composites, increasing its diversification and valorization of the use of lignocellulosic materials of lower earned value, making them an eco-efficient alternative.

This chapter aims to demonstrate, through this new product patented by the UNESP Agency of Innovation (Agência UNESP de Inovação – AUIN), a possibility to use and valuation of this important material, the bamboo, through a composite of high structural performance, formed by particles of waste and with reinforcement with bamboo laminas.

2. LITERATURE REVIEW

2.1 BAMBOO

According to Pereira and Beraldo (2007), bamboo is an ancient plant and of a crescent importance to humanity, and it is known as the "poor's wood" in India, "The people's friend" in China and "the brother" in Vietnam; in the west it is less known and is usually associated to lesser importance constructions.

Pereira (1997) comments that the bamboo is a natural resource that spend less time to be renewed, and there is no forest species that can compete in growth speed and profitability per area. He adds that its structural properties, in relation to weight-resistance outweigh the woods, being compared with steel and fibers.

To Lima Júnior and Dias (2001), the bamboo is a vegetal material whose mechanical properties indicate good potential to be exploited for engineering. The plant has long stems, internally hollow, which are closed in approximately regular intervals, by a diaphragm in the regions of the nodes; its walls have excellent tension and compression strengths, comparable to most hardwoods, emphasizing its low specific weight about 8.5 kN/m^3.

The stems are formed by an alternate series of nodes and internodes. With the growth of bamboo, each new internal node is surrounded by a protective stem leaf (sheath). The stems are formed by fibers, vessels and sap conductors, which are non-uniformly distributed in transversal section, surrounded by a kind of matrix called parenchyma. These stems differ according to species in length, wall thickness, diameter, nodes spacing and strength. They are mostly hollow, and in some species can find solid internodes (GHAVAMI, 2004).

According to Beraldo, Espelho and Ferreira (2006), bamboo stems are normally attacked by insects when they are exposed to the environment or by microorganisms when they are in contact with the ground. The young stems harvested before they have branches and leaves, these stems are not attacked by woodworms, although they have the same dimensions of mature stems. The real explanation for this fact is related to the absence of starch, which is only metabolized by mature stems.

The *Dendrocalamus giganteus* species has stems with height among 24 and 40 meters, internodes among 0.40 to 0.50 meters, diameters among 0.10 to 0.20 meters and with dense wall, which however varies with the height. It is a bamboo species of general uses and it adapts to tropical and subtropical regions. Some characteristics of giant bamboo are shown in Table 1 for a better understanding of this species (PEREIRA, 1997).

Table 1 – Characteristics of *Dendrocalamus giganteus* stem

Stem layer	Vessels (%)	Fibers (%)	Parenchymas (%)
Internal	11	16	73
Intermediate	9	32	59
External	8	55	37

Source: Pereira (1997).

Pereira (1997) incites that the fibers are the primarily responsible for the resistance of bamboos, with in general a distribution of 40-90% in external part and of 15-30% internally. Although it is a grass, bamboos have arborescent habit, and in the same time that tress, they have an aerial part composed by stem, leaves and branches, and another, underground, with rhizome and roots (Fig. 1).

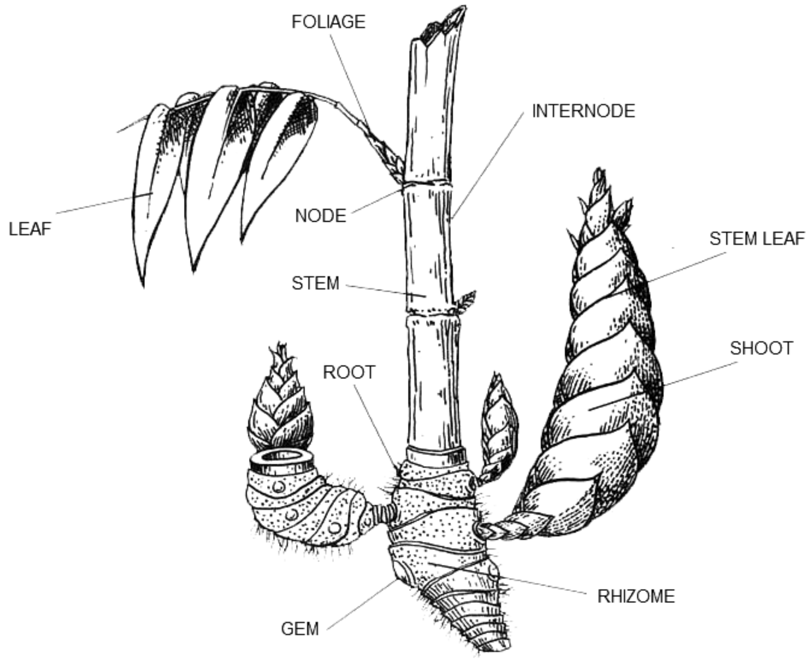


Figure 1 – Bamboo parts. Source: National Mission on Bamboo Application (2004).

Hidalgo-Lopez (1974) emphasizes the rhizome function is related to store nutrients and also it serves as reproducing structure. Bamboos present three types of rhizomes (Fig. 2):

i) Pachymorph: clumping and sympodial, present genres of *Dendrocalamus*, *Bambusa* (with sub-genre *Guadua*), *Elystrosthachys*, *Gigantocloa*, *Oxytenantheru*, etc.;
ii) Mixed type: semi-clumping and anfipodial, present in almost all genres;
iii) Leptomorph: stolon or running and monopodial, present genres of *Phyllostachys*, *Arundinaria*, *Sasa*, *Shibataea* and *Sinobambusa*. (LOPEZ, 1974)

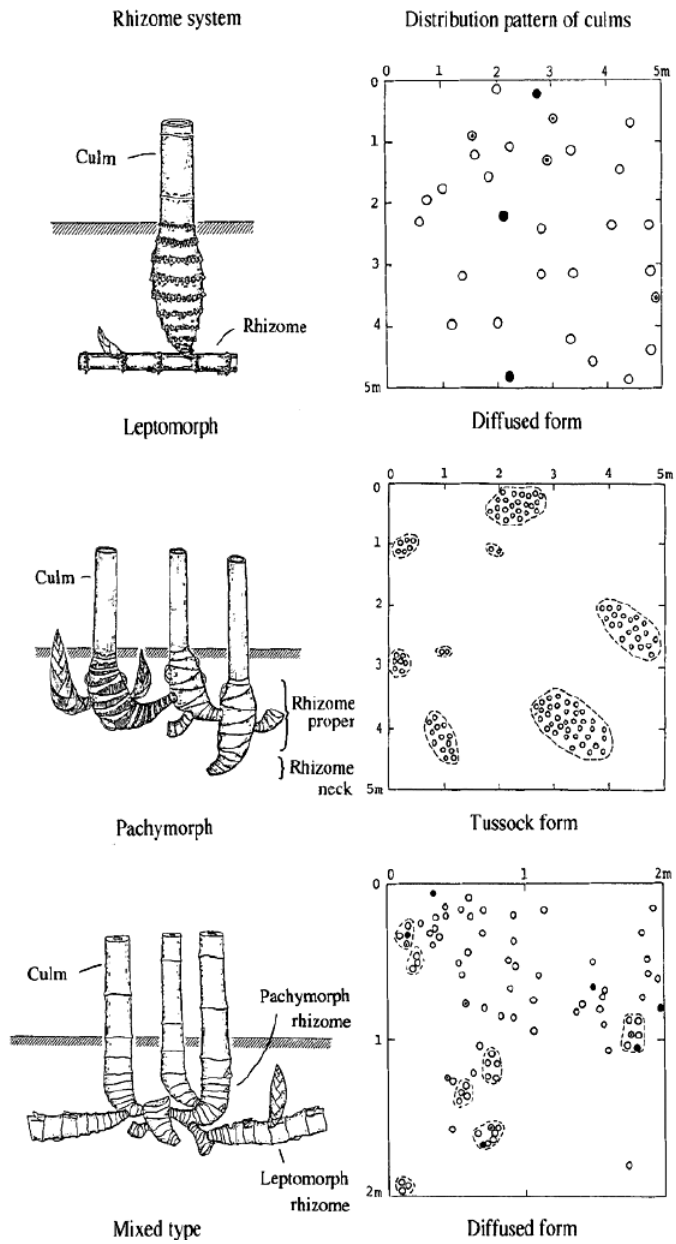


Figure 2 – The rhizomatic systems of bamboos and spatial distribution of woody bamboos culms. Source: Makita (1998).

The Figure 3 shows the applications of the bamboo parts according to the age of the plant.

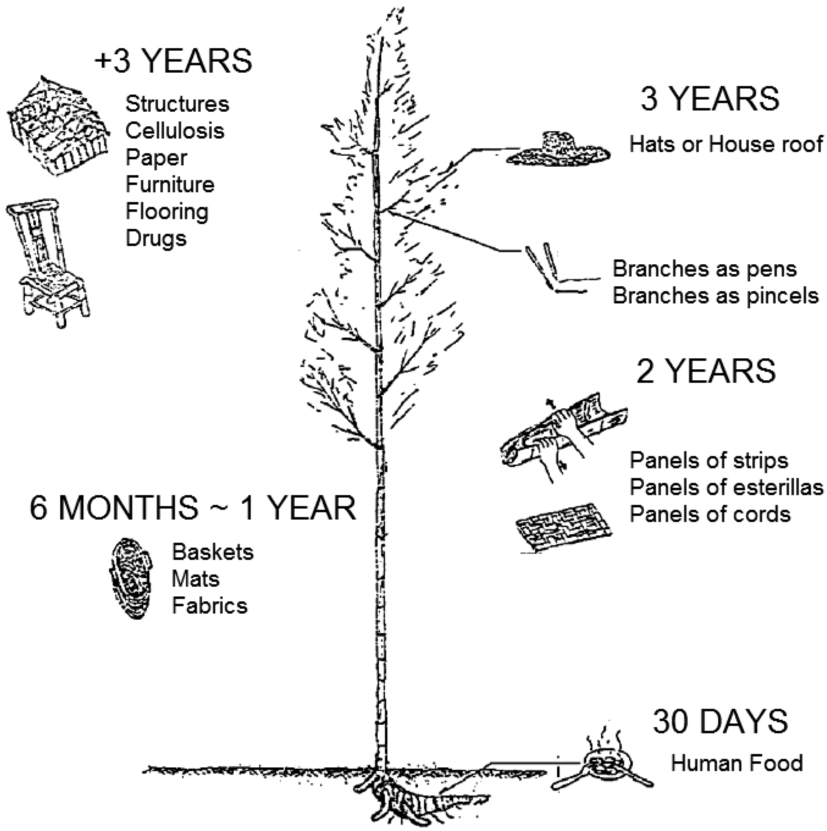


Figure 3 – Classification of the commercial parts of a bamboo plant. Source: Jaquez (1990).

2.2 PARTICLEBOARD

First particleboard industry in Brazil was created in 1966 in Curitiba, Paraná. Thenceforth, many industrial plants emerged in South and Southeast regions, and the Brazilian production of particleboards achieved the mark in 1998 of 1,313 million of m^3. Particleboard has multiple applications, contrasting with the uses for furniture and room partitions, and secondarily in the construction (IWAKIRI et al., 2006).

According to Dacosta et al. (2005), in recent years, raw material yield in sawmills has been characterized in a relatively low level, increasing the volume of waste, causing a strong tendency of use of these same and of lower quality wood for the particleboard production.

Particleboard is a panel produced with the use of a synthetic adhesive, wherein the particles are consolidated by an application of heat and pressure in a specific press. The geometry of the particles, their origin in relation to the species and their homogeneity, types of adhesives, pressing time, density and manufacturing processes can be modified to produce different products.

According to Nascimento (2003), the raw material for the particleboards production can be: forest material from pruning and thinning; coarse industrial waste such as slabs, regular and irregular pieces, waste rolls from lamination, etc.; fine industrial waste, such as sawdust, shavings; wood chips of industrial processing of furniture and carpentry; lignocellulosic materials such as bagasse, rice straw and other agricultural waste, this latter pure or mixed with wood particles.

During the manufacturing process, special additives may be added to improve dimensional stability of the board, increasing the fire resistance, among other properties.

Wood low density is one of the main requirements regarding the suitability of a species for particleboard production. The compaction ratio, which is the ratio of the specific gravity of the board and the wood used in this board, defines the level of densification of this material, and it will reflects in the physical mechanical properties of the boards. Suitable compaction ratio for particleboards production is in the range of 1.3 to 1.6, and therefore low density species are the most recommended. Values above 1.6 can improve the strength properties, but on the other hand, the thickness swelling will be superior due to the higher compression on the material during the pressing stage of the board (IWAKIRI et al., 2006).

The particle size influences in the classification of the boards as homogeneous or multilayer. In homogeneous boards, particles with different granulometry have the same proportion, resulting in a single operation in the forming stage of the board. Multilayer boards are formed by three layers or more. Constituent particles are distributed in successive operations, symmetrical about a central layer. Internal layers are composed of larger particles and outer layers are arranged with smaller particles (NASCIMENTO, 2003).

Properties such as static bending and internal bond are significantly affected with variations in dimensional elements of the particles. Other process variables such as type and amount of resin, chemical additives, moisture of the particles and pressing cycle must be controlled to ensure the required quality according to standard documents (IWAKIRI, 2003).

Santos et al. (2009) emphasize particulate products formed by particleboards, mineral boards and fiberboards have replaced the products traditionally used and many particleboard types are conquering commercial space because of: best price/performance ratio, range of available products, flexible application for various purposes and growing awareness within modern society that is no longer viable the processes with high levels of losses of wood.

In the search for alternative processes for industrial production, which predatory processes are conventionally used, it was found, in the bamboo material, a great alternative for the production of particles. Bamboo is present in the culture and life of humans since the beginning, serving as food, shelter, tools, utensils and a myriad of other items. Currently, it is estimated that about one billion people worldwide have bamboo as a source of livelihood. Due to its contribution, today there is a large industrial development of the use of this material (LIMA, 2008).

Despite its reduced diameter, when bamboo is compared to wood, it can achieve standards of boards considerable for certain applications. The machinery for wood, some methods and processes can be adapted for bamboo. Furthermore, despite its large size, this material has small distortions and a good stability for the production of panels (MOIZÉS, 2007).

It is a plant that offers many economic advantages, such as fast-growing, perennial, and ease of establishment, maintenance and harvesting, because it does not require techniques with complexity for its establishment as planting. It can be used as a substitute agronomic in marginal areas, optimizing productions which receive more attention of foreign markets, thus replacing wood in several aspects (SLONGO; KUPERSTEIN; BUENO NETTO, 2009).

The panels of bamboo particle emerged with the objective to utilize the waste of bamboo processing such as tops, bases and stems of small diameter (KAI; XUHE, 2005). Therefore, according to these authors, the great advantage of these types of panels is that the supply of raw material is abundant.

Calegari et al. (2007) accept the utilization of bamboo stems/culms for the production of particleboard, since these boards behaved similarly to those produced exclusively from wood.

Recently, the increase in timber prices and the declining of the availability of wood resources promoted the search for some alternative. Similar to wood, bamboo is a natural organism. It is resistant, light and renewable, and with a strong ability to adapt to the environment. The growth speed is much higher than that of most trees and their properties are superior to those of juvenile wood of rapid growth. For example, in comparison with the wood, bamboo has a higher strength/weight ratio, superior abrasion resistance, and a low expansion ratio after moisture absorption. The best way to use bamboo on a large scale is to design and produce a series of bamboo panels based on different structures and functions according to the properties of bamboo (KAI; XUHE, 2005).

With respect to wooden particleboards Iwakiri et al. (2000) evaluated the feasibility of using woods of *Eucalyptus maculata*, *E. grandis* and *E. tereticornis* as waste of processing in sawmills, for production of chipboards. It was produced boards of these three species, and also of their proportional mixing, with two levels of resin (8 and 12%). The panels were manufactured with nominal density of 0.75 g/cm^3 with pressing temperature of 140°C and pressing time of 8 min. The panels produced with 12% of resin showed better results than those with 8%.

Haselein et al. (2002) produced structural particleboards using *Pinus elliottii* (Engelm) particles with nominal dimensions of 110, 75 and 40 millimeters in length, 0.5 to 1.0 mm thick and 20-millimeter wide. The particles were randomly oriented in molds without background with dimensions of 50 x 50 x 20 cm. The mats were pressed at 180°C for 10 min to obtain a thickness of 9.5 mm and a density 0.7 g/cm³, approximately.

Dias (2005) presents a study on using of castor oil-based polyurethane in chipboards manufacture. Panels were produced with a composition of *Eucalyptus grandis*, *Eucalyptus urophilla* e *Pinus elliottii*, pressed at a temperature of 60°C and 90°C with addition of paraffin emulsion to this mix, with the objective to improve their hygroscopic properties of the panels.

Dacosta et al. (2005), evaluated mechanical properties of wood chipboards, made from waste of *Pinus elliottii* (Engelm.). Two residues, wood chips and shavings, were used pure or mixed with urea-formaldehyde-based adhesive. Nominal densities of the boards were 0.6 and 0.7 g/cm³. The specific pressure applied was 30 kgf/cm and the temperature of boards was set at 180°C. The closing time of the press was 40s, and the total pressing time, applied to promote the evaporation of water and the adhesive curing was 8 min. Among results of other tests, in the screw pullout strength test, it was observed that with the increase of density this property showed a higher value.

Cabral et al. (2007) evaluated the properties of Oriented Strand Boards (OSB) produced with wooden flakes of *Eucalyptus grandis*, *Eucalyptus urophylla* and *Eucalyptus cloeziana*. The density of the boards was close to 0.70 g/cm³, and with phenol-formaldehyde resin in a proportion of 8% of solids in dry mass of particles. Boards were pressed at 32 kgf/cm² and at a temperature of 170°C.

Melo and Del Menezzi (2010) evaluated the influence of density on physical-mechanical properties of particleboards made with particles of *Eucalyptus grandis* W. Hill ex Maiden. Thereunto, three densities were tested: 0.6, 0.7 and 0.8 g/cm³. In each density level were produced panels with 8% of urea-formaldehyde resin and 1% of wax/paraffin. The pressing occurred at 3.0 MPa for 8 min at a temperature of 180°C.

With respect to bamboo chipboards, Lima et al. (2008) made homogeneous chipboards manufactured with bamboo of *Dendrocalamus giganteus* species, with the addition of bract (leaf stem), arising from the clump of bamboo used, high in fiber, with the objective of using it to replace solid wood and also to add earned value to the material. Five treatments were considered: 100% bract, 75% bract and 25% bamboo, 50% of each material, 25% bract and 75% bamboo and finally 100% bamboo. The same were produced with urea-formaldehyde resin (10% of solids in dry mass) and composed with 20% of fine chip and 80% of thick chip.

Silva et al. (2008) produced homogeneous chipboards with leaf stems and reinforced with bamboo waste of the species *Dendrocalamus giganteus*, in the proportion of 75% of bamboo and 25% of leaf stems manufactured with different percentages of urea-formaldehyde resin (8%, 10% 12% to 15% by weight of dried material), composed of 80% of coarse particles and 20% of fine particles.

Carvalho, Valarelli and Visnardi (2009) produced chipboards with particles of bamboo and Pine. The materials used were: urea-formaldehyde adhesive, in the proportion of 10% (dry weight of material), bamboo particles from the apical part of the stems and Pine particles from industrial processing. The particles suffered the action of a chipper, and then they were classified in two types of sieve: one of 1.2 mm (fine) and other of 4 mm (thick). Particles were pressed at a temperature of 130°C for a period of 10 min.

Laemlaksakul (2010) evaluated the technical feasibility of experimental particleboards (single-layer) from bamboo waste of *Dendrocalamus asper* (Backer) species, by converting bamboo into strips, which are used to make laminated bamboo furniture. The materials were placed in a mold box of 400 mm x 400 mm, and then the panels were compressed with a hot press until it reached 15 mm at a temperature of 120°C, and a pressure of 150 kg/cm^2 for 5 min. The adhesive used was urea-formaldehyde at 86.94% of solid content.

The values of the physical mechanical properties obtained for mentioned boards will be explained in tables in the results topic, for better interpretation and comparison of the data.

2.3 RESINS AND APPLICATIONS

Organic polymers of natural or synthetic origins are the principal chemical ingredients in all formulations of adhesives for wood. A polymer is compound formed by reaction of small and simple molecules with functional groups which allow their combination to proceed to a higher molecular weight under suitable conditions. First adhesives for wood based on synthetic polymers have been produced commercially in the 1930s. This marked the beginning of fundamental changes in the composition of adhesives of natural synthesized polymers. These resins should not be stronger, tougher and more durable than wood, but also have much higher water resistance than resins based on natural polymers (VICK, 1999).

According Plepis (1991), polyurethane-type polymers appeared in 1937 and achieved great importance during the Second World War, and its production was tripled in the 70's.

The adhesive glues for wood have an important role in the development and growth of forest products industry, and they have been a key factor in the efficiency of use of wood products. By far, most uses of wood resins have been applied in the manufacture of building materials such as: plywood, particleboards, fiberboards, laminated boards, etc. (VICK, 1999).

Marques (2009) considers applications of polyurethane-based resins started in Germany for bonding of non-vulcanized rubber with steel using triisocyanato triphenylmethane; this technology has been extended to wooden planes in early 40s. Currently, polyurethane resins are used in numerous examples for various markets, they are known for their excellent adhesion, good flexibility, hardness, high cohesion, abrasion resistance and fast cure. The polyurethane adhesives are mainly used in the respective sectors: packaging, instruments, books, footwear, plywood, furniture, medicine, flexible laminates, assemblies, electronics, aerospace, automotive, abrasives, and other textiles.

Natural adhesives can be of animal proteins (albumin, gluten and casein) or vegetal (potato, soy, wheat and latex).

According Maloney (1996), due to the need to decrease the formaldehyde emission, a carcinogenic product, derived from urea-resins, various studies were developed through their mixtures with other resins, such as melamine resins, which also provide greater moisture resistance to the boards.

There is a global trend in demand for biodegradable materials, non-polluting and biomass-based products. According to Araújo (1992), this trend has leveraged researches with polyurethane derived from castor oil, thus expanding new perspectives for its development.

According to José and Beraldo (2006), internationally known as "castor-oil" and in Brazil as "caturra" or "mamona", the castor bean (*Ricinus communis*) is a plant of Euphorbiaceae family, from which castor-oil is extracted. This plant is found in tropical and subtropical regions, and is very abundant in Brazil.

It is classified as waterproof and it has characteristic of non-aggressive to the environment and humans. The curing is processed with room temperature, and it can be accelerated with temperature of 60 to 90°C (DIAS, 2005).

From the castor-oil makes it possible to synthesize polyols and prepolymers with different characteristics which, when combined, result in a polyurethane. This polyol mixture (castor oil-based) and prepolymer, in cold situation, cause the polymerization reaction of the mixture. This reaction leads to the formation of the polyurethane, and the percentage of polyol can vary, which define a greater or lesser hardness, as well as the use of suitable catalyst to increase the reaction rate (JOSÉ; BERALDO, 2006).

According to Pereira and Beraldo (2007), disturbances caused by the presence of starch particles contained in bamboo are not so important for the adhesion of binder in chipboards using organic or vegetal resins, contrary to the situation when inorganic binders are used.

3. METHODOLOGY

Materials and machineries used in this study were: bamboos of exotic species popular in Brazil *Dendrocalamus asper* (very confused by *Dendrocalamus giganteus*), castor oil-based polyurethane adhesive, trimmer saw with adapter for cylindrical pieces (circular saw), band saw, surface planer, vibrating screen, kilns with and without air circulation, gluing machine, analog digital scale, caliper and digital caliper, hydraulic press, universal testing machines (EMIC DL30ton and Dartec 10ton). The methodology and laboratories where the research was developed is described briefly in next chapters.

3.1 LABORATORIES

For the present study, specimens from the combination of waste and bamboo laminas of the species *Dendrocalamus asper* were used. Waste and bamboo laminas were produced in the sawmill laboratory at Campus of Itapeva, of the Wood Industrial Engineering course, of São Paulo State University (UNESP). Tests of density, water absorption and thickness swelling (2h and 24h), moisture content and static bending were conducted in the Laboratory of Materials of the same academic Campus of UNESP/Itapeva.

The boards were manufactured in Laboratory of Wood and Timber Structures (LaMEM), of Structures Department (SET), at School of Engineering of São Carlos (EESC) of University of São Paulo (USP), located in the Campus of São Carlos, where tests of internal adhesion and screw pullout strength (top and faces) were also performed.

3.2 BAMBOO LAMINAS MANUFACTURING

For the manufacture of laminas to be used as reinforcement has been necessary to machine the whole bamboo, using a support (see Fig. 4) to adapt the trimmer saw to enable the cut stage, since it is a cylindrical material, with lower dimensions than the woods normally used in this machine.

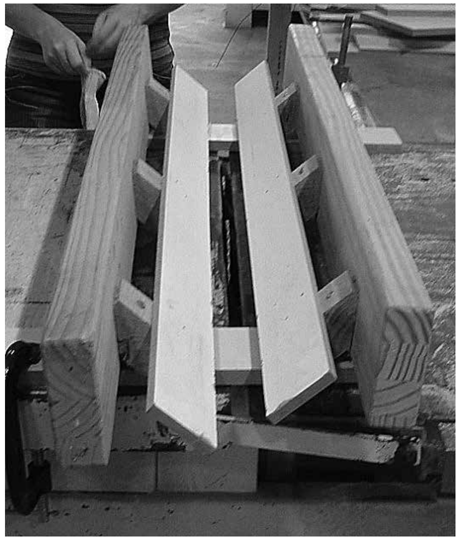


Figure 4 – Support for circular saw.

Bamboos were machined into six parts with circular saw and each one was machined in the band saw to remove diaphragms (Fig. 5). After, these pieces were machined in the surface planer to reach the desired thickness, ranging among 1.0 to 3.0 mm.

Figure 5 – Diaphragm removal.

3.3 WASTE

The waste used in the manufacture of boards were collected during the processing of the laminas and separated through a vibrating screen

(Fig. 6). They were divided into three groups: wood dust and particles retained in the sieves of 3 and 7 mm of diameter. After this step, part of the waste was treated in hot water to reduce starch amount of the residues.

Figure 6 – Vibrating screen.

3.4 WASTE TREATMENT

Part of the bamboo waste was inserted in containers with a capacity of 18 liters and the waste was submerged in water for 20 hours in a kiln. This time was needed for the water reached a temperature of 100°C, recommended in the literature for this kind of treatment, which serves to remove the starch present in the bamboo. The starch is savor to woodworms as well as this substance could damage the process of bonding for some types of resins.

3.5 DRYING

The drying stage occurred in a kiln (Fig. 7) at a temperature of 60°C. Treated and untreated bamboo wastes were dried in the same manner.

Figure 7 – Waste drying.

3.6 BOARD MANUFACTURING

The wastes were weighed by particle size, separated two groups: dust and particles (3 and 7 mm). The latter was homogeneously mixed with the adhesive, castor oil-based polyurethane resin through a gluing machine, and finally they were placed in the mold for pressing (Fig. 8).

Nine boards were produced, all with same standard material amount, and pressed at high temperature. Four of them suffered previous waste treatment (with reinforcement), three boards without the treatment (with reinforcement), two panels without treatment (without reinforcement) to analyze the influence the treatment and the reinforcement in the boards. It is noteworthy that the number of board produced was resulted from the amount of available bamboo stems and waste.

Figure 8 – Forming stage of the board.

3.7 TESTS

The specimens for physical and mechanical tests were produced according to the orientation of the laminas, in the reinforced panels, which were arranged in the same direction, parallel to each other (Fig. 9).

Figure 9 – Arrangement of the laminas for the tests.

The dimensions, number of specimens and their respective normative standard documents used for particleboards are presented in Tab. 2.

Table 2 – Dimensions, number of specimens and their respective normative documents.

Tests	Standards	Sample numbers (Specimen/panel)	Dimensions (mm)
Density	NBR 14810	5	50 x 50
Moisture Content	NBR 14810	5	50 x 50
Thickness Swelling / Water Absorption	NBR 14810	5	25 x 25
Static Bending (E_m and f_m)	EN 310	5	330 x 50
Internal Adhesion	NBR 14810	5	50 x 50
Screw Pullout Strength	NBR 14810	2	150 x 75

The boards were trimmed and then the reinforced as both the unreinforced panels were cut according the scheme shown in Fig. 10. Specimens with dimensions of 330 x 50 mm for static bending test and of 150 x 75 mm for screw pullout strength test (face and top) were used. Specimens for tests of internal adhesion, density, moisture content, thickness swelling and absorption of water were used from specimens of static bending tests (330 x 50 mm).

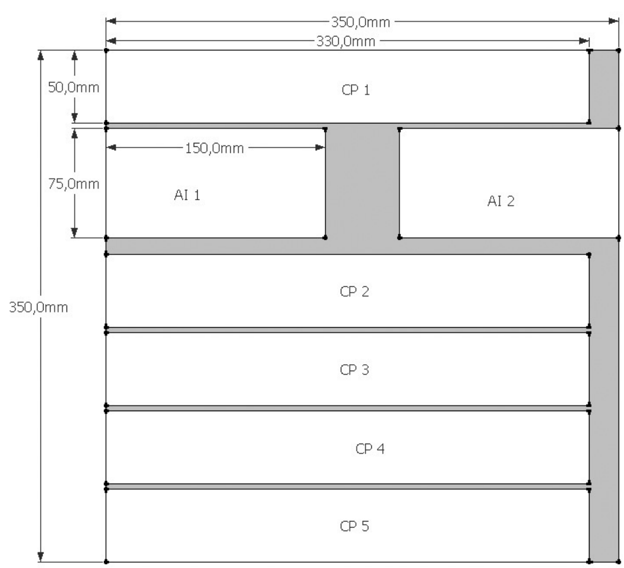


Figure 10 – Cut scheme of the boards.

4. RESULTS AND DISCUSSION

In this chapter are presented and discussed the results of tests of density, moisture content, thickness swelling, water absorption, static bending, internal adhesion, screw pullout strength (face and top) performed according to the standards NBR 14810/2002, and EN 310/2000. All calculations were performed using software *Microsoft Office Excel* 2007. Average thicknesses of the panels are shown in Tab. 3.

The acronyms correspond respectively to:

a) CP: specimens from bamboo particleboards;
b) CT: board with reinforcement and with treatment;
c) CST: board with reinforcement and without treatment;
d) C: board without reinforcement and without treatment;
e) $\bar{x}$: average value;
f) *sd*: standard deviation;
g) CV: coefficient of variation (%).

Table 3 – Average values of the thicknesses of the bamboo particleboards.

	Thickness of the bamboo particleboards (mm)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	14.50	14.95	13.63	15.47	12.58	13.33	13.95	9.33	10.38
2	14.48	14.72	13.86	15.40	12.93	13.45	13.42	9.40	10.54
3	15.53	15.05	13.93	14.65	12.53	13.45	13.58	9.73	10.31
4	15.07	15.48	14.45	15.03	12.85	13.55	13.55	10.10	10.04
5	14.63	15.22	13.83	15.13	12.65	13.27	13.23	9.63	10.15
$\bar{x}$	14.84	15.08	13.94	15.14	12.71	13.41	13.55	9.64	10.28
sd	0.45	0.29	0.31	0.33	0.17	0.11	0.26	0.31	0.20
CV	3	2	2	2	1	1	2	3	2

The variation in the thickness of the boards with reinforcement may be consequence of the variation of the thickness of the bamboo laminas, which it is verified in Tab. 4, as well as the average values of the thicknesses of bamboo laminas.

Table 4 – Average values of the thicknesses of the bamboo laminas.

	Average of thicknesses of bamboo laminas (mm)						
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*
$\bar{x}$	1.92	1.93	1.63	2.13	1.72	1.78	1.82
sd	0.53	0.52	0.43	0.37	0.39	0.31	0.25
CV	27	27	27	17	23	18	13

In some static bending specimens occurred the detachment of part of the bamboo laminas. It is probably because of the moisture content of the bamboo laminas present larger in relation to the moisture of bamboo waste.

4.1 DENSITY TEST

Table 5 present the average values of the density of the particleboards in kg/m³. Through this table can be noted that the authors had problems to manufacture the specimen number 2 of the board CST 5 (board with reinforcement and without treatment).

Table 5 – Average density of the bamboo particleboards.

	Density of the bamboo particleboards (kg/m³)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	866	869	844	854	897	897	887	767	799
2	920	870	938	962	931	997	–	935	885
3	875	924	949	933	901	990	919	966	917
4	882	928	896	894	856	887	935	984	991
5	826	775	886	904	898	871	890	915	961
$\bar{x}$	874	873	902	910	897	929	908	913	911
sd	34	62	42	41	27	60	23	86	74
CV	4	7	5	4	3	6	3	9	8

The results presented in Table 5 showed in general a small variation in density for different treatments evaluated, as evidenced by coefficients of variation less than 10%. Besides these variations among treatments, small variations among panels of the same treatment and among samples originating from the same board were evidenced.

These variations occur during the manufacturing of the compounds, and their main cause reflects in variations in mass, moisture content and in the lack of homogeneity of particle distribution on the mattress (MELO; DEL MENEZZI, 2010). Regardless of treatment or presence of reinforcement of bamboo laminas, the average density of the boards was 900 kg/m³.

4.2 MOISTURE CONTENT TEST

Table 6 shows the values for moisture content of all the particleboards tested.

According to Pierre (2010), there is significant effect of final moisture content of board on physical and mechanical properties, with a generalized downward trend in mechanical properties when the moisture content increases.

Table 6 – Moisture content of the boards.

	Moisture content (%)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C1*	*C 2*
1	5.36	6.31	6.25	6.02	5.50	5.57	6.50	7.21	8.42
2	5.30	5.50	5.09	4.63	3.96	3.73	–	5.66	6.63
3	5.17	5.46	4.52	4.55	4.83	4.07	4.88	5.32	6.07
4	6.04	5.38	5.55	5.40	5.95	5.44	4.84	4.97	4.78
5	6.71	7.11	6.26	5.66	5.70	5.60	6.78	6.14	4.98
$\bar{x}$	5.72	5.95	5.53	5.25	5.19	4.88	5.75	5.86	6.17
sd	0.65	0.75	0.75	0.65	0.80	0.91	1.03	0.87	1.47
CV	11	13	14	12	15	19	18	15	24

Regardless of the presence of treatment or reinforcement, the average moisture content of boards was 5.6%, which is in the range 5 to 11% prescribed by NBR 14810/2002. There was small variation in moisture content among boards of different types of treatments, as evidenced by the differences among average values of boards and total average value.

4.3 THICKNESS SWELLING AND WATER ABSORPTION

Tables 7, 8, 9, 10 and 11 show the values for the water absorption (WA), thickness swelling (TS) and the average values for 2 hours and 24 hours.

Table 7 – Values of the water absorption test in 2 hours.

	Water absorption in 2h (%)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	7.04	3.55	1.86	2.91	3.13	3.20	3.64	6.17	6.48
2	3.50	2.72	3.94	9.51	5.70	3.86	–	3.28	3.78
3	6.85	2.12	2.90	2.80	4.40	3.52	4.61	2.32	3.55
4	4.61	3.25	4.35	2.64	6.85	5.31	3.83	2.39	2.88
5	5.20	3.47	4.72	3.62	3.36	4.78	4.26	4.55	3.21
$\bar{x}$	5.44	3.02	3.55	4.30	4.69	4.13	4.08	3.74	3.98
sd	1.50	0.60	1.17	2.94	1.58	0.88	0.44	1.63	1.44
CV	28	20	33	68	34	21	11	44	36

Table 8 – Values of the water absorption test in 24 hours.

	Water absorption in 24h (%)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	17.67	9.61	8.23	9.73	10.47	14.08	15.23	23.31	32.02
2	10.62	9.10	10.65	23.83	17.54	12.79	–	11.72	16.09
3	15.33	7.37	9.28	9.29	13.60	12.50	16.84	8.77	14.66
4	12.00	9.15	11.18	8.85	18.54	17.60	12.72	9.70	10.62
5	13.81	10.52	12.82	10.21	12.38	16.71	14.44	18.00	14.93
$\bar{x}$	13.89	9.15	10.43	12.38	14.51	14.74	14.81	14.30	17.67
sd	2.77	1.15	1.76	6.42	3.43	2.31	1.72	6.19	8.29
CV	20	13	17	52	24	16	12	43	47

Table 9 – Values of thickness swelling test in 2 hours.

	Thickness swelling in 2h (%)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	5.04	4.80	4.79	5.33	6.67	1.53	1.66	4.70	4.37
2	4.17	2.11	3.13	3.95	3.55	2.97	–	2.70	2.33
3	3.71	2.50	1.04	3.81	4.03	4.59	5.62	2.36	2.97
4	2.76	2.47	2.37	2.21	3.85	3.00	2.61	0.93	2.11
5	1.53	2.52	4.56	0.82	3.12	4.94	1.98	3.69	3.32
$\bar{x}$	3.44	2.88	3.18	3.22	4.24	3.41	2.97	2.87	3.02
sd	1.35	1.09	1.56	1.74	1.40	1.38	1.81	1.42	0.90
CV	39	38	49	54	33	41	61	49	30

Table 10 – Values of thickness swelling test in 24 hours.

	Thickness swelling in 24h (%)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	8.51	5.20	2.84	8.49	4.62	8.91	4.53	8.78	10.93
2	6.79	5.78	7.71	6.47	8.43	5.72	–	7.12	8.44
3	8.24	4.01	4.36	5.55	6.01	7.44	6.28	7.60	7.14
4	6.60	5.07	5.26	4.97	7.41	8.85	5.72	2.69	6.43
5	5.94	4.52	7.21	4.70	5.20	6.46	6.47	10.46	7.59
$\bar{x}$	7.22	4.92	5.48	6.04	6.33	7.48	5.75	7.33	8.11
sd	1.11	0.68	2.01	1.53	1.57	1.42	0.87	2.90	1.74
CV	15	14	37	25	25	19	15	40	21

Table 11 – Average of the water absorption and thickness swelling

CP	WA 2h (%)	**TS 2h (%)**	**WA 24h (%)**	**TS 24h (%)**	**Moisture (%)**
CT	4.08	3.18	11.16	5.91	5.61
CST	4.30	3.54	14.68	6.52	5.27
C	3.86	2.95	15.98	7.72	6.02

According to prescription of NBR 14810/2002 standard, the values of thickness swelling and water absorption (for 2 hours immersion) must not exceed 8%. In Table 11, in the thickness swelling test this value was not reached, even for a 24 hour of immersion time, whereas for the water absorption test occurred the same behavior (for 2h), and the highest average value occurred for particleboards without treatment and without reinforcement (double of value) for the 24h of immersion time, once this maximum value for this property is not stipulated by the standard document aforementioned.

Independently of the treatment, chipboards with reinforcement showed the lowest average values of water absorption and thickness swelling for a greater exposure to moisture, due to a certain contention in swelling by the presence of a layer of bamboo laminas. Another factor that may have contributed in this behavior is the use of castor-oil polyurethane resin as a binder adhesive.

Figure 11 shows the specimens after the test of 24 hours, which is observed that there was no substantial change in the appearance of these specimens, in relation to aspect observed in the same test for other composites of wood particulates, in view of they are two delicate tests for wood-based derivatives.

Figure 11 – Aspects of the specimens after test of 24 hours.

Briefly, the Table 12 shows the results of several authors regarding of water absorption and thickness swelling for comparison with the data for this study, which are inserted at the end of it, named as "*current study". Castor oil-based polyurethane and urea-formaldehyde resins are represented, respectively, by CP and UF.

Table 12 - Results of studies regarding of water absorption and thickness swelling.

Authors	Composition	WA 2h (%)	WA 24h (%)	TS 2h (%)	TS 24h (%)	Resin
Iwakiri et al. (2000)	*Eucalyptus maculata*	27.95	50.06	21.25	32.22	UF
	Eucalyptus grandis	13.94	37.37	12.38	24.23	
	Eucalyptus tereticornis	15.67	37.82	12.48	23.51	
	Mixture of the 3 species	18.29	45.59	15.55	28.37	
Cabral et al. (2007)	*E. urophylla* / *P. elliottii*	9.08	–	6.12	–	UF
	100% *Eucalyptus grandis*	10.64		6.67		
	E. urophylla / *P. elliottii*	9.69		6.23		
Carvalho, Valarelli and Visnardi (2009)	100% Bamboo	59.48	77.49	7.73	9.33	UF
	75% Bamboo / 25% Pine	22.22	56.78	4.04	9.02	
	50% Bamboo / 50% Pine	26.17	62.77	5.13	9.58	
***current study**	*D. Asper* (unreinforced panel)	3.86	15.98	2.95	7.72	CP
	D. Asper (reinforced panel)	4.18	12.79	3.34	6.18	

In Table 12, the results show that the values for these two physical properties, in tests with 2 and 24 hours of immersion, were below the obtained in studies of particleboards realized by other authors, with wood particles or bamboo, and in most studies higher values were found than those obtained in the treatments of this work.

4.4 STATIC BENDING

Iwakiri et al. (2008) state the influence of density on mechanical properties of chipboards can be attributed to the compression ratio of the particles, which constituting the mat. If there had been a difference among the densities, it was expected the higher density particleboard presented higher values of modulus of rupture (f_m) and modulus of elasticity (E_m) in static bending. Tables 13 and 14 show, respectively, the average values for modulus of rupture (f_m or MOR) and modulus of elasticity (E_m or MOE) in static bending.

The average values of f_m (Table 13) for boards with reinforcement and treatment, with reinforcement and without treatment, and without reinforcement and treatment respectively were 137 MPa, 153 MPa and 38 MPa, as evidenced that the addition of reinforcement of bamboo laminas in the particleboards generates an increase of over 200% in the value of strength in static bending, although the same do not affect the final density of the composite.

These data also overcame and surpassed the required values of standard documents NBR 14810/2002 of 16 MPa for wooden particleboards, and EN 300/2002 for OSB board type 4 of 28 MPa, even for panels produced without the addition of reinforcement.

Table 13 – Average values of modulus of rupture in static bending.

	f_m (MPa)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	80	99	134	137	146	160	143	26	21
2	124	140	135	185	134	169	–	41	29
3	110	149	157	174	103	188	179	55	37
4	135	148	129	177	127	147	164	54	45
5	105	127	139	153	189	105	140	41	26
$\bar{x}$	111	133	139	165	140	154	156	44	31
sd	21	21	11	20	31	31	18	12	10
CV	19	16	8	12	23	20	12	27	30

On the other hand, the average value of f_m of the chipboards with treatment was lower than the untreated boards, evidencing that a prior treatment to reduce the starch did not affect the board bonding process with the castor oil-based polyurethane adhesive, as cited by José and Beraldo (2006). Table 14 presents the average values for the E_m in static bending.

Table 14 – Average values of modulus of elasticity in static bending.

	E_m (MPa)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	10284	12779	15110	16174	14787	16716	15103	5567	7102
2	17989	15625	15166	18648	12681	14572	–	8379	4974
3	11442	15864	17159	19619	12647	17452	16738	5262	4623
4	18029	15591	12995	19600	13516	14062	13664	3810	4788
5	14910	14726	15614	18764	16277	14185	11597	6841	7204
$\bar{x}$	14531	14917	15209	18561	13982	15397	14275	5972	5738
sd	3603	1271	1490	1410	1550	1573	2183	1724	1298
CV	25	9	10	8	11	10	15	29	23

Average values of E_m in Table 14 for particleboards with reinforcement and treatment, with reinforcement and without treatment, and without reinforcement and treatment respectively were 15804 MPa, 14551 MPa and 5855 MPa, evidencing that the addition of reinforcement of bamboo laminas in the panels generates an increase of over 200% in value of modulus of elasticity in static bending, although they do not influence final density of the composite.

These data also overcame and extrapolated that required by EN 300/2002[38] for OSB type 4 4800 MPa, even for boards produced without the addition of reinforcement.

Briefly, in the Table 15 are presented the values of f_m and E_m obtained by several authors regarding particleboards of wood and bamboo, for comparison with the data of this study, which are placed at the end of it. Castor oil-based polyurethane, urea-formaldehyde and tannin-formaldehyde adhesives are represented, respectively, by CP, UF and TF.

In Table 15 may be noted the values for strength and modulus of elasticity in static bending for chipboards of this study were much higher than those found by other authors, regardless of treatment, presence of reinforcement or to be made with bamboo or wood.

It also highlights the fact that the presence of reinforcement with bamboo laminas increased the values for these properties, probably because of the laminas were manufactured with the outside of stems, where bamboo has a higher amount of fiber.

There are some papers on mechanical properties of particleboards of bamboo, but each one has a special feature, which impedes a more accurate and direct comparison in this specific topic.

Table 15 – Values of the properties for lignocellulosic particleboards.

Authors	Composition	Density (kg/m³)	Resin	f_m (MPa)	E_m (MPa)
Haselein et al. (2002)	*Pinus elliottii*	700	TF	10	1863
Dias (2005)	*P. elliottii* (48%) / *E. grandis* (47%) / *E. urophilla* (5%)	810	CP	18	3034
Lima et al. (2008)	100% Bamboo bract	870	UF	11	1335
	75% Bract / 25% Stem			11	1332
	50% Bract / 50% Stem			15	2105
	25% Bract / 75% Stem			17	2654
	100% Bamboo stem			21	3901
Silva et al. (2008)	*Dendrocalamus giganteus*	–	8% UF	8	1315
			10% UF	9	1452
			12% UF	10	1732
			15% UF	12	1976
***current study**	*D. Asper* (unreinforced panel)	912	CP	38	5855
	D. Asper (reinforced panel)	899		142	15297

In some boards occurred a partial separation of the laminas due to the difference of strength between the chipboard with the bamboo fibers, or through the difference in moisture of the material, as shown in Fig. 12. These unattached parts were not used for the following tests.

Figure 12 – Detachment of the reinforcement after the static bending test.

4.5 INTERNAL ADHESION

Table 16 shows the results for the internal adhesion test obtained for manufactured boards. Several attempts were performed to enable the test. Various materials and adhesives were tested, and only the metal traction blocks resisted this test. Due to the bonding time and the amount of traction blocks available, the test was not realized in all of specimens.

The results show that regardless of treatment and presence or absence of bamboo laminas as reinforcement, the values were higher than those prescribed by the standard documents NBR 14810/2002 at 0.40 MPa for wood chipboards and EN 300/2002 at 0.45 MPa to OSB type 4. Prior treatment of particles did not present different results in untreated boards.

Higher values of internal adhesion for particleboards without reinforcement were evidenced, which can be explained by the rupture of reinforced particleboards have occurred in some specimens, particularly in the glue line, between the reinforcement and the board surface, and probably at the limit of resistance of castor oil-based polyurethane adhesive. In the unreinforced panels, the ruptures occurred in the center (core) of the specimens (Fig. 13).

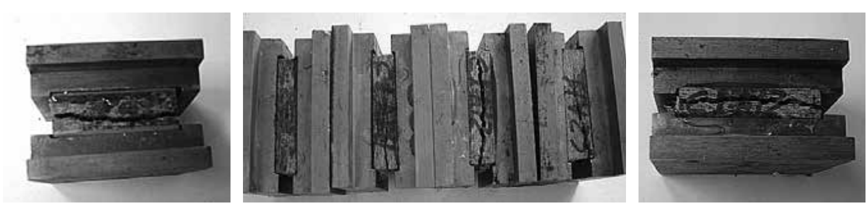


Figure 13 – Aspect of the specimens after the internal adhesion tests.

Table 16 – Average values of internal adhesion test.

Internal adhesion (MPa)				
CP	**Force (kgf)**	**Area (mm²)**		**IA (MPa)**
CT 1 / 1	395	50.67	51.43	1.52
CT 2 / 2	640	50.60	50.34	2.51
CT 2 / 4	770	49.82	50.76	3.04
CT 3 / 4	450	50.19	50.60	1.77
CT 4 / 4	555	50.08	50.50	2.19
CST 3 / 5	340	50.70	50.67	1.32
CST 4 / 3	610	51.11	50.57	2.36
CST 5 / 1	780	50.48	50.48	3.06
C 1 / 1	1100	50.04	50.62	4.34
C 1 / 2	1120	50.09	51.09	4.38
C 1 / 3	720	50.75	50.15	2.83
C 1 / 4	480	50.63	51.21	1.85
C 1 / 5	510	50.64	50.31	2.00
C 2 / 1	715	50.09	50.00	2.85
C 2 / 2	630	50.25	50.69	2.47
C 2 / 3	870	50.41	50.78	3.40
C 2 / 4	705	50.51	50.29	2.78
C 2 / 5	800	50.35	49.16	3.23
$\bar{x}$	677	50.41	50.54	2.66
sd	214.91	0.32	0.50	0.85
CV	32.73	0.64	0.98	32.08

Briefly, in Table 17 are presented the values from internal adhesion tests of several authors regarding particleboards of wood and bamboo, for comparison with the data found in this study, which are cited at the end of it, where internal adhesion is named by IA. It is observed that the values obtained exceeded those found by other authors, regardless of treatment, especially for unreinforced boards.

Table 17 – Values of internal adhesion for particleboards.

Authors	Composition	Density (kg/m³)	Resin	IA (MPa)
Haselein et al. (2002)	*Pinus elliottii*	700	TF	0.18
Dias (2005)	*Pinus elliottii* (48%) / *E. grandis* (47%) / *Eucalyptus urophilla* (5%)	810	CP	0.88
***current study**	*D. Asper* (unreinforced panel) *D. Asper* (reinforced panel)	912 899	CP	3.01 2.22

4.6 SCREW PULLOUT STRENGTH

Tables 18 and 19 present the obtained results in the screw pullout strength test on the face and on the top of panel. The results obtained for the chipboards, regardless of treatment and presence or absence of reinforcement, exceeded the required by NBR14810/2002, which stipulates a minimum value 1020N, emphasizing the reinforced boards, on average, reached more than twice for that value, and for treated boards the values were superior to untreated boards. The reinforcement in particleboards improves the performance on the face of boards.

Table 18 – Average values of the screw pullout strength on the face of board.

	Screw pullout strength on the face of board (N)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	3000	1750	2300	2900	3750	2950	2450	1950	1400
2	2150	2400	2200	2200	2300	3050	3700	2450	2200
$\bar{x}$	2575	2075	2250	2550	3025	3000	3075	2200	1800
sd	601	460	71	495	1025	71	884	354	566
CV	23	22	3	19	34	2	29	16	31

Table 19 – Average values of the screw pullout strength on the top of board

	Screw pullout strength on the top of board (N)								
CP	*CT 1*	*CT 2*	*CT 3*	*CT 4*	*CST 3*	*CST 4*	*CST 5*	*C 1*	*C 2*
1	2200	2900	2200	1900	3350	2600	2050	2800	3100
2	2100	2400	1850	2100	2850	2400	3800	3150	2950
$\bar{x}$	2150	2650	2025	2000	3100	2500	2925	2975	3025
sd	71	354	247	141	354	141	1237	247	106
CV	3	13	12	7	11	6	42	8	4

The results obtained for the chipboards, regardless of treatment and presence or absence of reinforcement, again exceeded that required by the standard document NBR 14810/2002, which stipulates a minimum value of 800 N, reaching more than double of this value. For the untreated boards, their values, on average, were superior to the treated panels. It is noted that expected values for screw pullout values on the top of panel are lower than those on the face, even by standard NBR 14810/2002, position which boards demonstrate a major fragility.

Figures 14 and 15 show the specimens of screw pullout strength test (on the face and top) of particleboards with and without reinforcement. It is observed that the specimens did not show major damage after the screw pullout strength test (face and top). This situation is common in wooden particleboards, and also it constitutes in a large problem in their utilization.

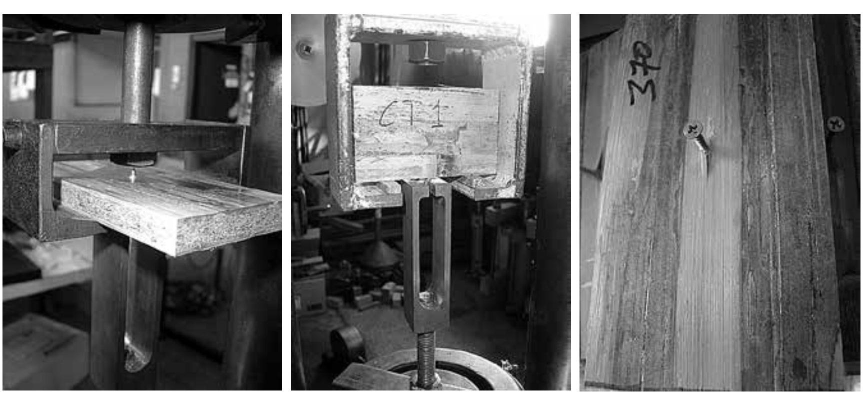


Figure 14 – Screw pullout strength test (reinforced boards).

Figure 15 – Screw pullout strength test (unreinforced boards).

Some values of screw pullout strength test (face and top) are presented in Table 20, according to the available values in the literature, where SPS is represented by screw pullout strength test. It is noted that the authors did not specify in their studies if the values are related to the screw pullout strength on the face or on the top of particleboards. In this test, they only focused on wooden panels. Urea-formaldehyde and castor oil-based polyurethane adhesives are represented, respectively, by UF and CP.

Table 20 – Values of the screw pullout strength test according to the literature for lignocellulosic particleboards.

Authors	Composition	Density (kg/m³)	Resin	SPS (N) Face	SPS (N) Top
Dacosta et al. (2005)	*Pinus elliottii*	700	UF	700.00	
Melo and Del Menezzi (2010)	*Eucalyptus grandis*	600	UF	710.00	
		700		891.00	
		800		966.00	
***current study**	*D. Asper* (unreinforced panel)	912	CP	2000	3000
	D. Asper (reinforced panel)	899		2650	2479

It is observed that values found for screw pullout strength test, regardless of the treatment, presence of bamboo reinforcement, or if the test was on the face or on the top of chipboard, they were superior to those found by the other authors. As mentioned Dacosta et al. (2005), a higher density value in manufactured chipboards may explain the higher values obtained in this test.

5. CONCLUSION

With the use of castor oil-based polyurethane resin in the manufacture of particleboards of bamboo, none treatment is necessary to remove the starch, because there is no difference in results of tests on physical and mechanical properties with varying concentration of starch.

The water absorption and thickness swelling (2h and 24h) for bamboo particleboards and bonding with castor oil-polyurethane adhesive, produced in the above conditions, present lower average values that those found in the literature of lignocellulosic composites, in other words, in wood or bamboo. Boards unreinforced have greater swelling in 24 hours compared to the reinforced panels, with respecting the EN 300/2002.

Bamboo particleboards bonding with castor-oil polyurethane resin, according to the standard documents described above, present equivalence and or superiority to the values found in the literature for particleboards produced with different characteristics and traditional resins. The particleboards can be considered equivalent in behavior, in particular, to the OSB type 4 boards, used in structural applications, and in slightly humid spaces.

Therefore, this particleboard proves to be viable economically and enables an alternative for the utilization of the industrial waste generated in the processing of bamboo, in this case the species of *Dendrocalamus asper*, combined with castor oil-based polyurethane resin.

Thus, this panel can be applied in structures, partitions, floors, furniture and other uses, with an advantage to have an aesthetically appealing surface finish.

ACKNOWLEDGEMENT

The authors thank the Campus of Itapeva of São Paulo State University (UNESP) and the Engineering School of São Carlos (EESC) of University of São Paulo (USP), and in particular the laboratory LaMEM and the Research Group LIGNO, by lending of their laboratories and staffs, which wholly help the authors in the performance of this study.

PERMISSION FOR PUBLICATION

It is the responsibility of the authors the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

ASSOCIAÇÃO BRASLEIRA DE NORMAS TÉCNICAS. **NBR 14810:** Chapas de madeira aglomerado. Rio de Janeiro, Brazil, 2002.

ARAUJO, L.C.R. **Caracterização química e mecânica de poliuretanas elastoméricas baseadas em materiais oleoquímicos.** 1992. 101p. Dissertação (Mestrado) - Instituto de Física e Química de São Carlos, Universidade de São Paulo. São Carlos, Brazil, 1992.

BERALDO, A.L.; ESPELHO, J.C.C. FERREIRA, G.C.S. Avaliação da Durabilidade de Taliscas de Bambu. In: ENCONTRO BRASILEIRO EM MADEIRAS E EM ESTRUTURAS DE MADEIRA, São Pedro, Brazil. **Anais.** Botucatu, Brazil: UNESP, 2006. 15 p.

CABRAL, C.P.E.; VITAL, B.R.; LUCIA, R.M.D.; PIMENTA, A.S. Propriedades de chapas de aglomerado confeccionadas com misturas de partículas de *Eucalyptus spp* e *Pinus elliottii*. **Revista Árvore**, Viçosa, Brazil, v. 31, n. 5, p. 897-905, 2007.

CALEGARI, L.; HASELEIN, C.R.; SCAVARELLI, T.L.; SANTINI, E.J.; STANGERLIN, D.M.; GATTO, D.A.; TREVISAN, R. Desempenho físico-mecânico de painéis fabricados com bambu (*Bambusa vulgaris Schr.*) em combinação com madeira. **Revista Cerne**, Lavras, Brazil, v. 13, n. 1, p. 57-63, 2007.

CARVALHO, M.R.O.; VALARELLI, I.D.; VISNARDI, O.C. Avaliação do comportamento das chapas aglomeradas de bambu e pinus em relação ao teor de umidade, absorção de água e inchamento em espessura. In: CONGRESSO DE INICIAÇÃO CIENTÍFICA, 21, São José do Rio Preto, Brazil, 2009. **Anais...** Bauru, Brazil: UNESP.

DACOSTA, L.P.E.; HASELEIN, C.R.; SANTINI, E.J.; SCHNEIDER, P.R.; CALEGARI, L. Qualidade das chapas de partículas aglomeradas fabricadas com resíduos do processamento mecânico da madeira de *Pinus elliottii* (Engelm.). **Ciência Florestal**, Santa Maria, Brazil, v. 15, n. 3, p. 311-322, 2005.

DIAS, F.M. **Aplicação de resina poliuretana à base de mamona na fabricação de painéis de madeira compensada e aglomerada.** 2005. 420 p. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo. São Carlos, Brazil, 2005.

EUROPEAN COMMITTEE FOR STANDARDIZATION. **European Standard - EN 310. Placas de derivados de madeira. Determinação do módulo de elasticidade em flexão e da resistência à flexão**. Lisboa, Portugal, 2000.

______. **European Standard - EN 300. Aglomerado de partículas de madeira longas e orientadas (OSB) - Definições, classificação e especificações.** Lisboa, Portugal, 2002.

GHAVAMI, K.; MARINHO, A.B. Propriedades físicas e mecânicas do colmo inteiro do bambu da espécie Guadua angustifólia. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, Brazil, v. 9, n. 1, p. 107-114, 2004.

HASELEIN, C.R.; CALEGARI, L.; BARROS, M.V.; HACK, C.; HILLIG, E.; PAULESKI, D.T.; POZZERA, F. Resistência mecânica e à umidade de painéis aglomerados com partículas de madeira de diferentes dimensões. **Ciência Florestal**, Santa Maria, Brazil, v.12, n.2, p. 127-134, 2002.

HIDALGO-LOPEZ, O. **Bambu:** su cultivo y aplicaciones in fabricación de papel, construcción, arquitectura, ingeniería y artesanía. Cali, Colombia: ETC, 1974. 318 p.

IWAKIRI, S. Painéis de madeira: características tecnológicas e aplicação. **Revista da Madeira**, Curitiba, Brazil, p. 4-10, 2003.

IWAKIRI, S.; CUNHA, A.B.; ALBUQUERQUE, C.E.C.; GORNIAK, E.; MENDES, L.M. Resíduos de serrarias na produção de painéis de madeira aglomerada de eucalipto. **Scientia Agraria**, Piracicaba, Brazil, v. 1, n. 1-2, p. 23-28, 2000.

IWAKIRI, S.; SILVA, J.R.M.; MATOSKI, S.L.S.; LEONHARDT, G.; CARON, J. Produção de chapas de madeira aglomerada. Revista da Madeira, n.99, p. 122-125, 2006. Available at: <http://www.remade.com.br/br/revistadamadeira_materia.php?num=967&subject=Pain%C3%A9is&title=Produ%C3%A7%C3%A3o%20de%20chapas%20de%20madeira%20aglomerada>. Accessed on: September 02.

IWAKIRI, S.; STINGHEN, A.B.M.; SILVEIRA, E.L.; ZAMARIAN, E.H.C.; PRATA, J.G.; BORONOSKI, M. Influência da massa específica sobre as propriedades mecânicas de painéis aglomerados. **Revista Floresta**, Curitiba, Brazil, v. 38, n. 3, p. 487-493, 2008. doi:10.5380/rf.v38i3.12414.

JAQUEZ, F. **Guía técnica para el fomento del bambú en la República Dominicana.** UASD, INDRHI. Santo Domingo, Dominican Republic, 1990.

JOSÉ, F.J.; BERALDO, A.L. END aplicado a chapas prensadas de partículas de bambu e adesivo poliuretana à base de óleo de mamona. In: SEMINÁRIO SOBRE APLICAÇÃO DE ENSAIOS NÃO DESTRUTIVOS EM MADEIRA E MATERIAIS À BASE DE MADEIRA, 1, Itatiba, Brazil. **Anais...** São Paulo, Brazil: ABENDE, p. 1-6, 2006.

KAI, Z.; XUHE, C. **Potential of bamboo-based panels serving as prefabricated construction materials.** International Network for Bamboo and Rattan, 2005. 38 p.

LAEMLAKSAKUL, V. **Physical and mechanical properties of particleboard from bamboo waste.** World Academy of Science, Engineering and Technology, Riverside-CT, United States, v.40, n.4, p. 507-511, 2010.

LIMA JÚNIOR, H.C.; DIAS, A.A. Vigas mistas de madeira de reflorestamento e bambu laminado colado: análise teórica e experimental. Campina Grande, Brazil, **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.5, n.3, p. 519-524, 2001.

LIMA, F.L.S.; VALARELLI, I.D.; GONÇALVES, M.T.T.; ALMEIDA, A.L.A. Caracterização física de chapas homogêneas aglomeradas de bambu fabricadas com adesivo poliuretana à base de óleo de mamona. In: ENCONTRO BRASILEIRO EM MADEIRAS E EM ESTRUTURAS DE MADEIRA, 11, Londrina. **Anais...** Londrina: UEL, IBRAMEM, 2008. 263 p.

MAKITA, A. The significance of the mode of clonal growth in the life history of bamboos. **Plant Species Biology**, Malden-MA, United States, v.13, n.2-3, p. 85-92, 1998. doi:10.1111/j.1442-1984.1998.tb00251.x.

MALONEY, T.M. The family of wood composite materials. **Forest Products Journal**, Madison-WI, United States, v.46, n.2, p.19-26, 1996.

MARQUES, J.L.S. **Desenvolvimento de adesivos nanocompósitos de poliuretano à base de óleo de mamona.** 2009. 92 p. Dissertação (Mestrado) - Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, 2009.

MELO, R.R.; DEL MENEZZI, C.H.S. Influência da massa específica nas propriedades físico-mecânicas de painéis aglomerados. **Silva Lusitana**, Lisboa, Portugal, v.18, n.1, p. 59-73, 2010.

MOIZÉS, F.A. **Painéis de bambu, uso e aplicações: uma experiência didática nos cursos de design em Bauru.** 2007. 116 p. Dissertação (Mestrado) - Faculdade de Arquitetura, Artes e Comunicação, Universidade Estadual Paulista, Bauru, Brazil, 2007.

NASCIMENTO, M.F. **CPH:** Chapas de partículas homogêneas - madeiras do Nordeste do Brasil. 2003. 134 p. Tese (Doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brazil, 2003.

NATIONAL MISSION ON BAMBOO APLICATIONS. **Processing bamboo shoots. Training manual**. New Delhi, India: NMBA, 2004. 27 p.

PEREIRA, M.A.R. O uso do bambu na irrigação: montagem de um sistema de irrigação por aspersão de pequeno porte, utilizando tubulação de bambu. In: CONGRESSO BRASILEIRO DE ENGENHARIA, 26, Campina Grande, Brazil, 1997. **Anais...** Campina Grande, Brazil: UFPB SBEA, v.1, p. 293-323, 1997.

PEREIRA, M.A.R.; BERALDO, A.L. **Bambu de corpo e alma**. Bauru, Brazil: Canal 6, 2007. 240 p.

PIERRE, F.C. **Caracterização físico-mecânica de painéis aglomerados de Eucalyptus grandis com adição de resíduos industriais madeireiros.** 2010. 122 p. Tese (Doutorado) – Universidade Estadual Paulista, Faculdade de Ciências Agronômicas, Botucatu, Brazil, 2010.

PLEPIS, A.M.G. **Caracterização térmica e viscoelastica de resinas poliuretanas derivadas de óleo de mamona.** 1991, 155 p. Tese (Doutorado) - Instituto de Química de São Carlos, Universidade de São Paulo, São Carlos, Brazil, 1991.

SANTOS, R.C.; MENDES, L.M.; MORI, F.A.; MENDES, R.F. Chapas de partículas aglomeradas produzidas a partir de resíduos gerados após a extração do óleo da madeira de candeia (*Eremanthus erythropappus*). **Scientia Forestalis**, Piracicaba, Brazil, v.37, n.84, p. 437-446, 2009.

SILVA, P.M.; VALARELLI, I.D.; SAMPAIO, R.M.; NASCIMENTO, M.F. Caracterização da chapa de partícula composta de resíduos de bambu *Dendrocalumus giganteus* e folha caulinar com diferentes teores de adesivo UF. In: ENCONTRO BRASILEIRO EM MADEIRAS E EM ESTRUTURAS DE MADEIRA, 11, Londrina, 2008. **Anais...** Londrina, UEL, IBRAMEM. 13 p.

SLONGO, D.R.; KUPERSTEIN, R.P.; BUENO NETTO, R. **Plantações energéticas de bambu.** Revista da Madeira, n.121. 2009. Available at:<http://www.remade.com.br/br/revistadamadeira_materia.php?num=1420&subject=E%20mais&title=Planta%E7%F5es%20energ%E9ticas%20de%20bambu>. Accessed on: September 02.

VICK, C.B. **Adhesive bonding of wood materials, Forest Products Laboratory.** Wood Handbook: Wood as an engineering material. FPL-GTR-113. Madison, WI, United States: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Cap. 9, p. 1-23, 1999.

COMPOSITES OF EUCALYPT AND SUGARCANE BAGASSE: TECHNOLOGICAL CHARACTERISTICS

Ugo Leandro Belini
Federal University of Santa Catarina, Forestry Engineering, Curitibanos-SC.
E-mail: ugo.belini@ufsc.br

Juliano Fiorelli and Holmer Savastano Junior
São Paulo University, Department of Biossystens Engineering, Pirassununga-SP.
E-mail: julianofiorelli@usp.br; holmersj@usp.br

Ângela do Valle and Poliana Dias de Moraes
Federal University of Santa Catarina, Department of Civil Engineering, Florianópolis-SC
E-mail: angela.valle@ufsc.br; poliana.moraes@ufsc.br

Mario Tomazello Filho
São Paulo University, Department of Forest Sciences, Piracicaba-SP
E-mail: mtomazel@usp.br

ABSTRACT: The increased use of wood-based products stimulates the development of research and technology for application of agricultural and forestry inputs, characterized as waste. In this respect, we highlight the extensive areas of sugarcane plantations annually generating a significant amount of bagasse from the stalks, which is preferentially used as an energy source. Likewise, there are the eucalyptus plantations, with high wood productivity, associated to an industrial park with advanced technology for the production of pulp and paper, fiberboards, particleboard, charcoal, etc. Therefore, this study aims to evaluate the potential of bagasse particles from sugarcane stalks and eucalyptus wood fibers for composites manufacture. Under laboratory conditions, the bagasse were characterized with respect to their size and mixed with eucalyptus fibers for composites with up to 25% sugarcane bagasse (increasing increments of 5%) and two levels of urea formaldehyde resin (13% and 16%). The physical (density, swelling and absorption) and mechanical (MOR, MOE, internal bond and axial screw withdrawal resistance) properties of the panels showed satisfactory average values for the design of a new product and mostly attended the current specifications. The application of 16% UF resin, compared with 13% UF resin, reflected in better physical and mechanical properties and the mean of the assays totally met NBR 15316 (2009) norm. Furthermore, the lowest content of free formaldehyde was detected in composites with higher percentage of sugarcane particles. The results indicate that the composite of eucalyptus particles and sugarcane bagasse fibers (in percentages of 5-25%) present technological properties that meet the standards and feasible production possibilities in the existing industrial conditions, indicating its potential for the manufacture of products with higher added value.

Keywords: Eucalyptus fiber. Sugarcane bagasse. Particleboard. Engineering. Sustainability.

1. INTRODUCTION

The use of natural fibers in composites manufacturing is ancient, although its industrial application is low due to the costs of adapting the industrial process, the lack of information and its availability in the market, despite its importance and applications, in particular, in developing countries. In this context, the generation of plant fibers, such as agricultural waste, is related to (i) the characteristics of the production process and its shredding, (ii) the selective and restricted market conditions, (iii) the perishability stage of the natural products and (iv) the limited information available for their destination and use (SAVASTANO JR., 2000).

Considering these aspects, it is desirable that institutions that develop research related to science and technology in agricultural resources submit work proposals that contribute to the resolution of questions regarding the use of these resources in a sustainable way, with improved yield potential and quality improvement of products generated by the agricultural bases industry, thus allowing increased competitiveness in this market segment.

On the other hand, industrial wastes have been used in conventional technological processes for fiberboards production and it is considered important to use waste wood from mechanical or chemical processing to produce panels, as already occurs in Europe (REZENDE et al., 2008; IPT, 2009). The research directed towards application of low cost fibrous raw material from, agricultural crop waste in the manufacture of composites in different regions of the world, has shown satisfactory results in the last decade (WIDYORINI et al., 2005; LEE at al, 2006; OSMAN et al., 2009; MENDES et al., 2010; ORTUNÕ et al., 2011; FIORELLI et al., 2012).

In the 1990s the use of residues from the manufacture of MDP (*Medium Density Particleboard*), among others, began primarily in Europe and should be applied in Brazil because of the the high availability of agricultural and forest residues. Regarding the industrial manufacturing process of fiberboard, the country has major challenges, such as reducing formaldehyde emission, panel recycling, the use of resins from renewable resources and the optimization of the principle of the 3 F's (Fiber, Food, Fuel), according Borges (2008).

In terms of sugarcane stalk bagasse, industrial projects have been presented for its use in the production of AFB (*Agricultural Fiber Board*) panels, integrated to the mills, enabling its use and value. The research carried out in the country and abroad indicate the feasibility of using bagasse particles in lignocellulosic matrices for making composites. Among these, we highlight the MDP panel due to the technical-operational difficulty in laboratory and pilot scale conditions for obtaining fibers with morphology similar to those used in MDF (*Medium Density Fiberboard*).

Thus, the objective is the implementation and effective use of lignocellulosic materials (BUCUR, 2003), serving the needs of modern society by developing new products based on wood. It is considered strategic for the country to develop technology for the application of bagasse as a fibrous raw material in the manufacture of fiberboard and particleboard, minimizing the demand for eucalyptus wood and providing additional value to an agricultural waste destined mainly for power generation.

Thus, the technological challenge was to develop a new product characterized by a fibrous eucalyptus matrix in which was incorporated crushed sugarcane particles as a sustainable biomass.

1.1 WHY COMPOSITES?

The reconstituted woodpanels sector, in Brazil, has invested about $1.2 billion in the installation of modern industrial parks providing a total installed capacity of approximately 10.3 million m^{-3} per year (2012), with 5.1

million m^{-3} of MDP and 4.8 million m^{-3} of MDF panels, making Brazil one of the most important countries in manufacturing reconstituted woodpanels in the world.

Industrial parks are located mostly in the Southern and Southeast regions of Brazil, which have a greater availability of wood from pine forests and eucalyptus plantations. There are furniture centers in these states in Bento Gonçalves (RS), Sao Bento do Sul (SC), Arapongas (PR), Mirassol, Votuporanga and São Paulo (SP), Uba (MG) and Linhares (ES), which widely use both types of reconstituted panels.

The significant use of MDF in furniture centers is a result of their technological characteristics, such as the homogeneity of physico-mechanical properties, excellent workability, especially in edging and surfacing, etc., supplying part of the technical requirements not met by the MDP (IPT, 2009) and opening new perspectives for the development of lignocellulosic resources for this already established and rapidly growing sector.

1.2 THE ISSUE OF FORMALDEHYDE

Until the decade of 80 urea resins contained large amounts of free formaldehyde to facilitate the production of particleboard and MDF panels, due to its high reactivity and higher operating speeds. Its major disadvantage was the emission of large amounts of formaldehyde during the panel production process resulting in a stronger odor and environmental problems in the factories. Likewise, formaldehyde emissions caused problems when panels were used for flooring, furniture, wall coverings, etc., with intensive research in the adhesives industry having resulted, before the 80's, in the development of UF resins to meet current legislation in certain countries, as regards the limits of free formaldehyde in woodpanels.

The formaldehyde used as a chemical adhesive in the manufacture of panels, constituting part of the polymer, can be degraded and released into the environment. The formaldehyde released and contaminating the environment is within the structure of the panels in free form or associated to water of the cell wall of the fiberous elements or even in the form of hemi-acetals, the most important.

The free formaldehyde content in woodpanels is affected by its moisture and which relates to the raw materials, production, structure and storage conditions of the panels (Irle et al., 2008). As it is classified as a carcinogen by the World Health Organization, it is important to decrease its content in the reconstituted composite and research has been directed to the application of "formaldehyde free" resins, as those based on tannins, and the incorporation of alternative raw materials (BORGES, 2008; MULLEN, 2008; BUYUKSARI et al., 2010; MOUBARIK et al., 2010).

1.3 WHY SUGARCANE STALK BAGASSE?

The planting of about 10 million hectares of sugarcane elevates Brazil to the position of the world's largest producer and annually promotes production of about 175 million t of bagasse, which is indicated as a raw material for numerous applications such as for the manufacture of reconstituted woodpanels.

The crushed sugarcane is a source of electricity and heat, for the sugar and alcohol mill itself or to be sold. From the 90s there was an increase in the surplus bagasse in light of the reduction of steam consumption by increasing efficiency in the industrial plant production processes, creating new opportunities for its use. Also in this respect, the straw recovery by improving the harvesting process, led to an increase in the biomass availability for heat and electricity generation in boilers, and to produce ethanol by hydrolysis, allowing the use of bagasse for making reconstituted panels.

The resulting biomass from agricultural and industrial segments of the sugar and ethanol industry has a competitive cost, with the sugarcane bagasse and straw with estimated costs (base year 2020) of less than \$10.00 and than \$10.00 per t (dry basis). Compared with the United States, for example, it indicates that the cost per ton of biomass will be \$30-35.00 in 2020 (BRAZIL, 2007).

Thus, Brazil brings together highly natural and geographical conditions to assume a leading position in the world scenario in the production and use of biomass from sugarcane and other agricultural and forest crops.

1.4 WHY *EUCALYPTUS SP* WOOD?

Eucalyptus plantations in Brazil occupy 4.5 million ha, an increase of 41.1% in the 2004-2009 period. Although they are located in a significant number of Brazilian states, those in the south-central region stand out and the growth of the planted area is associated with increased productivity and wood quality, reducing the rotation cycle due to selection of new genotypes and hybrids, advances in management, mechanization of forest plantations and other factors.

On the other hand, there is a significant increase in investment by forest-industrial sector companies using eucalyptus wood as exclusive raw material, resulting in a strategic global position. In this respect, for the production of MDF panels in Brazil, there is a significant increase in the use of eucalyptus wood in relation to pine. While in the 1997-2002 period pinus wood was used exclusively, in 2003-2006, the eucalyptus wood was used in the production of 17% of MDF panels. From 2006 it was found that 23% of MDF panels were made of eucalyptus wood, currently followed by an upward trend (BELINI; TOMAZELLO FO, 2010).

The main advantages of using eucalyptus wood in the production of MDF panels relate to the (i) lower cutting cycle and tree rotation of eucalyptus forest plantations and, consequently, return on invested capital, (ii) higher wood density, resulting in higher yield in terms of relative volume of timber / panel, (iii) use of wood and bark (full use of the logs); for the pine trees, the bark needs to be removed, (iv) wood consisting of shorter fibers providing better post-machining quality.

2. METHODOLOGY

2.1. OBTAINING NATURAL FIBER COMPONENTS FOR COMPOSITES MANUFACTURE

Sugarcane stalk bagasse: samples were collected in the patio of São Manuel SA Sugar Mill in São Manuel-SP (Fig. 1A, B and C) at the outlet of the crushing and broth obtaining system. Subsequently, they were dried in an oven at 105ºC, to 5% moisture to prevent the growth of microorganisms, and submitted to particle size classification for panels manufacture. The previous year's crop of bagasse particles stored in piles were separated and not collected because of their degradation by thermophilic microorganisms (Fig. 1D).

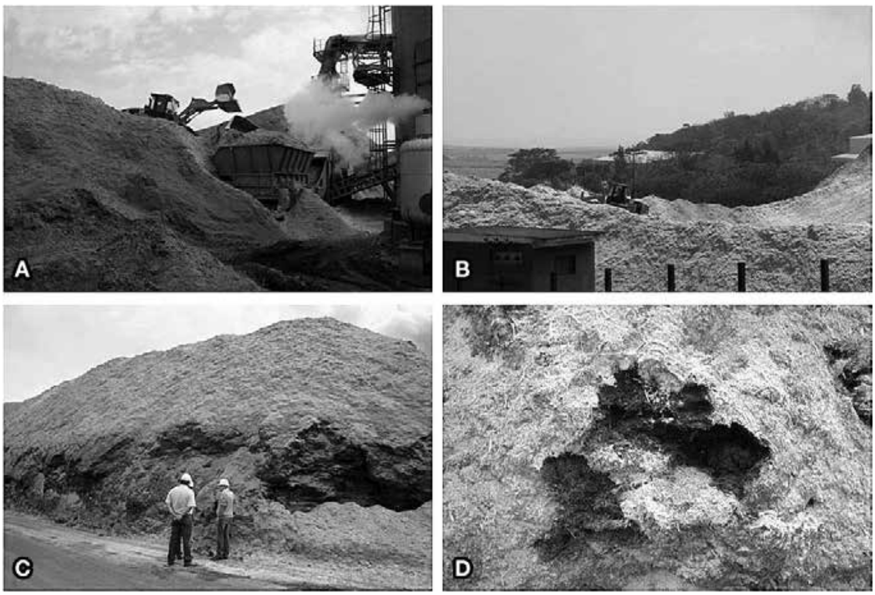


Figure 1 – Loading and layout of the sugarcane stalk bagasse on the patio (A, B, C); partially degraded appearance of the particles inside the hill (D).

For laboratory preparation of the composite, bagasse samples were granulometrically classified in the vibrating screens of the Produtest, model G equipment, through 5 openings (12.0 mm, 6.3 mm, 3.15 mm, 2.0 mm and <2.0 mm - collector). Exploratory classification evaluations indicated that the fraction passing through the sieve of 3.15 mm is characterized by large fiber bundles which differ in particle size from the fibers used in the manufacture of MDF panels.

Thus, all the fibrous material that passed through the sieve of aperture 2.0 mm and was retained in the collecting vessel was used in the manufacture of composites (Fig. 2). Other authors, Widyorini et al. (2005) and Ortunõ et al. (2011) used the same aperture sieve (2.0 mm) in the separation of sugarcane bagasse particles and *Arundo donax* L., a mediterranean tree species, respectively, for particleboard manufacture.

Eucalyptus wood fibers: the trunks of *Eucalyptus grandis* trees, 7 years old, from plantations of Duratex S.A. in Botucatu-SP, were turned into wood chips and then defibered through thermo-mechanical friction of 2 discs at high rotation, in an industrial MDF panel making process. The wood chips defibering conditions were (i) heating time = 4 min, (ii) digestion pressure = 8.0 bar (0.8 MPa) (iii) refining pressure = 8.2 bar (0.82 MPa) and (iv) specific energy consumption = 100 kWh/t (360 MJ), usual on an industrial scale. The eucalyptus wood fibrous components were collected on the industrial production line before *blow line* process.

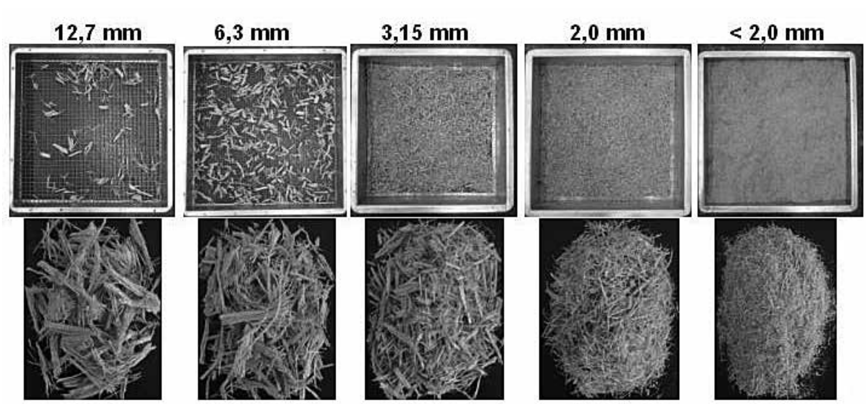


Figure 2 – Screening, opening (mm) and particle size fractions of crushed stalks from sugarcane.

2.2. PRODUCTION OF NATURAL FIBER COMPOSITES

Treatments of fibrous components and UF adhesive: 12 treatments (Tab. 1) were evaluated with varying eucalyptus fiber and sugarcane particle mix percentage and two urea formaldehyde adhesive percentages (13%

and 16 %). In the manufacture of composites the bagasse percentage was 0-25% in relation to the eucalyptus fibers, with 5% increases The utilization of a maximum of 25% bagasse particles for composites manufacture was defined for (i) a detailed characterization with small additions of raw materials, (ii) appropriate standards and consumer product market, (iii) greater acceptance of using small percentage of new raw materials, (iv) better coordination with the raw material logistic supply chain and (v) capability to use in current manufacturing conditions. 4 composites / treatment were made under laboratory conditions in a total of 48 panels.

Additivies used in composites manufacture: the urea formaldehyde adhesive (UF) and wax, used in bonding of the fibers/particles and as a water-repellent agent, respectively, were those commonly employed in MDF and MDP production industries and their chemical characteristics are shown in Tab. 2 and 3.

Table 1 – Treatments for panel manufacture with eucalyptus fibers and sugarcane stalk particles with 13% and 16% of UF adhesive.

Treatment	UF	Wax	Raw Material	
			Eucalyptus fibers	Bagasse particles
(Nº)	(%/dry fiber)	(%/dry fiber)	(%)	(%)
1	13	0.8	100	0
2	16		100	0
3	13		95	5
4	16		95	5
5	13		90	10
6	16		90	10
7	13		85	15
8	16		85	15
9	13		80	20
10	16		80	20
11	13		75	25
12	16		75	25

Table 2 – Characteristics of urea formaldehyde adhesive (UF) used in panel manufacture.

Variables	Unit	Results
Brookfield viscosity	cP	350
pH		8,6
Gel time	s	50
Solids content	%	65
Density	g cm^3	1,28

Table 3 – Characteristics of wax used in panel manufacture

Variables	Unit	Results
Viscosity CF 4	s	30
pH		10
Solids content	%	70

Composites manufacture: eucalyptus fibers were dried in an oven (2 - 3% humidity) separated into samples and transferred to the rotating drum (Fig. 3A, B) and mixed for 2 minutes followed by the batch period with the addition of the resin and wax through spray nozzles using compressed air (Fig. 3C) for 3 minutes, providing the spraying of the resin on the fiber mass under constant agitation, with homogenization of the fibrous matrix (Fig. 3D, E), with a final moisture content of 7% ± 0.5%.

The mass of sugarcane particles and eucalyptus fibers was was manually arranged in a forming box (300 x 370 x 370 mm) (Fig. 4A). Then, this mattress of particles was conveyed to a hydraulic system for applying pressure (Fig. 4B) for 20 seconds to remove internal air, this being a pre-pressing, necessary for the correct mat formation (Fig. 4C, D).

This mattress of fibers of the composite was arranged on a laboratory press (Fig. 4E) with a programmed pressing cycle consisting of pressure and time maintained in steps in each pressing cycle stage, which remained unchanged during pressing of the composites, for a target density in 750 $kg.m^{-3}$ and thickness in 15 mm. The nominal pressing cycle was 10 s at a pressure of 0-100 $N.cm^{-2}$, 5 s at 100 $N.cm^{-2}$, 20 s for reduction to 20 $N.cm^{-2}$, 15 s to reduce to 10 N. cm^{-2}, pressure maintained for 50 s, increasing to 30 $N.cm^{-2}$ in 10 s and maintained for 40 s, which was later reduced to 0 $N.cm^{-2}$ in 5 s. After pressing, the composite was conditioned at room temperature and adjusted to 370 mm x 370 mm.

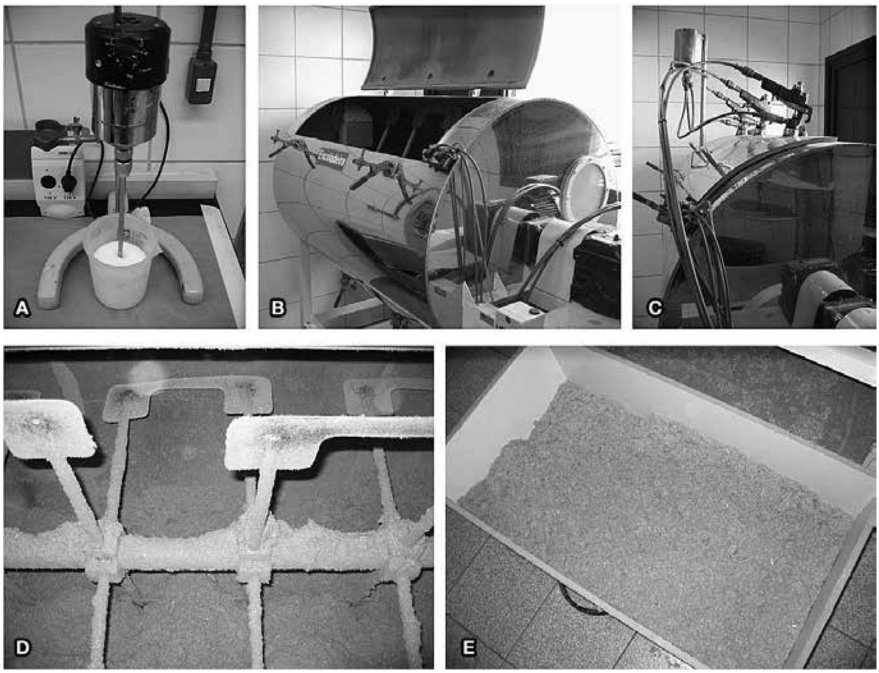


Figure 3 – Composite manufacture: (A) resin and wax mixture; (B, C, D) rotating drum for gluing, interior detail with nozzles, indicating the agitators; (E) fibers + particles bonded prior to mat formation.

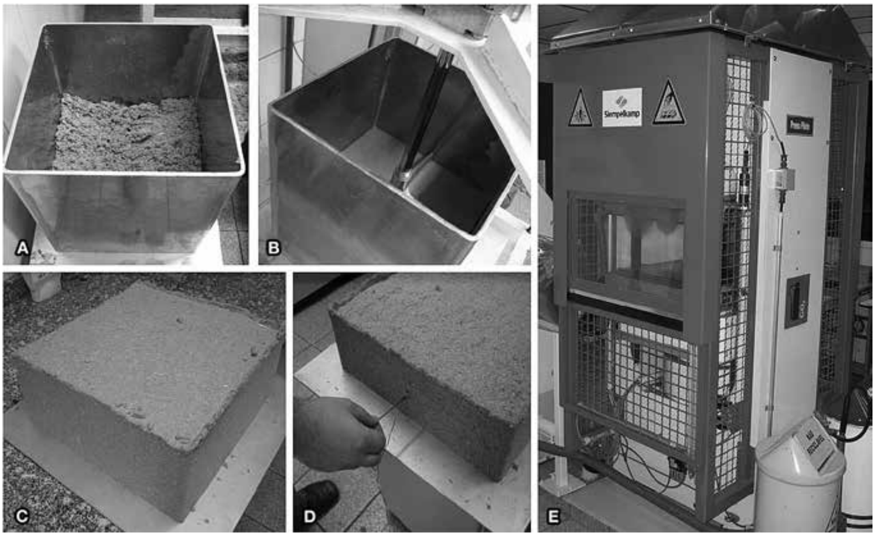


Figure 4 – Composites manufacture. (A) fibers + particles glued in the mattress formation box; (B, C) pre-pressing (removal of the internal air and the formation of mattress); (D) placing a thermocouple for monitoring the pressing cycle (E) laboratory press used.

2.3. CHARACTERIZATION OF PHYSICO-MECHANICAL PROPERTIES OF COMPOSITES

For composite of the 12 treatments (Tab. 1), 24 determinations of density and internal bond were performed; 18 determinations for swelling in thickness and absorption; 12 determinations of MOR, MOE, and screw withdrawal of (top). The mechanical analysis of the composites were performed on a servo-controlled universal testing machine. Tests of technological characterization of composites met the norm NBR ABNT 15316, 2009.

2.4. CHEMICAL CHARACTERIZATION (FREE FORMALDEHYDE)

The free formaldehyde levels were determined according to norm NBR ABNT 15316, 2009. 100 g of composite (15 mm x 25 mm x 25 mm) were obtained from the test bodies of the composites used in the evaluation of MOR and MOE for each treatment, to determine the concentration of free formaldehyde by the "*perforator*" method.

3. RESULTS AND DISCUSSION

3.1. SUGARCANE PARTICLE SIZE CLASSIFICATION

The classification in the sieve (Tab. 4) indicates the passage of 58.3% of the particles through the <2.0 mm opening which were retained in the collector. This particle fraction was separated and used in composites fabrication since the particle size is similar to that of MDP and suitable for blending with eucalyptus fibers.

The possibility of treating sugarcane particles in a defibrator results in a raw material of more uniform particle size and better uniformity, with the possibility of their full utilization, significantly above the 58% of the mass of particles retained in the sieve. It should be noted that the retention of the particles in the sieves is influenced by variables in their processing in the industry, according to the type and model of crushing equipment. As a reference it is mentioned that obtained retention values 13, 30, 5, 8 and 45% in sieves with openings of 12.7; 6.3; 3.0; 2.0 mm and collector, respectively, using the Produtest equipment.

Table 4 – Classification of cane bagasse particle size in vibrating screen openings from 12.7 to 2.0 mm and their average retention values (%)

Sieves (mm)	Retention (%)
12,7	**0,8** (1,2-0,5) (0,2) (23,6)
6,3	**7,6** (10,1-5,6) (1,5) (20,0)
3,15	**15,7** (18,7-13,5) (1,6) (10,3)
2,0	**17,6** (19,1-15,7) (1,2) (6,9)
colector	**58,3** (61,1-55,8) (1,8) (3,1)

Average values followed by (max-min) (standard deviation) and (coefficient of variation).

3.2 CHARACTERIZATION OF PHYSICO-MECHANICAL PROPERTIES

3.2.1 Panels of eucalyptus fibers and bagasse particles, with 13% UF adhesive (Tab. 5)

Density: There was no statistical difference in panel density in all treatments, classified as “Standard” MDF. The low coefficient of variation value indicates homogeneity of panel intra and inter-treatment density and the statistical similarity indicates no influence of this variable on the physico-mechanical properties.

Modulus of rupture (MOR): All modulus of rupture values are above those indicated in the norm and slightly lower than those of commercial MDF panels in Europe, with 38 $N.mm^{-2}$ (BEKHTA; NIEMZ, 2009); however, the results were similar to those determined by Aisyah et al. (2013)

for *Hibiscus cannabinus* MDF panels with 12% UF resin (30.3 $N.mm^{-2}$). In Brazil, Torquato et al. (2010) obtained values between 33 $N.mm^{-2}$ at 42 $N.mm^{-2}$ for panels from different manufacturers made with eucalyptus and pine fibers.

Modulus of elasticity (MOE): There was no statistically significant difference between treatments, with average values between 3067-3419 $N.mm^{-2}$, above the minimum specified by the norm. Particleboard panels of sugarcane bagasse and eucalyptus with 12% UF resin showed a MOE of 1063 $N.mm^{-2}$ (MENDES et al., 2010), lower than in the present work. MDF from *Hibiscus cannabinus* L., with 12% UF resin and nominal density 700 $kg.m^{-3}$ showed a MOE of 3619 $N.mm^{-2}$ (AISYAH et al., 2013) slightly higher than in this present evaluation.

Internal bond: There was significant difference between panels with 15% and 25% bagasse, with all being within the norm. The coefficient of variation, indicative of the dispersion of the resistance value of the panels between the treatments, results from the laboratory sizing process; it does not reproduce the conditions of the industrial line - blow line application - in the uniform distribution of the adhesive on the panels, inspite of the equipment and technology applied.

Internal bond values of commercial MDF panels in Brazil are 0.30 to 0.53 $N.mm^{-2}$ according Torquato et al. (2010), not meeting the specifications of the norms. On the other hand, particleboard made of sugarcane and eucalyptus fibers with 12% UF resin showed a value of 0.85 $N.mm^{-2}$ (MENDES et al., 2010). Also, MDP (15 mm, density 700 $kg.m^{-3}$, 6, 9 and 12% UF resin) showed an internal bond of 0.49 $N.mm^{-2}$, similar to those with 0, 10 and 20% cane particles (Hein et al., 2011).

Screw withdrawal: There was no statistical difference for the panels of the treatments, with correlation with density (VASSILIOU & BARBOUTIS, 1985) and internal bond (NIKVASH et al., 2010).

Swelling in thickness and absorption: The panels with 25% bagasse exhibited an average value less than the maximum prescribed by NBR 15316, 2009. There was a reduction in the swelling of the panels with the increase in the bagasse percentage, but with higher values compared to the panels with 16% resin (Table 6). Mean absorption values indicated statistical similarity to the panels of all treatments, not showing the same absorption decrease trend with the bagasse addition, verified in the swelling test.

3.2.2 Panels of eucalyptus fibers and bagasse particles, with 16% UF adhesive (Tab. 6):

Density: The panels show statistical similarity for all treatments, with no influence of this parameter on the physical-mechanical properties.

Modulus of rupture (MOR): There was a less than 10% statistical difference between the panels with 20% and 25% sugarcane particles, with classification within the norm.

Modulus of elasticity (MOE): There was a statistical difference for the panel of 25%, lower than that of the 10% bagasse panel. The lowest mean value found for the parameter was 43.5% above the minimum of NBR 15316, 2009.

Internal bond: There was a statistical significance for the 25% panels (0.65 $N.mm^{-2}$), lower than the 10 and 15% bagasse. The value of 0.42 $N.mm^{-2}$ was obtained in panels of sugarcane bagasse and wood chips (Nikvash et al., 2005) and 0.43 $N.mm^{-2}$ in MDF of wheat fiber and 15% urea formaldehyde adhesive (Halvarsson et al., 2008), both lower than in present work.

Screw withdrawal: There was a statistically significant difference for the 0% panel, higher than that of 25%, with a decrease in the average value starting from 20%. This variable is related to the internal bond and has its performance parameters specified by EN 320, 1997(27), where all the values determined in this study are within the specifications.

Swelling in thickness and absorption: There was a reduction in the swelling percentage with increased sugarcane particle percentage, especially for panels with 20%, similar to the panels with 13% resin, all within the norms. There was no statistical difference for panels from different treatments, with absorption values ranging from 54.7 to 68.1%.

Table 5 – Technological properties of panels from eucalyptus fibers and sugarcane particles, with 13% UF adhesive.

Variables	Bagasse particles (%), 13% UF adhesive						NBR 15316
	0	5	10	15	20	25	
Density ($kg.m^{-3}$)	**751 a** (7,6)	**722 a** (9,9)	**750 a** (10,0)	**763 a** (6,7)	**755 a** (9,2)	**764 a** (8,0)	
Modulus of rupture ($N.mm^{-2}$)	**30,2 ab** (17,4)	**24,6 b** (16,5)	**25,1 b** (25,4)	**32,0 a** (11,6)	**29,3 ab** (11,0)	**28,8 ab** (24,3)	minimum 20 $N.mm^{-2}$
Modulus of elasticity ($N.mm^{-2}$)	**3398 a** (12,9)	**3067 a** (11,9)	**3256 a** (10,2)	**3419 a** (11,2)	**3213 a** (8,3)	**3345 a** (10,8)	minimum 2200 $N.mm^{-2}$
Internal bond ($N.mm^{-2}$)	**0,49 b** (22,9)	**0,44 b** (34,6)	**0,52 b** (29,0)	**0,69 a** (20,9)	**0,52 b** (23,2)	**0,68 a** (14,2)	minimum 0,55 $N.mm^{-2}$
Screw withdrawal (kgf)	**113 a** (17,7)	**122 a** (32,7)	**119 a** (18,7)	**139 a** (20,8)	**116 a** (20,9)	**130 a** (14,9)	
Swelling in thickness (%)	**13,4 a** (29,0)	**13,8 a** (13,2)	**14,0 a** (22,4)	**13,4 a** (12,8)	**14,7 a** (13,6)	**10,2 b** (26,5)	maximum 12,0 %
Absorption (%)	**67,1 a** (28,7)	80,4 a (23,9)	75,2 a (30,0)	71,3 a (13,5)	74,5 a (25,0)	73,9 a (28,9)	

Average values followed (coefficient of variation); different letters in the same row differ at 5% probability level (Tukey test).

Table 6 – Technological properties of panels from eucalyptus fibers and sugarcane particles, with 16% UF adhesive

Variables	Bagasse particles (%), 16% UF adhesive						NBR 15316
	0	5	10	15	20	25	
Density ($kg.m^{-3}$)	**763 a** (9,9)	**767 a** (8,1)	**795 a** (6,5)	**793 a** (6,0)	**760 a** (9,4)	**775 a** (6,4)	
Modulus of rupture ($N.mm^{-2}$)	**30,6 ab** (18,6)	**30,1 ab** (18,8)	**36,4 a** (11,0)	**34,2 ab** (10,7)	**29,5 b** (24,7)	**27,2 b** (20,6)	minimum 20 $N.mm^{-2}$
Modulus of elasticity ($N.mm^{-2}$)	**3643 a** (8,0)	**3533 ab** (10,8)	**3732 a** (9,4)	**3543 ab** (11,8)	**3408 ab** (12,9)	**3158 b** (9,1)	minimum 2200 $N.mm^{-2}$
Internal bond ($N.mm^{-2}$)	**0,80 ab** (23,7)	**0,71 bc** (21,5)	**0,89 a** (14,0)	**0,88 a** (13,6)	**0,71 bc** (22,3)	**0,65 c** (16,3)	minimum 0,55 $N.mm^{-2}$
Screw withdrawal (kgf)	**168 a** (21,9)	**143 ab** (20,4)	**165 ab** (21,7)	160 ab (17,9)	135 ab (22,6)	129 b (17,1)	
Swelling in thickness (%)	**9,8 ab** (30,6)	**10,4 a** (18,7)	**9,8 ab** (26,5)	**9,2 ab** (22,7)	**6,7 c** (32,1)	**7,9 bc** (25,0)	maximum 12,0 %
Absorption (%)	**63,5 a** (29,2)	**68,1 a** (24,1)	**61,3 a** (18,7)	**56,3 a** (21,8)	**54,7 a** (29,4)	**56,2 a** (25,6)	

Average values followed by (coefficient of variation); different letters in the same row differ at 5% probability level (Tukey test).

3.3 EFFECT OF UF DOSAGE ON NATURAL FIBER COMPOSITES

Composites made with 16% UF adhesive showed better physical and mechanical properties compared to those with 13% UF, with a statistically significant difference between treatments (Tab. 7) however, as the costs of UF resin in MDF or MDP panels represent 30% of the final cost, optimization is required on an industrial scale.

The composites with 13% UF met the NBR 15316 (2009) for indoor application (Tab 7), except for the swelling, which had a value above the maximum allowed; for the best performance of these panels, increasing the water repellent wax is recommended, which represents 3% of the final cost of MDF and MDP. The literature reports the application of different percentages of UF adhesive in the manufacture of composites, with values of 8-12% (LAHR & CAMPOS, 2004), 11% in MDF of eucalyptus fibers (KRZYSIK et al., 2001; Ye et al., 2007) and 12-15% for panels of agricultural residues (HALVARSSON et al., 2008; BELINI et al., 2013).

Likewise, particleboard from bagasse with 8% UF resin showed MOR, MOE and internal bond of 10, 1600 and 0.2 $N.mm^{-2}$, respectively (WIDYORINI et al., 2005), lower than those obtained in the present work, with MOR, MOE and internal bond of 28, 3279 and 0.56 $N.mm^{-2}$, respectively (Tab. 5, UF 13%), possibly due to the lower resin percentage.

Furthermore, the longer pressing of composites, at a same temperature, can cause hydrolysis of aminoplastic resin with a decrease of their mechanical properties. The balance between the pressing time and resin percent in the manufacture of new panels with a higher percentage of adhesive should be analyzed in scientific research that, generally, implies in shorter pressing time and the densitometric profile determination and evaluation may be a powerful tool for this interpretation (BELINI et al., 2013).

Table 7 – Technological variables of composite with 13% and 16% UF adhesive

Variables	UF adhesive (%/dry fiber)		NBR 15316
	13	16	
Density (kg.m^{-3})	**751 b** (8,6)	776 a (7,9)	
Modulus of rupture (N.mm^{-2})	**28,3 b** (19,8)	**31,4 a** (19,4)	minimum 20 N.mm^{-2}
Modulus of elasticity (N.mm^{-2})	**3279 b** (11,3)	**3517 a** (11,2)	minimum 2200 N.mm^{-2}
Internal bond (N mm^{-2})	**0,56 b** (28,7)	**0,77 a** (22,8)	minimum 0,55 N.mm^{-2}
Screw withdrawal (kgf)	**122 b** (22,4)	**151 a** (22,3)	
Swelling in thickness (%)	**13,3 a** (22,1)	**9,0 b** (29,2)	maximum 12,0 %
Absorption (%)	**73,7 a** (25,5)	**60,1 b** (25,9)	

Average values followed by (coefficient of variation); different letters in the same row differ at 5% probability level (Tukey test).

3.4 LEVELS OF FREE FORMALDEHYDE IN NATURAL FIBER COMPOSITES

Panels with 25% sugarcane particles showed a reduction of up to 4 mg/100 of free formaldehyde content (Tab. 8), compared with the panels with 100% eucalyptus fibers, related to the release of furfural as acid that reacts with formaldehyde present in the adhesive. This reduced content of free formaldehyde was likewise detected in MDP of *Pinus pinea* cones particles and wood chips from *Pinus nigra* and *Fagus orientalis* (50/50%)

and 10% UF resin compounds as a function of the phenolics in the pine cones (BUYUKSARI et al., 2010).

Regarding the emission of free formaldehyde, the panels were classified in E2 class (8-30 mg/100 g). The free formaldehyde content of panels in industrial production line is related to the percentage of adhesive and, in the panel manufacturing process, greater exposure to formaldehyde occurs in the stages of glue preparation, mat forming, pressing and sanding, according Markessini et al., 2010.

In the panels of treatments 1-2, 3-4 and 5-6, made with the same percentage of feedstock and resin, the lowest free formaldehyde value was observed, generally, applying 16% UF resin. It is considered that the increase in UF resin percentage results in higher moisture content of mat fibers and in the laboratory pressing, the transfer of heat along its thickness (the inner surface) is more efficient and promotes faster resin curing, and therefore the consolidation of the panel. Thus, a consolidated panel is subjected to a temperature of the heated press platens for a longer curing period, resulting in more efficient reaction of the formaldehyde and urea molecules and reducing the free formaldehyde content.

However, it is noteworthy that the recent development of aminoplast resins has led to the manufacture of panels with low free formaldehyde content (MARKESSINI et al., 2010).

Table 8 – Content of free formaldehyde (mg/100 g) in panels with 13% and 16% UF adhesive

Treatment	Eucalyptus fibers	Sugarcane bagasse	UF	Free Formaldehyde
	(%)	(%)	(%)	(mg/100g)
1	100	0	13	**21,0**
2			16	**19,0**
3	95	5	13	**20,3**
4			16	**18,9**
5	90	10	13	**20,4**
6			16	**19,1**
7	85	15	13	**18,6**
8			16	**18,3**
9	80	20	13	**18,7**
10			16	**18,6**
11	75	25	13	**16,9**
12			16	**18,8**

4. CONSIDERATIONS

The technological challenge of this work was to develop a new product characterized by a matrix of eucalyptus fibers in which a percentage of up to 25% of sugarcane bagasse particles was embedded, as a sustainable biomass, in two different dosages of urea formaldehyde adhesive (UF) for composites production. The results show that:

The use of bagasse particles has become feasible to manufacture composites in a predominant matrix of eucalyptus fibers.

To prepare the composites, the recommended mat particle size is <2.0 mm.

Regarding the mixture of two raw materials, the use of up to 25% of bagasse in panels manufacture under current industry conditions for obtaining MDF panels, with small adjustments of the pressing conditions, is recommended.

Composites made with 16% UF resin showed better performance and met the NBR 15316-2 (2009) standards.

Increase in bagasse percentage reduced free formaldehyde content**.**

ACKNOWLEDGMENT

The authors thank UFSC, ESALQ/USP, FZEA/USP, Duratex S.A, BioSMat and FAPESP. And in particular, to Mr. José Reinaldo S. Astolphi (*in memoriam*).

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

AISYAH, H.A. et al. **Properties of medium density fiberboard (MDF) from Kenaf (*Hibiscus cannabinus* L.) core as function of refining condictions**. Composites Part B, v. 44, p. 592-596, 2013.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 15316 - Painéis de fibra de média densidade**: Métodos de ensaio, Rio de Janeiro, pt. 3, 2009. 48 p.

BELINI, U.L.; TOMAZELLO FILHO, M. Avaliações tecnológicas de painéis MDF de madeira de *Eucalyptus grandis* confeccionados em laboratório e em linha de produção industrial. **Ciência Florestal**, Santa Maria, v. 20, n.3, p. 495-502, 2010.

_________. et al. Density profile as a tool in assessing quality of new composite. **Materials Research**, São Carlos, v. 17, p. 138-145, 2013. doi:10.1590/S1516-14392013005000186 .

BEKHTA, P.; NIEMZ, P. Effect of relative humidity on some physical and mechanical properties of different types of fibreboard. **European Journal of Wood and Wood Products**, Berlin, v. 67, p. 339-342, 2009. doi:10.1007/s00107-009-0330-4.

BORGES, J.C. **Tecnologia de resinas e painéis de madeira**: passado, presente e futuro. Curitiba: Chimar Hellas S.A, 2008. 37 p.

BRASIL. **Plano Nacional de Energia 2030.** Ministério das Minas e Energia, Rio de Janeiro, 2007. 408 p.

BUCUR, V. **Nondestructive characterization and imaging of wood.** Berlin: Springer-Verlag, 2003. 354 p.

BUYUKSARI, U. et al. Evaluation of the physical, mechanical properties and formaldehyde emission of particleboard manufactured from waste stone pine (*Pinus pinea L.*) cones. Fayetteville: **Bioresources Technology,** v. 101, p. 255-259, 2010. doi:10.1016/j.biortech.2009.08.038

ECKELMAN, C.A.; CASSENS, D.L. Withdrawal strenght of dowels from wood composites. **Forest Products Journal**, Madison, v. 35, n. 5, p. 55-60, 1985.

EUROPEAN STANDARD. **EN 320 - Fibreboards – determination of resistance to axial withdrawal of screws.** Bruxelas, 1997. 5 p.

FIORELLI, J. et al. Particulate composite based on coconut fiber and castor oil polyurethane adhesive: An ecoefficient product. **Industrial Crops and Products**, v.40, p. 69-75, 2012. doi:10.1016/j.indcrop.2012.02.033

HALVARSSON, S.; EDLUND, H.; NORGEN, M. How to produce high performance straw MDF. In: INTERNATIONAL PANEL PRODUCTS SYMPOSIUM, Espoo, **Proceedings...**, p. 189-200, 2008.

HEIN, P. R. G. et al. Evaluation of bio-based particleboards properties by near infrared spectroscopy. **Holz als Roh- und Werkstoff**, Berlin, v. 68, n. 4, 2011.

INSTITUTO DE PESQUISAS TECNOLÓGICAS – IPT. **Madeira:** uso sustentável na construção civil. 2. ed., São Paulo, 2009. 99 p.

IRLE, M.; BELLONCLE, C.; GUEZGUEZ, B. Free formaldehyde - Where can I find It? In: INTERNATIONAL PANEL PRODUCTS SYMPOSIUM, Espoo, **Proceedings...** p. 31-38, 2008.

LAHR, F.A.R.; CAMPOS, C.I. Estudo comparativo dos resultados de ensaio de tração perpendicular para MDF produzido em laboratório com fibras de Pinus e Eucalipto utilizando uréia formaldeído. **Revista Matéria**, Rio de Janeiro, v. 9, p. 32-42, 2004.

KRZYSIK, A. M. et al. Medium density fiberboards from plantation grown Eucalyptus saligna. **Forest Products Journal**, Madison, v. 51, n. 10, p. 47-50, 2001.

LEE, S.; SHUPE, T. F.; HSE, C. Y. Mechanical and physical properties of agro based fiberboard. **Holz als Roh – und Werkstoff**, Heidelberg, v. 64, p. 74-79, 2006.

MARKESSINI, C.; ATHANASSIADOU, E.; TSIANTZI, S. Producing panels with formaldehyde emission at wood level. In: EUROPEAN WOOD BASED SYMPOSIUM, Hannover **Proceedings...** 2010.

MENDES, R. F. et al. Painéis aglomerados produzidos com bagaço de cana e madeira de eucalipto. **Scientia Forestalis**, Piracicaba, v. 38, n. 86, p. 285-295, 2010.

MOUBARIK, A. et al. Preparation and mechanical characterization of particleboard made from maritime pine and glued with bio-adhesives based on cornstarch and tannins. **Maderas: ciencia y tecnologia**, v. 12, n. 3, p. 189-197, 2010. doi:10.4067/S0718-221X2010000300004

MULLEN, J. D. Formaldehyde-free adhesive system provides a cost-competitive, environmentally-friendly alternative for interior wood products market. In: INTERNATIONAL PANEL PRODUCTS SYMPOSIUM, Espoo, **Proceedings...** p. 117-120, 2008.

NIKVASH, N. et al. Comparative properties of bagasse, canola and hemp particle boards. **European Journal of Wood and Wood Products**, Berlin, v. 68, p. 323-327, 2010. doi:10.1007/s00107-010-0465-3

ORTUNÕ, T. G. et al. Evaluation of the physical end mechanical properties of particleboard made from giant reed. (*Arundo donax* L.). **BioResources**, Raleigh, v. 6, n. 1, p. 477-486, 2001.

OSMAN, Z.; PIZZI, A.; ALAMIN, I. H. Comparative properties of agrofiber based particle boards using newly developed bonding materials. **Journal of Biobased Materials and Bioenergy**, v. 3, n. 3, p. 275-281, 2009. doi:10.1166/jbmb.2009.1034

REZENDE, J. L. P.; COELHO JR., L. M.; BORGES, L. A. C. Madeira e derivados: oportunidades dos Brasil no mercado internacional. In: OLIVEIRA, J. T. S.; FIEDLER, N. S.; NOGUEIRA, M. (Org.). **Tecnologias aplicadas ao setor madeireiro III**. Jerônimo Monteiro: UFES, cap. 1, p. 11-42, 2008.

SAVASTANO JR., H. **Materiais à base de cimento reforçados com fibra vegetal: reciclagem de resíduos para a construção de baixo custo.** 2000. 144p. Tese (Livre-Docência) - Escola Politécnica, Universidade de São Paulo, São Paulo, 2000.

TORQUATO, L. P. et al. Avaliação das propriedades físicas e mecânicas de painéis MDF produzidos pela indústria brasileira. **Floresta**, Curitiba, v. 40, n. 2, p. 275-280, 2010. doi:10.5380/rf.v40i2.17823.

VASSILIOU, V.; BARBOUTIS, I. Screw withdrawal capacity used in the eccentric joints of cabinet furniture connectors in particleboard and MDF. **Journal of Wood Science**, Kyoto, v. 51, 2005. P. 572–576. doi:10.1007/s10086-005-0708-9.

WIDYORINI, R.; XU, J.; UMEMURA, K.; KAWAI, S. Manufacture and properties of binderless particleboard from bagasse. I: Effects of raw material type, storage methods, and manufacturing process. **Journal of Wood Science**, Tokyo, v. 5, p. 648-654, 2005. doi:10.1007/s10086-005-0713-z.

YE, P. X. et al. Properties of medium density fiberboards made from renewable biomass. Amsterdam, **Bioresources Techonology**, v. 98, p. 1077-1084, 2007. doi:10.1016/j.biortech.2006.04.022.

DEVELOPMENT OF INNOVATIVE SUSTAINABLE WALLS COMPOSED OF BY-PRODUCTS OF RICE

João António Soares de Almeida
Institute for Research and Technological Development in Construction Sciences, 3030-289 Coimbra, Portugal; Centro de Química de Coimbra (CQC), Department of Chemistry, University of Coimbra, 3004-535 Coimbra, Portugal.
E-mail: joao.almeida@itecons.uc.pt

Maria Inês Vitória dos Santos
Institute for Research and Technological Development in Construction Sciences, 3030-289 Coimbra, Portugal.

António José Barreto Tadeu
Institute for Research and Technological Development in Construction Sciences, 3030-289 Coimbra, Portugal; Department of Civil Engineering, University of Coimbra, 3030-290 Coimbra, Portugal.

Nuno Albino Vieira Simões
Institute for Research and Technological Development in Construction Sciences, 3030-289 Coimbra, Portugal; Department of Civil Engineering, University of Coimbra, 3030-290 Coimbra, Portugal.

João Pedro Faria Rama
Department of Civil Engineering, University of Coimbra, 3030-290 Coimbra, Portugal.

ABSTRACT: The construction sector is becoming increasingly concerned with the management of resources and energy. New approaches to minimize the negative impacts of the construction and use of buildings include not only protecting natural resources and energy, but also designing better solutions in terms of the impact that is estimated to be incorporated throughout their life-cycles. A more sustainable construction has also been achieved by exploiting the latent value present in industrial waste materials. In this respect, it should be noted that agro-industries generate a significant amount of different waste products that have the potential to be used in the development of innovative building materials. In this work, models of wood walls, composed of straw and husk left over from rice cultivation and processing, have been prepared and studied. The density of straw and husk contained within the wall was varied and the respective models tested for their thermal and acoustic insulation properties. The best models were subsequently subjected to an environmental analysis. The life-cycle assessment (LCA) carried out in this work was based on the rice production of Baixo Mondego in the Centre Region of Portugal. Both the experimental studies and the LCA results suggest that straw and husk from rice are suitable materials for incorporation in wall solutions, providing a good functional and environmental performance.

Keywords: Sustainable wall panels. Rice by-products. Thermal and acoustic performance.

1. GENERAL INTRODUCTION

1.1 SUSTAINABLE CONSTRUCTION

The construction industry is associated with huge environmental impacts as it uses many natural resources and produces significant amounts of waste and CO_2. Society's growing concern with the environmental deterioration and with the over-exploitation of natural resources has generated a need for more sustainable construction. It is, thus, essential to consider the impacts associated with the construction and use of buildings, and to seek alternatives to minimize them.

International authorities have established important goals in this respect. The European Community, for example, demands greater use of renewal energy sources, more energy-efficient solutions and a significant reduction in the emission of greenhouse gases (EUROPEAN COMISSION, 2012). The same principles are implicit in the new regulation covering building products (EUROPEAN, 2011), which stipulates basic requirements as regards the sustainable use of natural resources, the protection of environmental quality and the economy of energy and thermal insulation.

Thermal insulation materials have an important role to play in this context, accounting for the management of energy and comfort levels. Hence, it is essential to study the viability of new materials in order to develop more sustainable solutions. The development of such products with less energy incorporation and lower environmental impact will benefit from the recovery of by-products and improvement of the performance and durability of the system.

1.2 CONSTRUCTION SOLUTIONS INCORPORATING WASTE MATERIALS

Although the use of sustainable materials is not new, there are still enormous technological opportunities available for the optimization and characterization of innovative construction solutions that have less environmental impact over their life-cycles. Examples of this are the systems that exploit the latent value of waste from various industrial sectors.

The incorporation of waste in cement mortars and concretes has been object of intense study. For example, there has been research into the incorporation of waste glass (MAIER, 2012; CASTRO, BRITO 2013; TAN, DU, 2013) cork (FRADE, TADEU, TORRES, 2012; CARVALHO, TEIXEIRA, VARUM, 2013), rubber (MERINO, ASTORQUI, CORTINA, 2007) and recycled plastic (FERREIRA, BRITO, SAIKIA, 2012) to substitute the traditional aggregate, and also ceramic waste (LAVAT, TREZZA, POGGI, 2009), stone dust (SILVA, 2010), blast furnace slag (ÖZKAN, YÜKSEL, 2008; ADOLFSSON, ROBINSON, 2011; RODRIGUEZ, MANSO, ARÁGON, GONZALES, 2009) and fly ash (ÖZKAN, YÜKSEL, 2008; BRITO, VEIGA, 2008), whose pozzolanic properties enable the quantity of binder to be reduced. Other materials of agricultural origin, such as sugar cane (JATURAPITAKKUL, KIATTIKOMOL, 2009), bamboo leaves (FRÍAS et al., 2012) and rice straw (WANG, WU, 2013), have also been studied.

Other types of mortars, containing lime and waste materials, have been studied in order to develop energy-efficient products with low environmental impact, such as in rehabilitation processes. In the case of aerated lime, there are studies related with the incorporation of ceramic waste (MATIAS, TORRES, FARIA, 2010; MATIAS et al., 2012), rice husk ash (MELO et al., 2011) and some organic materials (VENTÓLA et al., 2011). As regards hydraulic lime, there is the incorporation of fly ash, metakaolin and anhydrous plaster, plastic waste (MORSY, ALSAYED, SALLOUM, 2012), asbestos-cement powder (COLANGELO et al., 2011) and waste from the metal industry (KATSIOTI et al., 2010).

Wastes from the construction industry itself, known as construction and demolition waste (CDW), have been intensely studied with a view to reducing the demand for new raw materials and the development of new materials and applications (CORINALDESI, MORICONI, 2009; BRAGA, BRIT, VEIGA, 2012).

As regards insulating materials, an important topic in the context of this chapter, research in recent years has focused on the development of new thermal insulation materials based on natural products, such as linen or hemp fibres (PEREIRA, EVANGELISTA, BRITO, 2012), cotton fibres (ZHOU et al., 2012), solid waste from the paper and corn husk processing (LERTUSUTTHIWONG et al., 2008) or durian and coconut shell waste (KHEDARI et al., 2004). Other natural products, such as corncobs, have also been used in the design of acoustic insulation materials (FAUSTINO et al., 2012). These insulation materials, though yielding promising results, do not generally match the performance of fibreglass or rock wool fibres.

Associated to sustainable construction, wood (GOVERSE et al., 2001) and cereal straw (ATKINSON, 2008) are commonly used, as they generally provide high levels of thermal insulation and consequent energy savings. These solutions are responsible for maintaining significant quantities of CO_2 sequestrated throughout the life of the buildings.

1.3 BY-PRODUCTS OF RICE CULTIVATION AND PROCESSING

Agriculture and the respective processing industries generate massive amounts of waste and by-products with enormous potential for valorization.

The Baixo Mondego is an agricultural region located in the central-coastal region of Portugal, with a long tradition of rice production (ALMEIDA; MARQUES, 2013). It corresponds to an extensive alluvial plain with fertile soils (silty loam and clay loam), crossed longitudinally by the River Mondego, the longest exclusively Portuguese river, with the greatest hydrographic basin and largest average annual discharge. The irrigation perimeter of the Baixo Mondego consists of a central valley, between the cities of Coimbra and Figueira-da-Foz, and secondary valleys of the tributaries of the Mondego, making a total area of around 13 000 ha.

A significant part of total area of this valley (56%) is given over to rice farming. There are around 6 300 rice farmers in the Baixo Mondego, though many more people than this are dependent on this economic activity, given the inclusion of family members.

Rice is the second most cultivated cereal in the world and is the staple food for over half the population. As regards its cultivation in Portugal, it has a vegetative cycle of 5 months, between May and September, when it is harvested. In the Baixo Mondego, approximately 30 000 tons of rice are produced annually, generating a profit of 6 000 000 Euros (a significant amount compared with other economic activities in the region) and producing a large amount of waste. In addition to its economic value, there is also cultural value associated to the tradition of rice production in this region, which influences other activities of a social and gastronomic nature.

The processing of the rice, from harvesting to the final product, gives rise to residues of low economic and nutritional value. Around 15 000 tons of straw and 6 000 tons of husk are produced annually in this region by the processing industry when the grains are shelled.

Currently rice straw is mostly used for animal bedding, and is sold to the livestock farms in the region, while the rest is burned and/or buried in the earth. This causes various environmental problems. The burning of straw releases significant quantities of CO_2 into the atmosphere (0.4 ton of CO_2 per ton of burnt straw), while burying it releases methane, whose emissions are even more harmful (RENEWABLE ENERGY INSTITUTE COLLEGE OF ARCHITECTURE & ENVIRONMENTAL DESIGN, 1997).

Although there is little legislation regulating the disposal of biomass waste, there has been some development as regards the promotion of it for energy purposes. In this sense, agricultural waste resulting from farming and the processing of raw materials has a great deal of potential for use as biomass for the production of energy.

2. WALL PANELS COMPOSED OF RICE BY-PRODUCTS

2.1 TECHNOLOGICAL SOLUTION

Sustainable product design is an essential part of the EU strategy. In this case, a preventive approach is pursued, seeking to optimize the energy and environmental performance of products without compromising their functional characteristics. It is also fundamental to study the viability of the application of new materials and products in the development of more sustainable solutions, giving expression to the concept of passive buildings.

The walls are an integral part of any construction, whether modern or old, and have developed alongside the sector. In the past, walls were made of stone masonry or solid stone, and had a structural role as there was no other means of support. With the development of reinforced concrete, walls no longer had a structural role. They then began to be built out of lighter materials, and their functional characteristics were improved.

Various functional demands are assigned to walls, such as comfort and safety. As regards the latter, a wall solution should be characterized with respect to its structural stability, behaviour in fire situations and risk of intrusion. In terms of comfort, it should present good hygrothermal and acoustic behaviour, as well as good visual appearance and tactile qualities.

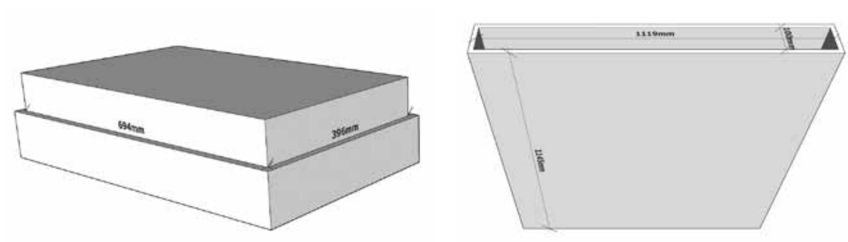
In the designing of new wall solutions, using innovative materials, it is necessary to meet technical demands while at the same time ensuring that the solution is sustainable and economically viable. These solutions should also present appropriate application and maintenance costs, as well as be appropriate for different building systems.

At present there are various sustainable materials on the market for use in the construction sector, although opportunities still exist for the development of more. Thus, this study aims to develop an innovative wall solution composed of wood and by-products from rice cultivation (straw and husk), able to provide hygrothermal and acoustic comfort inside houses. This study focuses particularly on the thermal, acoustic and environmental characterization of the solution, and compares these properties with those obtained in equivalent solutions made of rock wool.

2.2 EXPERIMENTAL DETAILS

The experimental models have involved wooden boxes of a size compatible with the testing equipment, filled with rice husk or straw (Figure

1). In the thermal tests, the box was of adjustable height so that the density of the filling material could be easily varied, while in the acoustic tests, it was of fixed size, compatible with the pre-fabricated frame used in acoustic chambers. In this case, density variation was achieved by increasing the mass of filling material inserted into the box. In the construction of these boxes, oriented strand boards (OSB) of 15,6 mm thick and with an average density of 593 kg/m³ were used.



(a) (b)

Figure 1 – Schematic representation of the wooden boxes used as experimental models in the thermal (a) and acoustic (b) tests.

The rice husk and straw used were of the species Oryza sativa L., subspecies Japónica, from the Baixo Mondego agricultural region. Rice straw (Figure 2a) is a cylindrical stalk of around 3 to 5 mm in diameter and 60 to 85 cm in length, consisting of 32% cellulose, 30% hemicellulose and 19% lignin on average (MURAKAMI et al., 2012). Rice husk (Figure 2b) is a woody sheath, around 3 to 5 mm in size, composed on average of 50% cellulose, 30% lignin and 20% silica (MEHTA, 2012). To study the influence of the presence of moisture and the size of the rice straw, some of these tests were carried out with material that had been dried to 60ºC until a constant mass was obtained, and also with ground material. For the purposes of comparison, models involving rock wool of three different commercial brands were also studied.

(a) (b)

Figure 2 – Photographic record of the rice straw (a) and rice husk (b) used in the models.

The experimental study took place in the laboratories of ITeCons (http://www.itecons.uc.pt). The thermal conductivity tests were done with the guarded hot plate λ-meter EP500e (Figure 3), stipulating an average temperature of 23ºC and a temperature variation between plates of 20ºC. The sound insulation tests were carried out using two acoustic chambers of approximately 204 m^3 (emitter chamber) and 182 m^3 (receiver chamber), intercommunicating through a 10 m^2 gap where the sample was inserted (Figure 4).

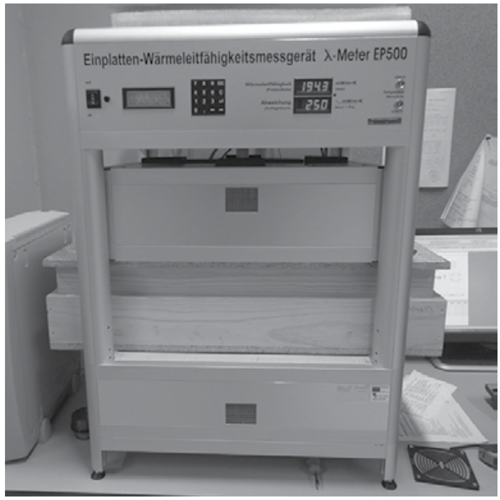


Figure 3 – Guarded hot plate λ-Meter used in the thermal conductivity tests.

(a) (b)

Figure 4 – Acoustic chambers (a) and pre-fabricated frame (b) used in the sound insulation tests.

2.3 LIFE-CYCLE ASSESSMENT

Life-cycle assessment (LCA) is a methodology that analyses input and output flows (mass and energy) during the life-cycle (LC) of a product or service from cradle to grave, so as to quantify and assess their potential environmental impacts (SANTOS, 2010). This methodology is based on the analysis of a group of subsystems that exchange inputs and outputs amongst each other (MALÇA; FREIRE, 2006), thereby enabling the most critical areas, or those requiring improvement, to be identified. The LCA consists of four fundamental phases (Figure 5).

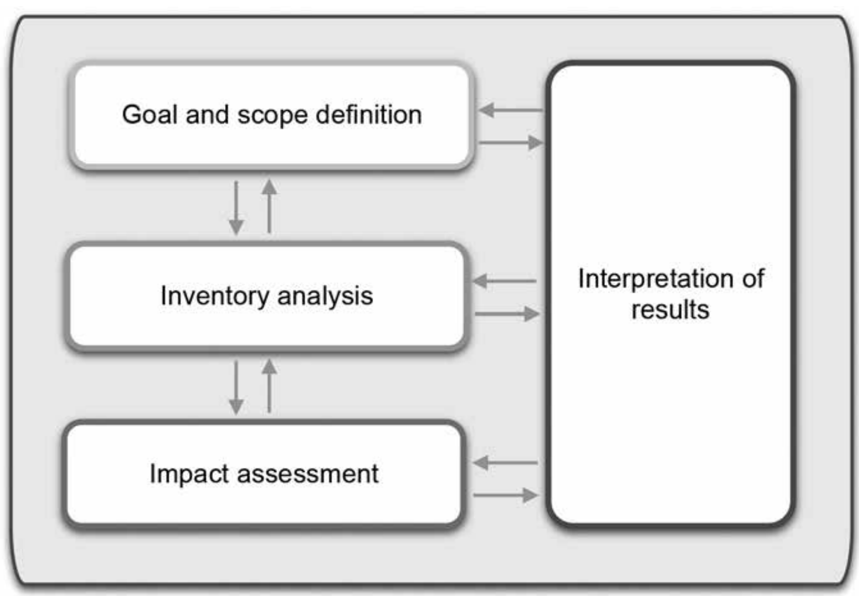


Figure 5 – Key phases of a Life-cycle Assessment, adapted from ISO 14040:2006.

The goal and scope definition is the phase where the purpose of the study is stated and the product or service system defined. It is also in this phase that functional unit, system boundaries and assessment criteria are established. In the inventory phase, all the inputs and outputs of energy and materials over its LC are quantified iteratively. After that, in the impact assessment phase, the potential environmental impacts related to the energy and material flows are assessed. Eventually, in the interpretation phase, information gathered in all the previous phases is analysed in accordance with pre-defined aims in order to draw conclusions and thereby assist decision-making (ENERBUILCA, 2012).

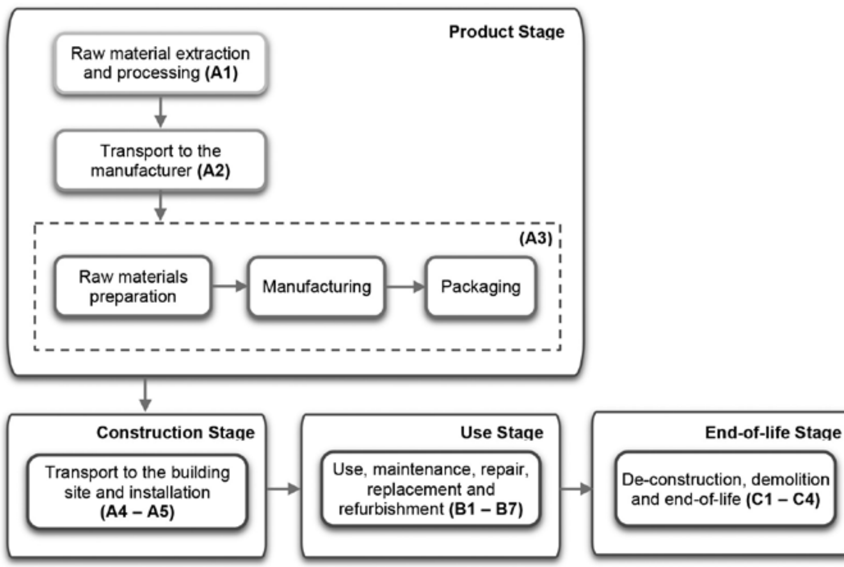


Figure 6 – Life-cycle stages and modules for the building assessment, adapted from EnerBuiLCA (2012).

This methodology is described by the international norms of the ISO 14000 family, particularly ISO 14040 and ISO 14044. Regarding the application of the LCA methodology to construction products and buildings, a series of methodological norms has recently been developed by the Technical Committee of Standardization 350 - Sustainability of construction works (EN 15643, EN 15643-2, EN 15804, EN 15941, EN 15942 and EN 15978).

This study was developed in accordance with the norms ISO 14040, ISO 14044 and EN 15804, as regards the nomenclature of stages and information modules (Figure 6) and the method of characterization used to assess the impacts.

3. RESULTS

3.1 HYGROTHERMICS

The different solutions were tested in order to determine the respective thermal conductivity (Table 1). As regards the wood boards, there was obtained an average thermal conductivity of 0,116 W/(m.°C). In the rice straw solution, there was a systematic reduction of thermal conductivity as the density increased. The lowest conductivity value (0,077 W/(m.°C) was obtained for a density of 43,4 kg/m^3, which was achieved with a thickness of 104 mm. As density variation was introduced by varying the thickness of the wooden box, it is plausible that part of this effect came from the varying thickness of the solution.

By filling the wooden box with a greater mass of straw, it was possible to study its behaviour with greater densities. It was found then that the increased density brought a reduction in thermal conductivity, resulting in a lower conductivity value of 0,070 W/(m.°C) for a density of 58,4 kg/m^3 and a straw thickness of 115 mm. In order to extend the thermal conductivity study of the rice straw solution to greater densities, the straw was ground up. The significant increase of density was reflected in a reduction of thermal conductivity, and a minimum value of 0,063 W/(m.ºC) was obtained for a density of 115,2 kg/m^3 and a straw thickness of 115 mm.

From the previous results it was also found that a thicker box was correlated with an equally greater thermal resistance. Hence, a more reliable idea of the thermal conductivity of rice straw as a function of the density may be obtained by comparing the results for the same thickness. For example, for a straw thickness of 135 mm, it was found that thermal conductivity decreases as the density increases.

In order to test the influence of the moisture present in the rice straw (8,5% in weight) on the thermal conductivity, tests were carried out using dry straw. There was a marked reduction in thermal conductivity of the respective solution. In this case, a value of 0,067 W/(m.ºC) was obtained for a density of 53,3 kg/m^3 and a straw thickness of 147 mm.

With rice husk, which has a similar chemical composition to straw but is significantly finer, it was possible to test even greater densities. A maximum value of 137,9 kg/m^3 yielded a thermal conductivity of 0,070 W/(m.ºC). Once more, the increase of density was found to be responsible for the reduction in thermal conductivity.

When straw and husk were compared, it was found that, although the level of insulation promoted by the rice husk was one of the best solutions, much greater densities were required to attain it. In this respect, it is important to point out that increasing the density of the rice straw to values near to that of rice husk (by using a grinding process) produced a solution with a level of insulation greater than that containing husk.

Eventually, the thermal performance of these solutions was compared with reference solutions consisting of three types of rock wool, using only a density of 120 kg/m^3. An average thermal conductivity of 0,052 W/(m.ºC), 0,051 W/(m.ºC) and 0,049 W/(m.ºC) was obtained for the different rock wools used.

Although the thermal conductivity of rice husk and straw are characteristics of insulating materials, solutions involving them had higher thermal conductivity than those containing rock wool. The simultaneous use of dry and ground straw (untested models) may produce a better thermal performance.

Table 1 – Thermal conductivity results obtained for the different wall models composed of rice straw, rice husk and rock wool.

Model	Filling mass (g)	Filling density (kg/m³)	Filling thickness (mm)	Total thermal conductivity (W/(m.°C))	Filling thermal conductivity (W/(m.°C))
OSB	-	593,0	-	0,116	-
OSB/Straw	1398	29,1	155,0	0,103	0,100
OSB/Straw		33,5	135,0	0,089	0,084
OSB/Straw		39,3	115,0	0,085	0,079
OSB/Straw		43,4	104,0	0,077	0,070
OSB/Straw	2080	43,3	155,0	0,090	0,090
OSB/Straw		49,8	135,0	0,080	0,074
OSB/Straw		58,4	115,0	0,070	0,065
OSB/Ground Straw	4100	98,1	135,0	0,066	0,060
OSB/Ground Straw		115,2	115,0	0,063	0,060
OSB/Dry Straw	1897	39,5	155,0	0,076	0,071
OSB/Dry Straw		45,4	135,0	0,069	0,063
OSB/Dry Straw		53,3	115,0	0,067	0,059
OSB/Husk	6031	125,7	155,0	0,078	0,073
OSB/Husk		137,9	141,3	0,070	0,064
OSB/Rock Wool 1	4900	120,0	101,5	0,052	0,045
OSB/Rock Wool 2		120,0	100,5	0,051	0,043
OSB/Rock Wool 3		120,0	100,6	0,049	0,041

3.2 ACOUSTICS

For each frequency band (1/3 of an octave), the average sound pressure was determined in each chamber. The results were corrected for background noise, and the equivalent absorption area was determined throughout the reverberation time. The sound reduction was calculated by adjusting a reference curve to the sound insulation curve, while the weighted sound reduction index (R_w) was given by the value of the reference curve in the 500 Hz frequency.

The acoustic behaviour of the empty wooden box, i.e., without any insulating filling material, produced an increasing level of sound insulation between the low and higher frequencies, with the maximum between the 400 and 1250 Hz bands, and a drop between the 1250 and 3150 Hz bands (Figure 7a). As regards low frequencies, there were variations in insulation resulting from resonance produced within the air space of the chamber itself. The drop in sound insulation between the 1250 and 3150 Hz bands possibly resulted from the many reflections of the sound in the air box, leading to a resonance phenomenon.

The introduction of straw produced an increase in the level of sound insulation from 35 to 38 dB in all the densities tested (Figure 7b). Increased density produced a complex effect on the level of sound insulation in different frequency regions. For the lower frequencies, the level of sound insulation was generally better for a density of 30 kg/m^3, while for middle frequencies, there was a significant increase in the level of sound insulation with the increase in density, particularly in the transition from 30 to 45 kg/m^3.

The introduction of rice husk led to a slight increase in the level of sound insulation, which for both densities was around 36 dB (Figure 7c). The resulting drop in frequencies associated to air box resonance reduced with the increase in the density of the rice husk. In no cases were drops attributed to critical frequencies of the panels, as these were situated at higher frequencies.

The introduction of rock wool led to a sound reduction index of 36 dB in one case and 37 dB in the other two (Figure 7d). The behaviour in the insulation curves was similar to that described above.

The results indicate that the sound reduction conferred by the rice straw solution is slightly better than that obtained with rice husk or rock wool.

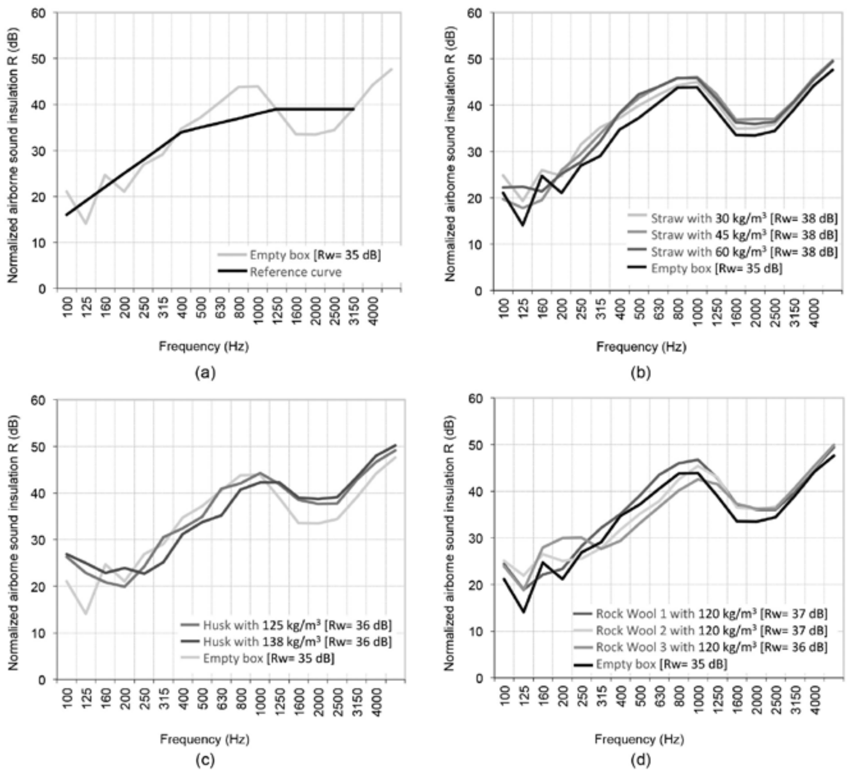


Figure 7 – Normalized airborne sound insulation curves obtained for the (a) empty wooden box, (b) wooden box containing rice straw, (c) wooden box containing rice husk, and (d) wooden box containing the different rock wools.

3.3 ENVIRONMENTAL ASSESSMENT

The main aim of the LCA study was to quantify and compare the environmental and energy performance of the LC of 1 m^2 of wall panel (declared unit), composed of different fillings: (i) P1 – wooden box with rice straw (ground); (ii) P2 – wooden box with rice husk; (iii) P3 – wooden box with rock wool. The LC model was developed in accordance with the experimental study carried out in the ITeCons laboratory, using SimaPro software. The inventory was prepared based on the experimental work and data available from the technical and scientific literature (e.g. Ecoinvent). This study considered the extraction and processing of raw materials (A1), transport to the site of production (A2) and the production of panels (A3) (Figure 8).

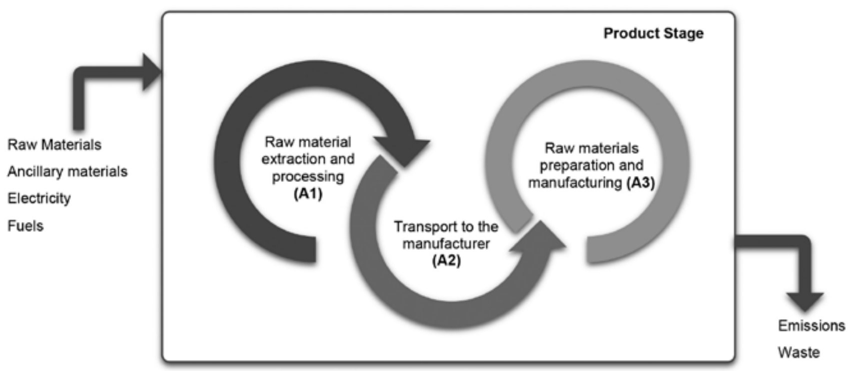


Figure 8 – System boundary of the wall panel life-cycle model.

The rice cultivation process is a multifunctional system, as a result of the several products obtained (rice, straw and husk). Therefore, environmental impacts have to be allocated to the different rice outputs, using physical properties (mass, energy content or carbon content) or other characteristics (economic value). However, the selection of the most appropriate allocation method was not always obvious. Hence, in accordance with the ISO norms mentioned above, a sensitivity test is recommended considering different methods to gauge the influence that this solution has upon the results (GARCIA; FREIRE, 2011). This study considered two scenarios, mass allocation and economic allocation (Table 2). The mass allocation was based on estimated rice production values in the Baixo Mondego in 2013, provided by the Agricultural Cooperative of the county of Montemor-o-Velho, compatible with the data presented in the BIODEN study provided by the Montemor-o-Velho Municipal Council (BLUE ERTH, 2008). For economic allocation, the market value of each product was considered in accordance with the data supplied by the Agricultural Cooperative of the county of Montemor-o-Velho and data in an article (DUARTE et al., 2007).

Table 2 – Allocation factors for rice and respective by-products.

Products	Annual Production (t)	Mass Allocation (%)	Market Price (€/kg)	Economic Allocation (%)
Rice	30000	58,82	0,27	85,44
Straw	15000	29,41	0,08	12,66
Husk	6000	11,76	0,03	1,90

In the impact assessment phase, two methods were used: the Cumulative Energy Demand (CED), for the energy assessment and CML – IA v4.1, for the environmental assessment. The energy was assessed in terms of the primary renewable and non-renewable energy consumptions, while the environmental was assessed in terms of the impact categories mentioned in EN 15804:2012, e.g., global warming, depletion of the ozone layer, acidification, eutrophication, photochemical ozone creation, depletion of abiotic resources (elements) and depletion of abiotic resources (fossil fuels).

The energy assessment results showed that the rock wool solution (P3) presents the most significant primary energy consumption (renewable + non-renewable). The results also showed that the consumption of non-renewal energy for this solution (P3) was higher than those obtained for the other solutions considered in the study (Figure 9). With regard to the rice husk (P1) and straw (P2) solutions, the consumption of renewable energy was significantly higher than the consumption of non-renewable energy.

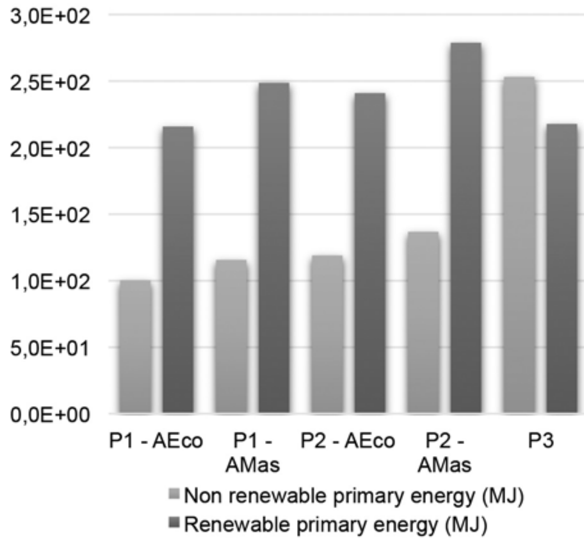


Figure 9 – Comparative energy assessment of the different models under study (product stage: A1-A3).

On the environmental level (Figure 10), it was found that the rock wool solution made the greatest contribution to all impact categories, with the exception of the depletion of abiotic resources (elements). Here, the rice husk and straw solutions had the greatest impact due to land-use for rice production. The husk solution performed best in all impact categories and in the different allocation scenarios considered. As for the allocation scenarios, it was found that impacts for all categories would be greater for the mass allocation than for the economic allocation. This was because, in the mass allocation, the impacts were distributed in accordance with the mass of the by-products, which had higher scores (29,41 % for straw and 11,76% for husk) than the economic allocation (12,66% and 1,90% respectively).

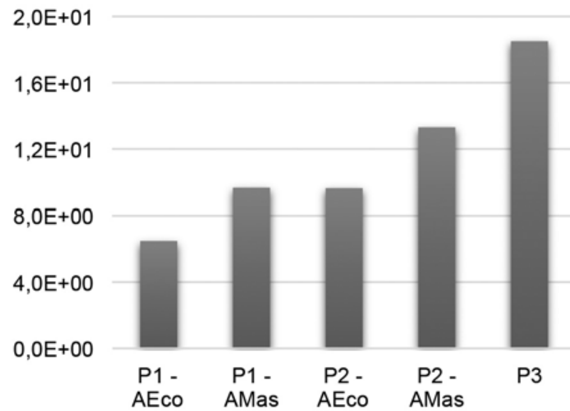


Figure 10 – Comparative environmental assessment regarding the global warming (kg CO_2 eq.) of the different models under study (product stage: A1-A3).

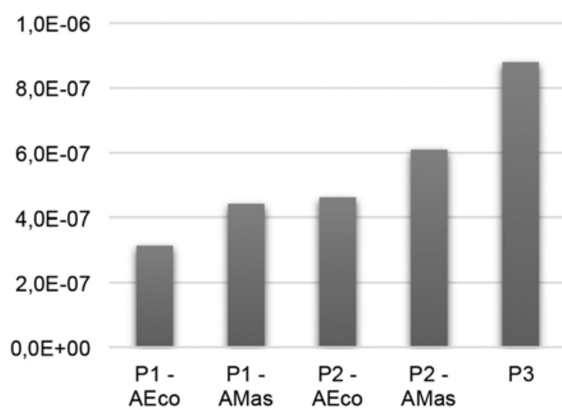


Figure 11 – Comparative environmental assessment regarding the ozone depletion (kg CFC-11 eq.) of the different models under study (product stage: A1-A3).

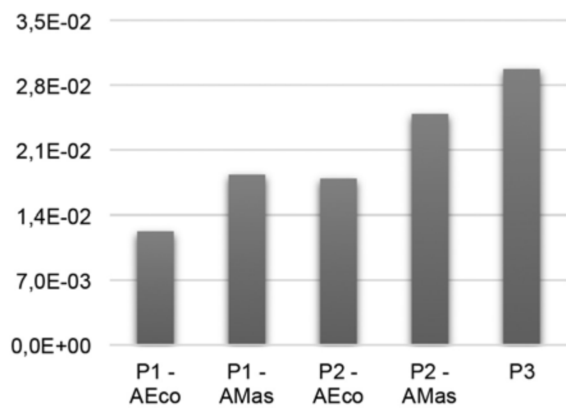


Figure 12 – Comparative environmental assessment regarding the eutrophication (kg $(PO_4)^{3-}$ eq.) of the different models under study (product stage: A1-A3).

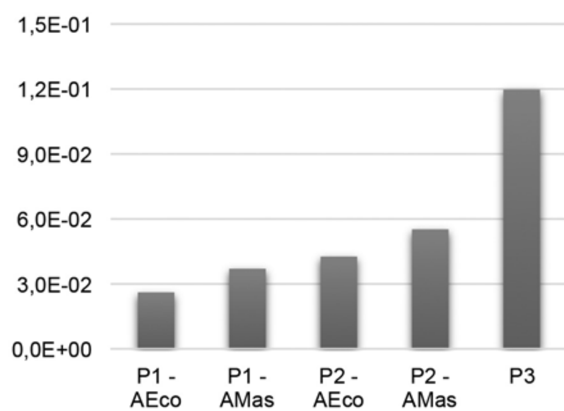


Figure 13 – Comparative environmental assessment regarding the acidification (kg SO_2 eq.) of the different models under study (product stage: A1-A3).

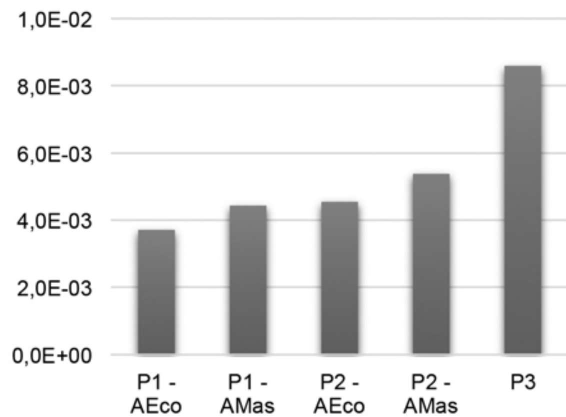


Figure 14 – Comparative environmental assessment regarding the photochemical ozone creation (kg C_2H_4 eq.) of the different models under study (product stage: A1-A3).

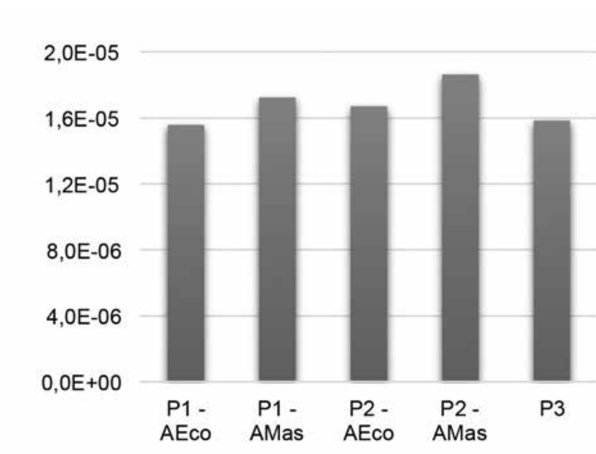


Figure 15 – Comparative environmental assessment regarding the depletion of abiotic resources - elements (kg Sb eq.) of the different models under study (product stage: A1-A3).

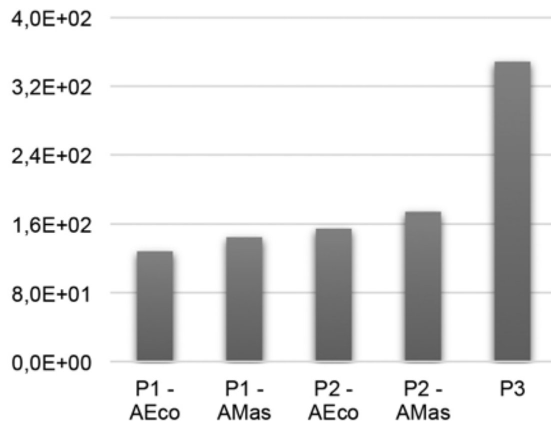


Figure 16 – Comparative environmental assessment regarding the depletion of abiotic resources - fossil fuels (MJ) of the different models under study (product stage: A1-A3).

4. CONCLUDING REMARKS

The construction sector is today increasingly concerned with the management of resources and energy, but also with the environmental, economic and social issues that these entail.

The main aim of this study was to develop an innovative wall solution composed of wood and rice husk or straw, oriented towards the eco-building market. It was shown that the use of these materials enables a sustainable product to be obtained. These products that has less environmental impact than conventional products yet offer levels of thermal and acoustic insulation suitable for this type of application.

Although the use of straw and wood in house building is not new, there are still great technological opportunities in the optimization and characterization of building solutions that maximise the benefits of these materials.

ACKNOWLEDGMENTS

This work has been framed under the Initiative Energy for Sustainability of the University of Coimbra and supported by the Energy and Mobility for Sustainable Regions - EMSURE - Project (CENTRO-07-0224-FEDER-002004).

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

ADOLFSSON, D.; ROBINSON, R.; ENGSTRÖM, F.; BJÖRKMAN, B. Influence of mineralogy on the hydraulic properties of ladle slag. **Cement and Concrete Research**, v.41, p. 865-871, 2011. doi: 10.1016/j.cemconres.2011.04.003

ALMEIDA, A.S.; MARQUES, P. A importância da cultura do arroz em Portugal e no Mundo. In: Boas Práticas no Cultivo de Arroz por Alagamento em Portugal. Oeiras, Portugal, 2013.

ATKINSON, C. **Energy Assessment of a Straw Bale Building.** MSc Architecture: Advanced Environmental and Energy Studies - School of Computing and Technology, University of East London, 2008.

BILLONG, N.; MELO, U.C.; KAMSEU, E.; KINUTHIA, J. M.; NJOPOWOU, D. Improving hydraulic properties of lime–rice husk ash (RHA) binders with metakaolin (MK). **Construction and Building Materials**, v. 25, p. 2157-2161, 2011. doi:10.1016/j.conbuildmat.2010.11.013

BLUE EARTH – Consultoria, Investigação e Desenvolvimento, Lda. **BIODEN-Densificação da Palha de Arroz:** Relatório Final. Lisboa, 2008.

BRAGA, M.; BRITO, J.; VEIGA, R. Incorporation of fine concrete aggregates in mortars. **Construction and Building Materials**, v. 36, p. 960-968, 2012. doi: 10.1016/j.conbuildmat.2012.06.031

CASTRO, S.; BRITO, J. Evaluation of the durability of concrete made with crushed glass aggregates. **Journal of Cleaner Production**, v. 41, p. 7-14, 2013. doi:10.1016/j.jclepro.2012.09.021

CHUSILP, N.; JATURAPITAKUL, C.; KIATTIKOMOL, K. Effects of LOI of ground bagasse ash on the compressive strength and sulfate resistance of mortars. **Construction and Building Materials**, v. 23, 3523-3531, 2009. doi:10.1016/j.conbuildmat.2009.06.046

COLANGELO, F.; CIOFFI, R.; LAVORGNA, M.; VERDOLOTTI, L.; STEFANO, L.D. Treatment and recycling of asbestos-cement containing waste. **Journal of Hazardous Materials**, v. 195, p. 391-397, 2011. doi:10.1016/j.jhazmat.2011.08.057.

CORINALDESI, V.; MORICONI, G. Behaviour of cementitious mortars containing different kinds of recycled aggregate. **Construction and Building Materials**, v. 23, p. 289-294, 2009. doi:10.1016/j.conbuildmat.2007.12.006.

CORINALDESI, V.; MORICONI, G.; NAIK, T.R. Characterization of marble powder for its use in mortar and concrete. **Construction and Building Materials**, v. 24, p. 113-117, 2010. doi:10.1016/j.conbuildmat.2009.08.013.

DE-CARVALHO, R.; TEXEIRA-DIAS, F.; VARUM, H. Cyclic behaviour of a lightweight mortar with cork granulate composite. **Composite Structures**, v. 95, p. 748-755, 2013. doi:10.1016/j.compstruct.2012.08.043.

DUARTE, L.C.; ESTEVES, M.P.; CARVALHEIRO, F.; VICENTE, P.; GÍRIO, F.M. **Os subprodutos agro-industriais de natureza lenhocelulósica: caracterização da situação portuguesa**. Dossier Tecnologia Agro-alimentar, p. 56-62, 2007.

ENERBUILCA. **Manual explicativo da Avaliação de ciclo de vida aplicada ao setor da construção.** EnerBuiLCA Project – Life Cycle Assessment for Energy Efficiency in Buildings, 2012.

EUROPE. Regulamento (UE) n.º 305/2011, do Parlamento Europeu e do Conselho, de 9 de Março de 2011. **Jornal Oficial da União Europeia**, Europe. L88, 2011.

EUROPEAN COMISSION (EC). **Europe 2020 targets:** Climate change and energy. EC, Bruxelles, 2012.

EUROPEAN COMMITTEE FOR STANDARDIZATION (CEN). **EN 15804:2012.** Sustainability of construction works - Environmental product declarations - Product category rules. Europe, 2012.

FAUSTINO, J.; PEREIRA, L.; SOARES, S.; CRUZ, D.; PAIVA, A.; VARUM, H.; FERREIRA, J.; PINTO, J. Impact sound insulation technique using corn cob particleboard. **Construction and Building Materials**, v. 37, p. 153-159, 2012. doi:10.1016/j.conbuildmat.2012.07.064.

FERREIRA, L.; BRITO, J.; SAIKIA, N. Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate. **Construction and Building Materials**, v. 36, p. 196-204, 2012. doi: 10.1016/j.conbuildmat.2012.02.098.

FRADE, D.; TADEU, A.; TORRES, I.; MENDES, P.; SIMÕES, N.; MATIAS, G.; NEVES, A. **Argamassas industriais com incorporação de granulado de cortiça**. In: Congresso Português de Argamassas e ETICS, 4 ed., 2012, Coimbra, Portugal.

FRÍAS, M.; SAVASTANO, H.; VILLAR, E.; ROJAS, M. I. S.; SANTOS, S. Characterization and properties of blended cement matrices containing activated bamboo leaf wastes. **Cement & Concrete Composites**, v. 34, p. 1019-1023, 2012. doi:10.1016/j.cemconcomp.2012.05.005.

GARCIA, R.; FREIRE, F. Modelação energética e ambiental do ciclo de vida de painéis aglomerados de partículas. **Construlink**, v. 28, n.28, p. 22-30, 2011.

GOVERSE, T.; HEKKERT, M. P.; GROENEWEGEN, P.; WORREL, E.; SMITS, R. E. H. M. Wood innovation in the residential construction sector; opportunities and constraints. **Resources, Conservation and Recycling**, v. 34, p. 53-74, 2001. doi:10.1016/S0921-3449(01)00093-3.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO). **ISO 14040:**2006. Environmental management – life cycle assessment –principles and framework. Geneve, 2006.

ITIM, A.; EZZIANE, K.; KADRI, E. Compressive strength and shrinkage of mortar containing various amounts of mineral additions. **Construction and Building Materials**, v. 25, p. 3603-3609, 2011. doi:10.1016/j.conbuildmat.2011.03.055.

KATSIOTI, M.; MAURIDOU, O.; MOROPOULOU, A.; AGGELAKOPOULOU, E.; TSAKIRIDIS, P. E.; AGATZINI-LEONARDOU, S.; OUSTADKIS, P. Utilization of jarosite/alunite residue for mortars restoration production. **Materials and Structures**, v. 43, p. 167-177, 2010. doi: 10.1617/s11527-009-9478-y.

KHEDARI, J.; NANKONGNAB, N.; HIRUNLAB, J.; TEEKASAP, S. New low-cost insulating particleboards from mixture of durian peel and coconut coir. **Building and Environment**, v. 39, p. 59-65, 2004. doi:10.1016/j.buildenv.2003.08.001.

LAVAT, A.E.; TREZZA, M. A.; POGGI, M. Characterization of ceramic roof tile wastes as pozzolanic admixture. **Waste Management**, v. 29, p. 1666-1674, 2009. doi:10.1016/j.wasman.2008.10.019.

LERTSUTTHIWONG, P.; KHUNTHON, S.; SIRALERTMUKUL, K.; NOOMUN, K., CHANDRACHANG, S. New insulating particleboards prepared from mixture of solid wastes from tissue paper manufacturing and corn peel. **Bioresource Technology**, v. 99, p. 4841-4845, 2008. doi: 10.1016/j.biortech.2007.09.051.

MAIER, P. L.; DURHAM, S. A. Beneficial use of recycled materials in concrete mixtures.

Construction and Building Materials, v. 29, p. 428-437, 2012. doi:10.1016/j.conbuildmat.2011.10.024.

MALÇA, J.; FREIRE, F. Renewability and life-cycle energy efficiency of bioethanol and bioETBE: assessing the implications of allocation. **Energy**, v. 31, p. 3362-3380, 2006. doi: 10.1016/j.energy.2006.03.013.

MATIAS, G.; FARIA, P.; TORRES, I.; TOMÁS, A.; FERREIRA, T.; DUARTE, T. Argamassas de cal aérea com resíduos de cerâmica. In: Congresso Português de Argamassas e ETICS, 4 ed., 2012, Coimbra, Portugal.

MATIAS, G.; TORRES, I.; FARIA, P. Argamassas de substituição com resíduos de tijolo cerâmico. In: Congresso Português de Argamassas e ETICS, 3 ed., 2010, Lisboa, Portugal.

MEHTA, P. K. Rice Husk Ash – A unique supplementary cement material. In: International Conference on Advance in Concrete Technology – CANMET, Greece. p. 407-431, 1992.

MERINO, M.R.; ASTORQUI, J. S. C.; CORTINA, M. G. Viability analysis and constructive applications of lightened mortar (rubber cement mortar). **Construction and Building Materials**, v. 21, p. 1785-1791, 2007. doi: 10.1016/j.conbuildmat.2006.05.014.

MORSY, M. S.; ALSAYED, S. H.; SALLOUM, Y. A. Development of eco-friendly binder using metakaolin-fly ash–lime-anhydrous gypsum. **Construction and Building Materials**, v. 35, p. 772-777, 2012. doi: 10.1016/j.conbuildmat.2012.04.142.

MURAKAMI, K.; SATO, M.; KATO, T.; SUGAWARA, K. Influence of difference in chemical compositions of rice straw on hydrogen formation in nickel-catalyzed steam gasification. **Fuel Processing Technology**, v. 95, p. 78-83, 2012. doi: 10.1016/j.fuproc.2011.11.020.

ÖZKAN, Ö.; YÜKSEL, İ. Studies on mortars containing waste bottle glass and industrial by-products. **Construction and Building Materials**, v. 22, p. 1288-1298, 2008. doi: 10.1016/j.conbuildmat.2007.01.015.

PEREIRA, P.; EVANGELISTA, L.; BRITO, J. The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates. **Construction and Building Materials**, v. 28, p. 722-729, 2012. doi:10.1016/j.conbuildmat.2011.10.050.

RENEWABLE ENERGY INSTITUTE COLLEGE OF ARCHITECTURE & ENVIRONMENTAL DESIGN. **Alternative uses of rice-straw in California**. Air Resources board – Research Division. Sacramento, United States of America, 1997.

RODRIGUEZ, Á.; MANSO, J. M.; ARAGÓN, Á.; GONZALES, J. J. Strength and workability of masonry mortars manufactured with ladle furnace slag. **Resources, Conservation and Recycling**, v.53, p. 645-651, 2009. doi: 10.1016/j.conbuildmat.2011.03.044.

SANTOS, M. **Avaliação de ciclo de vida de louça cerâmica sanitária**. Dissertação (Mestrado) - Departamento de Engenharia Mecânica, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, 2010.

SILVA, J.; BRITO, J.; VEIGA, R. Fine ceramics replacing cement in mortars. Partial replacement of cement with fine ceramics in rendering mortars. **Materials and Structures**, v. 41, p. 1333-1344, 2008. doi: 10.1617/s11527-007-9332-z.

SILVA, J.; BRITO, J.; VEIGA, R. Incorporation of fine ceramics in mortars. **Construction and Building Materials**, v. 23, p. 556-564, 2009. doi: 10.1016/j.conbuildmat.2007.10.014.

TAN, K.H.; DU, H. Use of waste glass as sand in mortar: Part I - Fresh, mechanical and durability properties. **Cement & Concrete Composites**, v. 35, p. 109-117, 2013. doi: 10.1016/j.cemconcomp.2012.08.028.

VENTOLÁ, L.; VENDRELL, M.; GIRALDEZ, P.; MERINO, L. Traditional organic additives improve lime mortars: New old materials for restoration and building natural stone fabrics. **Construction and Building Materials**, v. 25, p. 3313-3318, 2011. doi: 10.1016/j.conbuildmat.2011.03.020.

WANG, W.; WU, C. Benefits of adding rice straw coke powder to cement mortar and the subsequent reduction of carbon emissions. **Construction and Building Materials**, v. 47, p. 616-622, 2013. doi: 10.1016/j.conbuildmat.2013.05.066.

ZHOU, X.; ZHENG, F.; LI, H.; LU, C. An environment-friendly thermal insulation material from cotton stalks fibres. **Energy and Buildings**, v. 42, p. 1070-1074, 2010. doi: 10.1016/j.enbuild.2010.01.020.

GRANULOMETRIC CLASSIFICATION OF BAMBOO CHIPS FOR THE PRODUCTION OF PANELS FOR CIVIL CONSTRUCTION

Maximiliano dos Anjos Azambuja
Departament of Civil Engineering, UNESP – State University of São Paulo, Bauru, Brazil.
E-mail: maximilianoazam@feb.unesp.br

Gabriela Perseguin Remedio
Department of Architecture and Urbanism, UNESP – State University of São Paulo, Bauru, Brazil.
E-mail: gabrielaperseguin@hotmail.com

Rosane Aparecida Gomes Battistelle
Departament of Civil Engineering, UNESP – State University of São Paulo, Bauru, Brazil.
E-mail: rosane@feb.unesp.br

Sérgio Augusto Mello da Silva
Departament of Civil Engineering, UNESP – State University of São Paulo, Ilha Solteira, Brazil.
E-mail: sams@dec.feis.unesp.br

Ivaldo De Demenico Valarelli
Departament of Mecanic Engineering, UNESP – State University of São Paulo, Bauru, Brazil.
E-mail: ivaldo@feb.unesp.br

Francisco Antonio Rocco Lahr
Departament of Structural Engineering, Engineering School of São Carlos (EESC/USP), São Carlos, Brazil.
E-mail: frocco@sc.usp.br

ABSTRACT: Particleboards, in general, are defined as the product of the agglutination of small particles of lignocellulosic materials, usually with the use of synthetic adhesives, under pressure and heat, for a certain period of time. In Brazil, the production of particleboards is performed only with reforested wood; however, the study of other materials in such processes would be interesting. The productivity of bamboo biomass can vary between 50 to100 ton/ha./year and harvesting the bamboo is advantageous after the third year because this crop does not need replanting. However, in Brazil, a study about the control of the sizes of the chips deriving from bamboo culms to manufacture particleboards has still not been outlined. The study of the combination between chips of different dimensions (determined by a set of sieves) was the main focus of the research. We elaborated traces to determine the better distribution of the percentage of particles relative to the physical properties and mechanics of the particleboards. We used chips with the following dimensions in millimeters: 4.75; 4.00; 3.35; 2.80; 2.00; 0.84 e 0.42. The percentage of adhesive resins was kept at 12% for all traces. The physical and mechanical characteristics of the particleboards were determined by standardized tests (14.810 ABNT standards), which are: absorption coefficient of water, relative humidity, specific mass, swelling, bending resistance and traction parallel to the fibers, as well the analysis of the internal adherence of the particles. The research demonstrated a potential to generate expressive results with respect to the characterization of the Bamboo particleboard product in compliance with the national interests in the support of research and technological development.

Keywords: Particleboard. Bamboo physical and mechanical tests.

1. INTRODUCTION

The term 'particle' is defined in the ASTM D 1554 (2010) standard as the aggregate component of a wood particleboard, or of other lignocellulosic materials, including all of the smaller subdivisions of wood, manufactured by mechanical means. Thus, the mechanical resistance of the particles obtained is considerably lower than the resistance of the wood from which they were made. In other words, the final structure of the panel represents a unit that has empty spaces and ruptures that reduce mechanical resistance instead of a massive element as stated in Dacosta et. al. (2005).

In this context, ABNT NBR14810-1 standard of March 2002 defines agglomerated wood board, or wood particleboard, as a "product in the shape of a board, 3 to 50 mm thick, composed of agglomerated wood particles with thermofixed natural or synthetic resins under pressure and heat. The geometry of the particles and their homogeneity, the adhesive types, the density and the manufacturing processes may be changed to create products for specific uses. Additives may also be incorporated during the manufacturing process to provide special characteristics to the panels.

The production of wood particleboards made a large progress worldwide from the sixties onwards. Nevertheless, and in spite of also having been influenced by such trend, Brazil had a small industrial production with significant advances only in the eighties while in other developed countries such as the United States, Canada and Germany research increased along with the manufacture of wood particleboards. Despite the potential of the sector, the development of research on the matter is scarce, Peixoto and Brito (2000). It is also important to consider the fact that, in Brazil, the studies on better particle granulometry has not been receiving the due attention.

It is also worth stressing the important role synthetic adhesives have in manufacturing wood particleboards for the final cost of the boards depends on the type of adhesive used. The production of synthetic adhesives with the purpose of being used in the production of plywood began with the production of phenol formaldehyde resins (1929), urea formaldehyde (1931), melamine formaldehyde in the late thirties, and resorcinol formaldehyde in 1943, Iwakiri (2005) apud Tsoumis (1991).

According to Iwakiri (2005), the urea formaldehyde resin developed in the early thirties has an extensive application in the worldwide wood industry. This type of resin is used in more than 90% of the wood panels manufactured because it represents low costs in relation to the other resins that exist in the market.

In recent studies accomplished by Alves & Silva (2013) and Marton & Silva (2013), they evaluated particleboards made from the waste of four species of native wood used by furniture manufacturers and from the waste of five species of native wood used by the woodwork industry in the region of São José do Rio Preto, respectively. Both studies considered the granulometric analysis of the waste in compliance with NHR 7217 of August 1987 and they reached the conclusion that granulometric strips with less than 2 mm significantly interfere in bending resistance; however, they may contribute to increase resistance to perpendicular traction and to screw removal.

The civil construction and real estate sectors are the main ones responsible for technological advancement in the wood particleboard industry. According to Weber (2011), long and thin particles result in a larger slenderness ratio and produce panels with greater resistance to static bending and dimensional stability. Industrially, larger particles are used in the internal layer and smaller, or thin, particles are used in the external layer. Using thin particles guarantees a better finish to the surface of the panel, mainly aiming at improving the conditions of applying revetment materials. On the other hand, a high percentage of thin particles increases resin consumption and affects the quality of the panels, because it reduces internal adherence between the internal and external layers of the panel.

Nevertheless, there are not any specifications or standards referring to the quantity and dimensions of the particles. Because of that, this paper intends to find trace of bamboo chips in which there is a better accommodation of the particles to decrease such empty spaces, thus improving their physical and mechanical characteristics, varying the percentage distribution of the particles according to their dimensions and keeping a standard percentage of adhesive resin in all of the boards. In order to achieve that, we will use chips with the following dimensions: 4.75; 4.00; 3.35; 2.80; 2.00; 0.84; and 0.42 mm. The same tests will be performed with different traces. The physical and mechanical characteristics of the particleboards will be determined by means of standardized testing, which are: absorption coefficient of water, relative humidity, specific mass, swelling, bending resistance and traction parallel to the fibers, as well as the analysis of the internal adherence of the particles.

The main control variables of the productive process when producing wood particleboards (chipboards) are: the density of the wood to be used, the density of the board, the geometry and humidity of the particles, the quantity of resin and the pressing cycle. The resistance and dimensional stability properties of the boards produced depend on the control of such variables, the most important of which are: static bending elasticity and rupture modulus, internal bonding, water absorption and thickness swelling, Iwakiri e. al, (1999).

According to Iwakiri et al., (1999), one of the characteristics of the particleboards produced in Brazil is the use of small-dimensioned particles that cause limitations in the dimensional stability and bending resistance. Therefore, such boards are used for furniture, internal environments (partition walls) and electronic device components. Moreover, the smaller the particle, the larger the surface area and the quantity of resin needed. However, the larger the density of the wood, the smaller the surface area and the smaller the area of contact between the particles, which results in a decrease in the mechanical resistance of the board.

There are many advantages in using the wood particleboards instead of wood in its natural status, since the dimensions of the panels are not related to the dimension of the trees and the quality of the wood. There is also a possibility of eliminating many defects arising from drying, the anatomy of the trees such as knots, tree medulla and reducing anisotropy, which gives the final product less heterogeneity than the one found in sawn wood as reported by Alves & Silva (2013).

Resin is the most expensive material in the production of particleboards; therefore, one is required to pay attention to its use and dosage. The most commonly used resins currently are composed of polymers of urea formaldehyde and phenol formaldehyde. The urea formaldehyde polymers are for internal use because of their low resistance to humidity and lower costs, and the phenol formaldehyde polymers are for external use due to their greater durability and resilience.

In consonance with Peixoto and Brito (2000), the density of the wood and the compacting ratio of the board are two important factors to be considered. Another factor that influences the mechanical properties of a particleboard is the dimension and shape of the particles themselves. The geometry of the particles is one of the basic factors that determine the properties and characteristics of the boards, together with the kind of wood, type and quantity of resin and other additives. Once the geometry or granulometry of the particles is changed, it is also necessary to investigate the best proportion of adhesives to be employed, among other variables of the process.

Brito & Silva (2002), in studies developed with particles of various sizes and shapes, have determined that the linear expansion of the boards at 40°C and 90% of the relative humidity was affected by the geometry of the particles. They also noted that boards with smaller particles presented greater linear expansion. Brito & Silva (2002) have concluded that the decrease in the size of the particles did not result in a decrease in bending resistance.

Consequently, for the purposes of this study, we performed assessments based on the procedures provided by the ABNT – Brazilian Association of Technical Standards through NBR 14.810 (2006) Wood Particleboards - Part 3: Testing Methods, of and the following activities were considered to develop the study:

i) Bamboo chips manufactured from bamboo waste by using cutting mills. Such waste are obtained from machining procedures at the UNESP/FEB Bamboo Experimentation Laboratory;
ii) Granulometric classification of the chips;
iii) Produce, at laboratory scale, bamboo particleboards with different configurations with respect to the size of the chips by evaluating the different stages involved in the process;
iv) Evaluate the physical and mechanical behavior of the boards produced.

2. MATERIAL AND METHODS

The bamboo used in this research belongs to the Dendrocalamus giganteus species which is classified as Bambusae, subfamily Gramineae, monocotyledon, and belongs to the angiosperms. It was taken from the Agricultural Experimental Area of UNESP/FEB and it is the waste material generated in the craftwork production process at the Bamboo Experimentation Laboratory of UNESP/FEB.

As reported by Hiziroglu et al., (2005) the bamboo is the most diverse group of plants in the gramineae family. With a 3 to 5-year plant maturity cycle, the bamboo is one of the renewable plants with the fastest growth. Some plants grow at the rate of one meter per day during the growth period. The bamboo is a robust plant and is tolerant to poor soils and to adverse topography and weather.

Similarly to wood, the bamboo is a lignocellulosic material that presents high resistance, broad geographic distribution in Brazil and is considered an underutilized species. Polucha (2006) clarifies that the bamboo has high levels of productivity per area and it can be grown in inhospitable and degraded land. Thus, the bamboo can be a good alternative for manufacturing reconstituted panels. As a result, the bamboo can promote the diversification of engineered products that are manufactured.

The physical properties of the panels made with bamboo chips (Dendrocalamus giganteus) and the addition of 12% of the SikaBond® T54 FC adhesive were evaluated according to traces established in the following table:

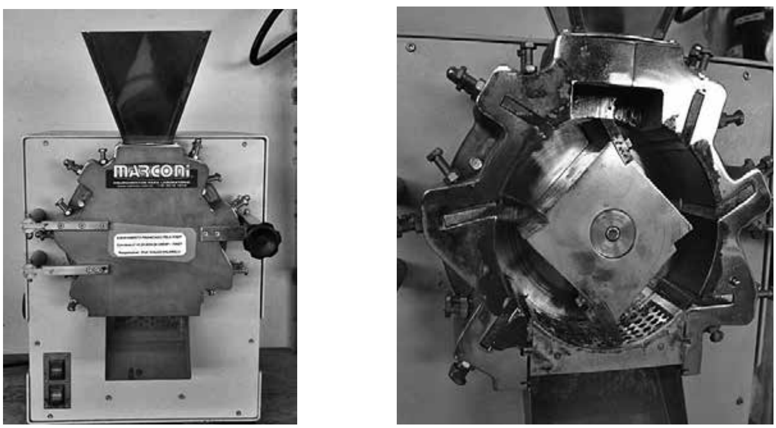
Table 1 – Traces and their respective percentages.

TRACES	Dimension of the chips (mm)						
(%)	4.75	4.00	3.35	2.80	2.00	0.84	0.42
T1	0	32	8	16	24	20	0
T2	8	24	24	4	20	15	5
T3	16	16	16	16	16	10	10
T4	24	8	24	12	12	5	15
T5	32	0	24	8	8	0	20

To manufacture the boards, after the bamboo was processed and chopped into chips, the chips passed through a cutting mill. Later, they were submitted to a classification performed by passing them through a set of sieves shaken by a mechanical shaker. The process was repeated innumerous times until the pre-established quantity of particles for all dimensions were obtained. This step was very slow because the sieves tolerated a limited quantity of material and it was necessary remove all the sieve meshes for each procedure. The particles took six minutes on average to pass through the set of sieves and the quantity of fine particles was much higher at the end of the classification.

More than 30 kilos of bamboo chips were sieved. An amount larger than the one that would be used in the composition of traces was necessary because the quantity of thin chips was much higher than the amount of thick and medium ones at the end of the classification. The process was repeated until the necessary quantity of chips for all dimensions was reached.

After the proper classification, we added the SikaBond® T54 FC. The percentage of the adhesive was maintained at 12% for all traces. The SikaBond® T54 FC is a mono component, solvent-free, elastic adhesive. It is certified by EMICODE EC 1 “very low emission”, GISCODE PU 10 “solvent-free”. The proposal of using this adhesive to manufacture bamboo panels is considered environmentally friendly and works towards sustainability.



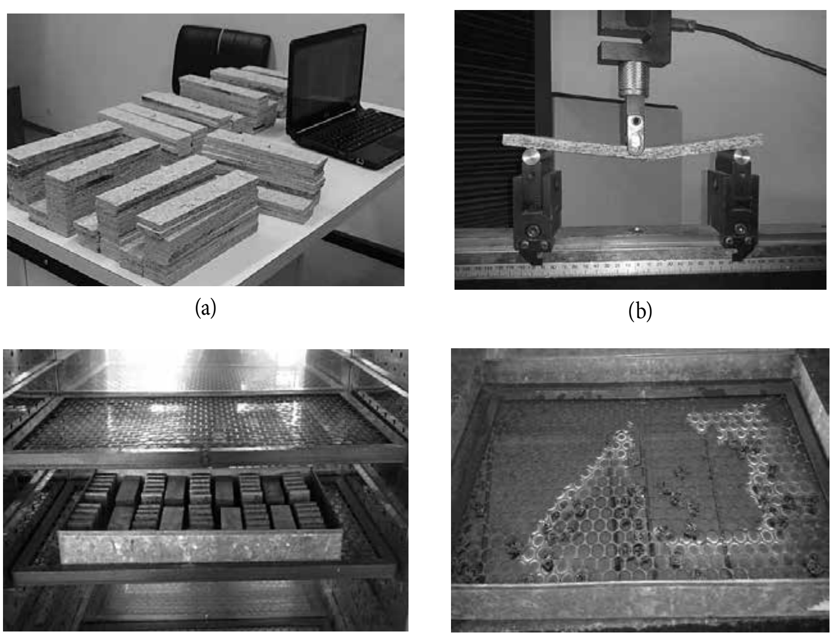
(a) (b)

Figure 1 – Cutting mill (a) and inside the cutting mill (b).

After the particles were sieved, they were separated in plastic bags according to their dimension. We used 1600g of dry weight of waste material for each homogeneous particleboard. Once the preparation of wastes was done, the due quantity of chips of a certain dimension was placed in other plastic bags according to the pre-established traces. A horizontal drum mixer with 137 liters of capacity that was available in the Bamboo Experimental Laboratory was used to obtain a homogeneous mixture. The mixing time was 5 minutes for each board manufactured.

The mixture removed from the drum was taken to a 45cm x 45cm wooden mold, supported on a metal plate covered with aluminum foil that works as nonstick coating. The mixture is distributed by hand as homogeneously as possible and pre-compressed with a wood pestle for a better particle accommodation. This step should be accomplished very carefully because badly formed or badly compacted boards present alterations in their properties due to the variation in their density. After that, the mold can be removed and the mattress can be pressed. A hot hydraulic press manufactured by PHS Máquinas Hidraulicas Ltda, model OHH 80T with a capacity for 80 tons and maximum temperature of 200º C was used in this study.

The particle mattress is slowly pressed until the final thickness of 12.7 mm. The board was kept in the press during 10 minutes at a temperature of 130º C. After the pressing, the boards were removed and left resting in a vertical position to cool off naturally. After the resting period, the samples were drawn on the boards and they were cut with a BALDAN Máquinas e Equipamentos Ltda circular saw, model SEC -3R, with the dimensions established by ABNT 14.810-3 for the several tests programmed in this study, for example, in Figure 2 for testing parallel traction, bending, humidity and thickness swelling.



(a) (b) (c) (d)

Figure 2 – Samples per traces for: (a) parallel traction testing; (b) static bending; (c) moisture content in kiln-dried bamboo; and (d) thickness swelling after immersion in water.

3. RESULTS AND DISCUSSION

Tables 2 and 3 present the results of the averages for physical and mechanical tests.

Table 2 –Mean values of Physical Testing

Traces	Density (g/cm^3)	Humidity (%)	Water Absorption (%)		Swelling (%)	
			two hours of	twenty-four hours	two hours of	twenty-four hours
1	0.80	10.20	59.42	68.73	11.04	17.83
2	0.79	8.11	48.07	53.98	10.10	10.10
3	0.76	8.57	48.19	54.47	19.53	25.13
4	0.80	9.88	50.87	55.10	11.26	16.22
5	0.74	9.74	69.01	73.69	18.31	24.41

Table 3 –Mean values of Mechanical Testing

Traces	Density (g/cm^3)	Static Bending (MPa)		Parallel Traction (MPa)	Perpendicular Traction (MPa)
		MOR	MOE		
1	0.74	10.33	2381.36	4.22	0.32
2	0.71	10.86	2479.89	3.45	0.15
3	0.72	9.71	2173.05	3.78	0.13
4	0.75	8.45	1767.60	3.45	0.19
5	0.70	10.28	2025.06	3.72	0.29

The mean values found in table 2 and 3 refer to the average of five plates made for each trace, using two samples per plate and totaling 10 samples for each test performed (with the exception of density and moisture tests in which three samples were used per board totaling 15 samples tested for trace). The Boxplot graphs below show a tendency found for the results.

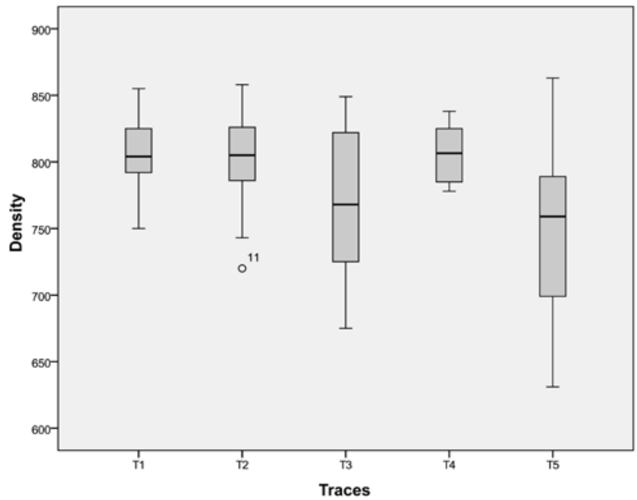


Figure 3 – Density

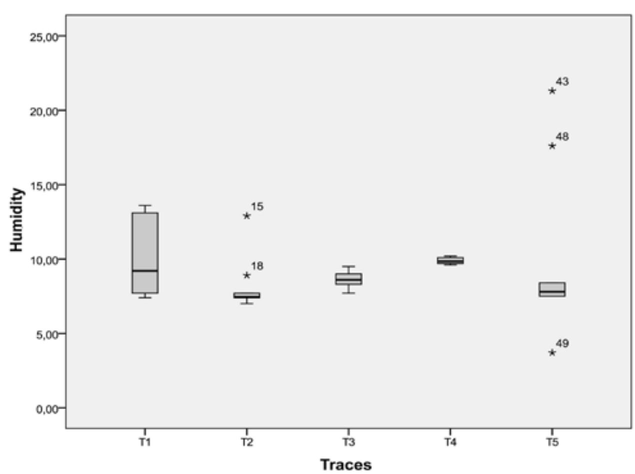


Figure 4 – Humidity

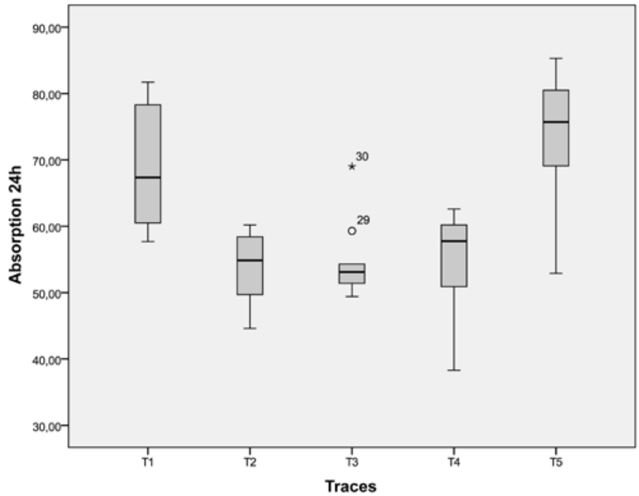


Figure 5 – Water Absorption twenty-four hours

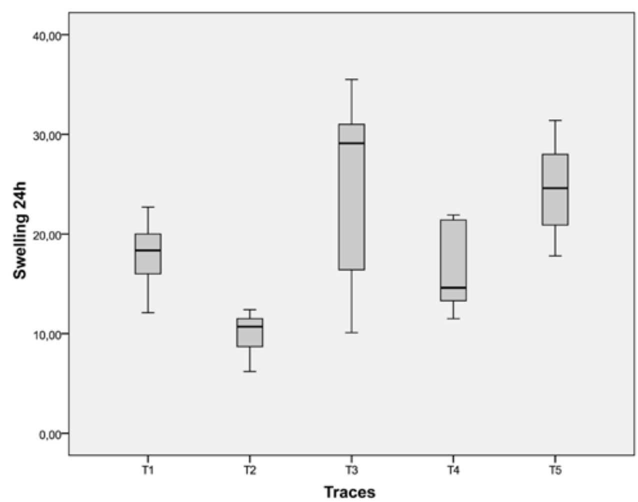


Figure 6 – Swelling twenty-four hours

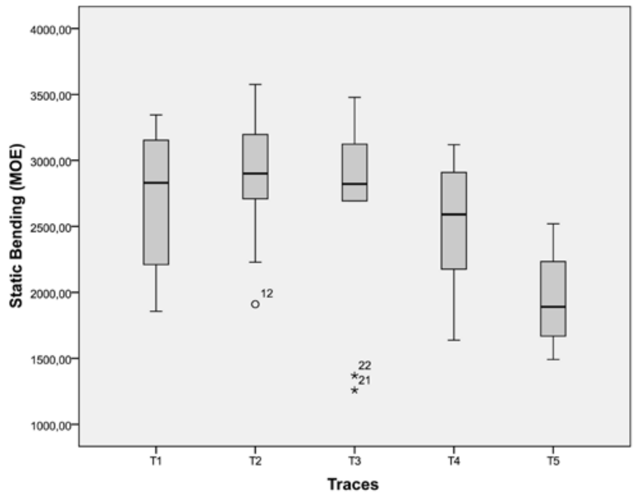


Figure 7 – Static Bending – Modulus of Elasticity (MOE)

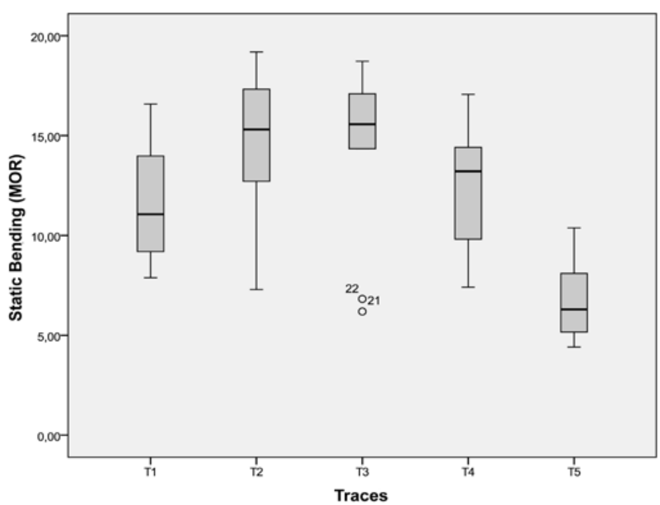


Figure 8 – Static Bending – Resistance Modulus (MOR)

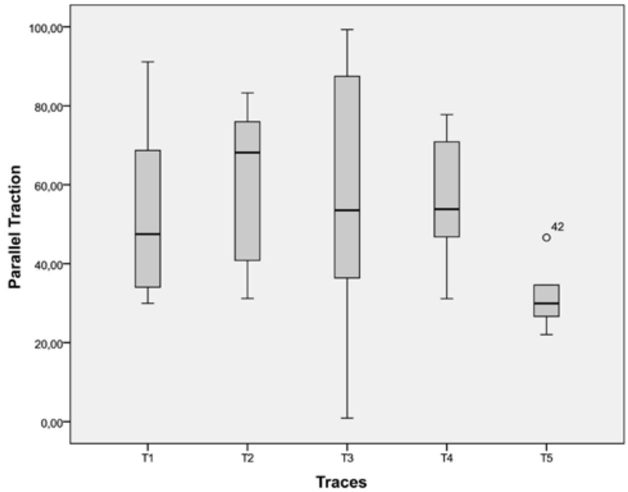


Figure 9 – Parallel Traction

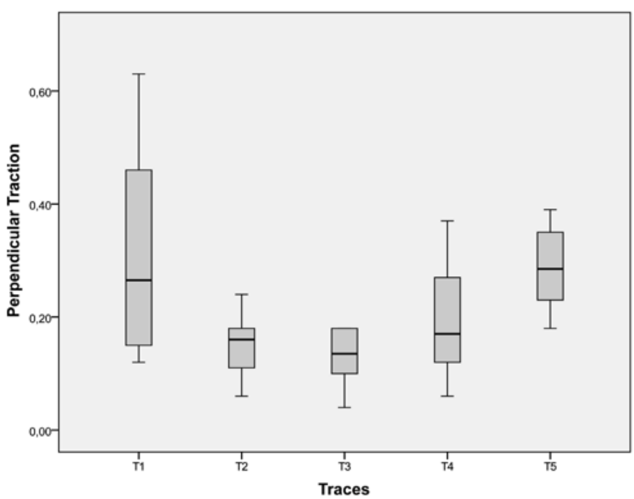


Figure 10 – Perpendicular Traction

Comparing the values of humidity found in this paper with those recommended by the NBR 14.810-3 (2006), between 5 and 11%, it is observed that all of traces satisfy the recommendations of this standard. Trace 1 had the highest moisture content of 10.2% and trace 2 had the lowest content with 8.1%; all of the results are very close, with a maximum variation of 1.9% humidity. For the immersion period of two hours of, the average absorption values were between 47.8% and 67.9%, respectively for traces 2 and 5. After twenty-four hours in water, the variation of the results was 53.8% to 73.6%, the smaller percentage of absorption related to trace 2 and the largest was trace 5.

For the thickness swelling test after two hours of immersion, trace 3 obtained the highest result with a 19.5% increase in thickness and the lowest, referring to trace 2 was 10.1%. As the standard did not have reference values, we compared the results of the research of Valarelli et al. (2008) because it was developed in the same laboratory that this study was performed and the values found in this study were generally lower than the ones presented by him. After twenty-four hours, we noted in Table 2 that trace 1 had the highest result of 24.6% and the lowest, referring to trace 2, remained at 10.1%. There was no significant difference between the densities of all of the traces in which the results presented are very close to what is established in the research.

After the first two hours of immersion in water, there was a significant difference in swelling between Trace 1, 2 and 4 and traces 3 and 5; and after twenty-four hours the results of traces 1 and 4 remained close; however, trace 2 had no similarity with any of the others traces and traces 3 and 5 were similar. For water absorption after twenty-four hours traces 1 and 5 had higher results than the ones referring ton traces 2, 3 and 4. Table 3 shows that trace 5, composed of larger particles, obtained inferior results as compared to other traces regarding mechanical characteristics, except for in the perpendicular traction tests.

In the static bending tests the results of traces 1, 2, 3 and 4; for both MOR and MOE, were very close, while trace 5 was much lower. The same occurred in the Parallel Traction test. For the Static Bending test none of the traces reached the specifications of NBR 14.810-2 (2006), which is 18

MPa, since the values varied between 5.75 MPa and 14.32 MPa, which referred to traces 5 and 3, respectively.

For the Perpendicular Traction testing, the traces did not reach the minimum value stipulated by the standard, which is 0.40 MPa. The results varied between 0.13 and 0.32 with respect to traces 3 and 1, respectively. Tables 4 and 5 show the results obtained by other researchers for comparison and analysis.

Table 4 – Results of physical tests of some authors in the literature.

Authors	Treatments	Adhesive	ρ (g/cm³)	IE (%)	IE (%)	AA (%)	AA (%)	TU (%)
Vieira et al. (2010)	100% Bamboo	UF10%	0.65	7.73	9.33	59.48	77.49	8.71
Vieira et al. (2010)	75% Bamboo 25% Pinus	UF10%	0.65	4.04	9.02	22.22	56.78	9.13
Vieira et al. (2010)	50% Bamboo 50% Pinus	UF10%	0.65	5.13	9.58	26.17	62.77	8.86
Vieira et al. (2010)	25%Bamboo 75% Pinus	UF10%	0.65	5.8	10.92	29.42	63.22	9.99
Vieira et al. (2010)	100% Pinus	UF10%	0.65	2.64	8.92	11.33	43.14	9.67
Morais (2011)	100% Bamboo	UF8%	0.65	24.1	29.8	91.5	101.4	10.1
Morais (2011)	100%	UF8%	0.65	26.3	36.0	78.2	104.8	11.9
Morais (2011)	100% Pinus	UF8%	0.65	19.0	23.6	88.6	100.6	11.7
Morais (2011)	75%Bamboo 25%Euc	UF8%	0.65	31.2	37.5	92.2	107.2	10.6
Morais (2011)	50%Bamboo 50%Euc	UF8%	0.65	30.0	39.7	92.4	108.6	10.8
Morais (2011)	25%Bamboo 75%Euc	UF8%	0.65	30.2	40.7	87.3	109.5	11.0

* UF – Urea Formaldehyde Glue, TU – Moisture Content, LI – Internal link or perpendicular traction.

Table 5 – Results of physical tests of some authors in the literature.

Authors	Treatments	Adhesive	ρ (g/cm³)	MOR (MPa)	MOE (MPa)	LI (MPa)	TP (MPa)
Vieira et al. (2010)	100%Bamboo	UF10%	0.65	9.34	1831.58	0.52	4.32
Vieira et al. (2010)	75%Bamboo 25% Pinus	UF10%	0.65	12.59	2011.14	0.79	5.51
Vieira et al. (2010)	50%Bamboo 50% Pinus	UF10%	0.65	12.99	1921.26	0.76	5.13
Vieira et al. (2010)	25%Bamboo 75% Pinus	UF10%	0.65	12.64	1995.20	1.14	5.12
Vieira et al. (2010)	100% Pinus	UF10%	0.65	13.64	2105.34	1.31	5.50
Morais (2011)	100%Bamboo	UF8%	0.65	5.48	747.92	0.20	-----
Morais (2011)	100%Euc	UF8%	0.65	7.63	1161.63	0.25	-----
Morais (2011)	100%pinus	UF8%	0.65	10.70	1321.84	0.50	-----
Morais (2011)	75%Bamboo 25%Euc	UF8%	0.65	5.57	643.35	0.15	-----
Morais (2011)	50%Bamboo 50%Euc	UF8%	0.65	6.74	895.56	0.19	-----
Morais (2011)	25%Bamboo 75%Euc	UF8%	0.65	6.84	932.19	0.22	-----

* UF – Urea Formaldehyde Glue, TU -- Moisture Content, LI –Internal link or perpendicular traction.

By comparing tables 4 and 5, the mechanical and physical research results of Morais (2011) did not reach the specifications of Standard 14.810, both using 8% UF adhesive, while Vieira et al. (2010) exceeded the specifications for physical and mechanical tests using 10% of UF adhesive. All of the results for humidity met the minimum requirements of the standard and are satisfactory as compared to the research of Valarelli et al. (2008) where the percentage of maximum and minimum humidity was evaluated as 8.67% and 7.89%, respectively.

The results for water absorption were inferior as compared to those obtained in the research conducted by Castro (2010) where the minimum absorption was 35% and the maximum was 55% for the *candeia* material. Swelling tests are quite competitive with results obtained in the research conducted by Sampaio et al. (2008) and Battistelle et al. (2009) where the maximum and minimum levels are 23.25% and 10.19%, and 75.98% and 10.22%, respectively.

4. FINAL CONSIDERATIONS

The results presented in tables 2 and 3 were compared with the recommendations of standard NBR 14.810 and summarized below:

i) The density proposed in the research was 0.75 g/cm^3 and the results obtained between 0.76 g/cm^3 and 0.80 g/cm^3 are satisfactory;
   All of the results for humidity met the minimum requirements established in the standard (it may not be less than 5% nor higher than 11%);
   The results of the swelling test for traces 1 to 5 do not meet the specification provided in the standards (less than 8%);
ii) The perpendicular traction of all traces does not meet the specifications of standard NBR 14.810-2 (higher than 0.4 MPa). Trace 1 is the best result and it reached 0.32 MPa.
iii) The MOR static bending of traces 1 to 5 was also below the one stipulated in the standard (18 MPa, NBR 14.810-2). Trace 3 is the one that obtained the best result with 14.32 MPa.

Upon analyzing the results, one reaches the conclusion that the manufacture of particleboards using bamboo, with a 0.75 g/cm^3 density, using 12% of adhesive has flaws in the compositions proposed because it does not me*et al*l of the minimum parameters recommended by the standards, reaching values for the physical and mechanical tests that are not always satisfactory for most of traces studied. Future research with different percentages of adhesive consumption would be interesting to reach superior results with respect to the physical and mechanical properties of the bamboo board with solvent-free mono component adhesives.

The final evaluation performed corroborated for the comprehension of the manufacturing process of products deriving from bamboo, as well as in the evaluation of the physical and mechanical properties of bamboo particleboards. This study demonstrated potential in the generation of expressive results related to the characterization of the product according to the national interests in research and technological development incentives.

ACKNOWLEDGMENTS

The authors thank the São Paulo Research Foundation (FAPESP) process Nº 2013/08859-0 for the grant given to the undergraduate researcher and for the support received from the Bauru School of Engineering to develop the research at the laboratories of UNESP/FEB.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM D1554.** Standard Terminology Relating to Wood-Base Fiber and Particle Panel Materials. 2010. 4 p.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT 14.810.** Chapas de Madeira Aglomerada – parte 3: Métodos de ensaio. Rio de Janeiro, 2006. 39 p.

ALVES, L. S.; SILVA, S. A. M. **Aproveitamento de resíduos de empresas moveleiras da região de São José do Rio Preto para confecção e avaliação de painéis aglomerados.** Dissertaçã (Mestrado), Universidade Estadual Paulista. Faculdade de Engenharia de Ilha Solteira. Área de Estruturas. Ilha Solteira, São Paulo. 2013.

BATISTTELLE, R. A. G.; LAHR, F. A. R. Emprego do bagaço da Cana-de-açúcar (*Saccharum officinarum*) e das Folhas Caulinares do Bamboo da Espécie *Dendrocalamus giganteus* na Produção de Chapas de Partículas. **Revista Minerva**, p. 297-305, 2009.

BRITO, E. O.; SILVA, G. C. Propriedades de chapas de partículas produzidas a partir de *Gmelina arborea Linn. Roxb*. e *Samanea saman (Jacq.) Merr*. **Floresta e Ambiente**, v. 9, n.1, p. 127-134, 2002.

CASTRO, M. B. DE; ABREU, R. DE; MENDES, L. M.; SANTOS, R. C. DOS. Painéis Aglomerados de Candeia e Eucalipto. In: Encontro Brasileiro em Madeira e Estrutura de Madeira, XII, Lavras, Minas Gerais. **Anais...** v.1, p. 1-10, 2010.

DACOSTA, L. P. E.; HASELEIN, C. R.; SANTINI, E. J.; SCHEIDER, P. R.; CALEGARI, L. Propriedades físicas de chapas de partículas aglomeradas fabricadas com resíduos do processamento mecânico da madeira de *Pinus elliotii Engelm*. **Ciência Florestal**, Santa Maria, v. 15, n. 4, p. 421-429, 2005.

HIZIROGLU, S. et al. Properties of bamboo-rice straw-eucalyptus composite panels. **Forest Products Journal**, v.55, n.12, p. 221-225, 2005.

IWAKIRI, S. **Painéis de Madeira Reconstituída.** Curitiba: FUPEF, 2005. 247 p.

IWAKIRI, S.; COSTA, A. F.; KLITZKE, R. J.; NIELSEN, I. R.; ALBERTI, R. A. R.; NIEFE, I. Produção de chapas de madeira aglomerada de *Pinus elliottii Engelm* com Inclusão Laminar, **CERNE**, v.5, n.2, p. 086-094, 1999.

MARTON, A.; SILVA, S. A. M. **Confecção e avaliação de chapas de madeira aglomerada com aproveitamento de resíduos de marcenaria industrial.** 2013. Dissertação (Mestrado), Universidade Estadual Paulista. Faculdade de Engenharia de Ilha Solteira. Área de Estruturas. Ilha Solteira, São Paulo. 2013.

MORAIS, W. W. C. **Propriedades Físico-Mecânicas de chapas aglomeradas produzidas com Bambum Pinus e Eucalipto.** 2011. Dissertação (Mestrado) – Centro de Ciências Rurais, Universidade Federal de Santa Maria. Santa Maria, Rio Grande do Sul, p. 31-32, 2011.

PEIXOTO, G. L.; BRITO, E. O. Avaliação da granulometria de partículas de *Pinus taeda* combinadas com adesivos comerciais para a fabricação de aglomerados. **Floresta e Ambiente**, v. 7, n.1, p. 60-67, 2000.

POLUCHA, F. S. Design para sustentabilidade: Bamboo Laminado e Vidro Reciclado na Produção de Móveis. In: Congresso de Pesquisa & Desenvolvimento em Design, 7, Curitiba, PR. **Anais...** Curitiba, 2006.

SAMPAIO, R. M.; VALARELLI, I. DE D.; SILVA, P. M. DA. Avaliação das Propriedades Físicas e Mecânicas de Chapas de Partículas Aglomeradas de Resíduos de Bamboo Dendrocalamus giganteus e Folha Caulinar. In: ENCONTRO BRASILEIRO EM MADEIRA E ESTRUTURA DE MADEIRA, XI, Londrina, 2008. **Anais...** UEL, Paraná, v.1, p.1-10.

VALARELLI, I. DE D.; BATTISTELLE, R. A. G; BUENO, M. A. P.; BEZERRA, B. S.; CAMPOS, C. I.; ALVES, M. C. Physical and mechanical properties of particleboard bamboo waste bonded with urea formaldehyde and castor oil based adhesive. **Matéria** (UFRJ), v. 19, p. 01-06, 2008. doi:10.1590/S1517-70762014000100002.

VIEIRA, K. A; CARVALHO, M. R. O; VISNARDI, O. C; VALARELLI, I.D. Avaliação do Comportamento das Chapas Aglomeradas de Bamboo e Pinus em relação ao Teor de Umidade, Absorção de Água e Inchamento em Espessura. In: ENCONTRO BRASILEIRO EM MADEIRA E ESTRUTURA DE MADEIRA, XII, Lavras, MG, 2010. **Anais...** UFV, v.1, p. 1-37, 2010.

WEBER, C. **Estudo sobre viabilidade de uso de resíduos de compensados, MDF e MDP para produção de painéis aglomerados.** 2011. Dissertação (Mestrado), Setor de Ciências Agrárias, Universidade Federal do Paraná, Curitiba, 2011.

INFLUENCE OF ALKALINE MERCERIZATION OF TREATMENT IN THE TENSILE STRENGTH OF AÇAÍ FIBER

Antonio Mesquita de Lima
Stadual University of Amazonas, Department of Forestry, Manaus, AM.
E-mail: antonio.mesquita@uol.com.br

André Luis Christoforo
Federal University of São Carlos (UFScar), Department of Civil Engineering, São Carlos, SP.
E-mail: alchristoforo@yahoo.com.br

Lênio José Guerreiro de Faria
Federal University of Pará, School of Chemical Engineering, Belém, PA.
E-mail: lenio@ufpa.br

Tulio Hallak Panzera
Federal University of São João del Rei, Department of Mechanical Engineering, São João del Rei, MG.
E-mail: tuliopanzera@hotmail.com

Nubia Garzón Barrero
Department of Biosystems Engineering, São Paulo University (FZEA/USP), Pirassununga, SP, Brazil.
E-mail: nubiagarzonbarrero@yahoo.com

ABSTRACT: To contribute with the dissemination of the use of lignocellulosic waste in the manufacture of composite materials, this research aimed to investigate the influence of alkaline mercerization treatment in the tensile strength of açaí fibers. The factors and levels stipulated were the NaOH and NaOH + autoclave and the concentration of NaOH solution in water (0.5%, 1%, 2%), leading to full experimental design with six different experimental conditions, together with the reference condition (untreated açaí fibers). The results of the analysis of variance (ANOVA) revealed that only the NaOH concentration was significant in obtaining the tensile strength, with the content of 0.5% the best values of the tensile strength, 36% and 16% higher (on average) than the five others treatments and the reference condition, respectively, showing the effectiveness of treatment by mercerization.

Keywords: Açaí fiber. Alkaline mercerization. Lignocellulosic residues.

1. INTRODUCTION

The search technology focused on preservation of the environment and the use of raw materials from renewable sources has motivated research centers around the world to study the use of natural resources and agro-industrial by-products (FROLLINI, 2004; WAMBUA, 2003; KEENER, 2004). The research of the last decade have evaluated the application of fibrous raw materials of agricultural crop residues with lower cost, for the manufacture of composites in different regions of the world, with satisfactory outcomes (WIDYORINI et al., 2005; ASHORI et al., 2009).

All countries which produce lignocellulosic fibers usually use the conventional way, such as inputs in industrial and domestic sectors, manufacturing handcrafted items like bags, carpets, desks etc. Sometimes they are used in composite materials when combined with clay in the industry of construction (SATYANARAYANA et al., 2007).

Industries of chipboard panels and fiber, in Brazil, preferably using wood chips from reforested Pinus sp and some species of Eucalyptus sp, which even provides a better quality product in order to better control homogeneity of the raw material. However, lignocellulosic materials from agricultural residues have been a new economic, social and environmental alternative to manufacturing MDP and MDF panels in Brazil.

Brazilian agribusiness presents numerous lignocellulosic residues with potential for use in the manufacture of new materials such as the coconut husk (BRITO et al., 2004; KHEDARI et al., 2004, peanut hulls CARASCHI et al., 2009 and GATANI, 2009 and bagasse cane sugar WIDYORINI et al., 2005; CONTRERAS et al., 2006; CARASCHI et al., 2009; SILVA et al., 2008; BATTISTELLE et al., 2009 and GARZON et al., 2012). The results of national and international with sugar cane bagasse surveys indicate its feasibility in different polymer matrices for making composites (ROWEL R. 1997; TEIXEIRA et al., 1997; WIDYORINI et al., 2005 and LEE et al. 2004).

Agribusiness açaí is an important economic resource in northern Brazil. Pará is currently the largest producer in Brazil, accounting for 87.1% of all flesh consumed in the country (SANTANA et al., 2012), with about 80-90% of that coming from the northeast state (SOUSA, (2011)). This production, about 24% are obtained in cultivated areas and 76% have extractive Source (SOUZA et al., 2006). The fibrous tissue of the açaí fruit (Euterpe oleracea Mart.) is dropped about 1,200 tons/day, in the metropolitan region of Belém (PA) after juice production. This agroindustrial residue is infrequently used in boilers for energy.

The treatments conventionally carried out on the surface of vegetable fibers hygroscopicity of these aim to reduce and/or increase the capacity of interaction of the fibers with the resin, which may influence the final characteristics of the composite.

The process of alkaline and also called mercerization is a common method of producing high-quality fibers. In this process the fibers are chemically treated to remove lignin, pectin, waxy substances, natural oils and covering the outer surface of the fiber cell wall. This shows the fibrils and provides a rough surface topography of the fiber. Sodium hydroxide (NaOH), is the most commonly used chemical bleaching and/or cleaning the surface of vegetable fibers. It also changes the fine structure of the native cellulose I to cellulose II, a process known as alkaline (MWAIKAMBO; ANSELL 2002).

The alkali treatment is one of the oldest methods for modification of plant fibers which aims to clean the surface of bees wax and grease from handling and possibly the manufacture of fibers, and partially remove the hemicellulose and lignin, hemicellulose is mainly very low concentrations of soluble alkali. The main effect of the alkali treatment is defibrillation, or breakage of the fiber bundles into smaller fibers (KALIA et al., 2009).

The process comprises alkali treatment of the fibers with NaOH solution, which causes a decrease in the degree of aggregation of the fibers, leading to a better interaction at the interface fiber/resin. The behavior of plant fibers subjected to alkaline process depends primarily on the conditions of treatment (concentration, time and temperature).

Generally, the alkaline treatment plant fibers causes swelling and partial removal of hemicellulose and lignin, which promotes a better packing of the cellulose chains, which are responsible for the crystallinity of the fiber (BLEDZK; GASSAN 1999). The alkali treatment causes increase in crystallinity and reduced diameter increases the length/diameter ratio, natural and artificial removes impurities from the surface of the fibers and density (PAIVA; FROLLINI, 1999). With this, leads to the development of a more topographically rough surface resulting in improved interfacial adhesion and an increase in the mechanical properties (MWAIKAMBO; ANSELL, 2002). Furthermore, the alkali treatment provides a decrease in spiral angle and an increase in the molecular orientation, but also increases the number of reactive sites and enables better wetting of the fibers (KALIA et al., 2009).

The effect of the alkali treatment in relation to the mechanical properties associated with increased tensile strength and modulus of elasticity and elongation decrease, with this behavior often associated with increased crystallinity (SILVA et al., 2006).

Sreenivasan et al., (1996) reported an increase in tensile strength and elongation decreased from coconut fibers under different conditions of alkali treatment.

Currently, this research consisted to obtain the fibers of açaí (extraction form) by alkaline mercerization, which sets in a relevant scientific contribution in the development of unconventional materials with respect to the application of treatment processes by alkaline mercerizing, aimed at improving the physical and mechanical properties of the açaí fibers.

In order to corroborate information about the mechanical properties of açaí fibers for subsequent use in the manufacture of composite materials, with applications in the manufacture of panels among others, this study aimed to investigate the influence of treatment by alkaline mercerization of fibers with açaí using NaOH and NaOH with autoclaved process in three concentrations to obtain the axial tensile strength.

2. MATERIAL AND METHODS

Fibrous tissue samples used in this research are of the species Euterpe oleracae Mart. Were collected from agribusinesses that prepare the açaí juice and discard the waste packing it in polypropylene bags in front of the establishments to be collected by the company from urban waste collection in the city of Belém, Pará (Brazil). The material obtained was washed in natura water (in tap), dried in an oven at a temperature of 60°C and packaged in plastic containers, and placed in the refrigerator at 15°C until the start of the alkaline mercerizing step.

2.1 OBTAINING FIBERS

The process for obtaining fibers of the experimental chemical condition (alkaline) was performed in two ways: first, we used an alkaline NaOH solution with 0.5%, 1% and 2% concentration and mass of cores (400 g). Second, in addition to using the alkaline solution of the fibers were placed in an autoclave for a time of 45 minutes exposed to a pressure of 10 atm and 40°C. We used a prototype fabricated tanks containing bench scale with a capacity of 5 liters, a portable pH meter brand (Lutron Ph-201). In addition, during driving of the experiments performed made up of data such as pH, solution temperature, environmental temperature and relative humidity. These processes are detailed below:

i) **Alkaline mercerizing (NaOH):** In the alkaline process the alkaline solution of sodium hydroxide (NaOH) was used in three concentrations: 0.5%, 1% and 2%, respectively. 1,200 kg of seed kernels were available. The three concentrations used were described earlier, maintaining the same weight ratios solution/mass of the core (2: 1, 4: 1 and 6: 1) and distributed as follows: in tank 1, the treatment was carried concentration 0.5% corresponding to 800g solution of 400g of seeds; in tank 2, the treatment was performed at a concentration of 1% corresponding to 1,600g of solution and 400g of lumps, and finally, in the tank 3, the concentration used was 2%, corresponding to 2400g solution and 400g of stones.

ii) **Alkaline mercerizing (NaOH in the autoclave):** In this process was used an alkaline solution of sodium hydroxide (NaOH) in three concentrations: 0.5%, 1% and 2%, respectively. For each of these concentrations were added 2.88kg of seed kernels of the autoclave, and the respective solution to achieve full immersion of lumps. The cores underwent a cooking time for approximately 45 min and exposed to a pressure of 10 atm and a temperature of 40°C.

During the two processes, 15 days (NaOH), 45 minutes (NaOH autoclave), the fiber samples were manually extracted to carry out mechanical tests and placed to dry in laboratory at room temperature conditions (28°C) and 80% relative humidity, and subsequently, the realization and the characterization of the mechanical microestutural property. In the natural condition (reference), extraction of fibers from the fruit of the açaí core was carried out by the use of a circular bench sander.

2.2 EXPERIMENTAL DESIGN

The factors and levels investigated in the experimental evaluation of the axial tensile strength of the fibers were treatment with NaOH and NaOH + autoclave and the concentration of solutions of NaOH in water (0.5%; 1%; 2%), leading to a full factorial design 2×3, providing six different experimental conditions (EC), explained in Table 1.

Table 1 – Treatments investigated for the Chemistry experimental condition (Alkaline Mercerization).

Experimental Condition	Alkaline mercerizing	NaOH*
N1	NaOH	0.5%
N2	NaOH	1.0%
N3	NaOH	2.0%
N4	NaOH + autoclave	0.5%
N5	NaOH + autoclave	1.0%
N6	NaOH+ autoclave	2.0%

* NaOH concentration by weight

The experimental design was designed with the aid of Minitab software, version 14, enabling analysis by ANOVA to investigate the influence of the factors (treatments) and the interaction among them in maximum tensile strength.

The analysis of variance (ANOVA) was used to investigate the influence of the factors isolated [Mercerization (M); Concentration of Water (% A) as well as the interaction (%M×A] in the axial tensile strength of the açaí fibers, at a level of significance (**α**) of 5%, with the null hypothesis (H_0) the equivalence of means between treatments and the non-equivalence between the mean as an alternative hypothesis (H_1). P-value less than the level of significance implies to reject H_0, and accept it otherwise.

To validate the model ANOVA, the Anderson-Darling test was used to check the normal distribution of the values of the axial tensile strength and F tests, Bartlett and Levene to assess the homogeneity of variances between the experimental conditions investigated. The tests were made at the 5% level of significance. For the Anderson-Darling test, the null hypothesis was the normality of the distribution, and the non-normality as an alternative hypothesis. P-value greater than the significance level of the test involves accepting H_0, rejecting it otherwise. For the F tests, the Bartlett and Levene, the null hypothesis was the equivalence of variances between the experimental conditions, and the non-equivalence between variances as alternative hypothesis. P-value greater than the level of significance implies to accept the null hypothesis, rejecting it otherwise.

2.3 TESTS FOR THE AXIAL TENSILE STRENGHT OF THE FIBROUS BUNDLES (FIBERS)

The tests of resistance to axial tensile of the fibrous bundles were performed in the Laboratory of Ambience Constructions at the Department of Biosystems Engineering, University of São Paulo (FZEA/USP), *Campus* Pirassununga (SP-Brazil), using a universal testing machine EMIC-DL 3000, with a maximum capacity of 300 kN with a data acquisition system, load cell 1 kN at a speed of 0.3 mm/min and pneumatic jaws of 200 kgf. Ten specimens were used for each one of the nine experimental over the control conditions (natural açaí fibers), totaling the making and testing of 100 samples. The samples were prepared with supports kraft paper called in the literature. The brackets are used to evenly distribute the load applied to the fiber being tested and also to protect the fibers from damage during the positioning of the jaws of the testing machine. The KRAFT paper supports (weight 200 g / m²) with dimensions of 25mm×55mm, were glued with cyanoacrylate (Loctite Super Bonder) in the ends of the effective length of the fibers, adapted from recommendations of the standard ASTM D3822-96. Figure 1a and Figure 1b illustrate the media used for testing the axial tensile strength and shows dimensions. After the tests, the results were statistically analyzed and selected experimental condition among treatments by alkaline mercerization.

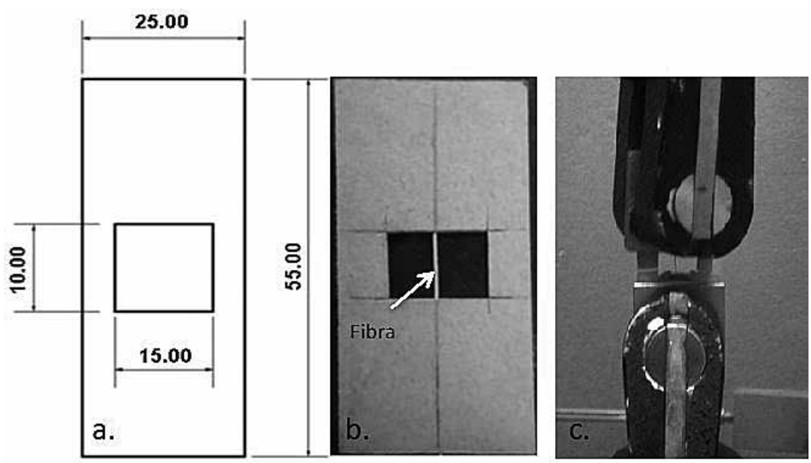


Figure 1 – Axial tensile test: (a) Schematic of the supports, (b) the fibrous support beam, (c) specimen in a universal testing machine design.

3. RESULTS AND DISCUSSION

Several studies on the application of alkaline treatment plant fibers show improved adhesion characteristics of the fiber / polymer matrix due to the increase of surface roughness. Some of these studies related alkaline surface treatment in vegetable fibers are reported below to compare the results obtained in this study chemical mercerization.

Table 2 shows the results of tensile strength of the experimental conditions from the alkaline mercerizing treatment with NaOH and without mercerizing (reference), the sample mean ($\overline{x}$), the variation coefficient Cv and Min and Max being the lowest and highest values found, respectively.

Table 2 – Results of the tensile strength.

Experimental Condition	$\overline{x}$ (MPa)	*CV (%)*	*Min.*	*Max.*
N1(0,5%)	27.79	31	16.16	40.36
N2(1%)	20.58	28	12.16	29.93
N3(2%)	25.84	24	15.79	40.86
N4(0,5%)	33.40	28	16.21	46.51
N5(1%)	24.31	22	18.95	35.8
N6(2%)	26.95	25	12.06	35.36
Reference	16.48	25	9.96	24.13

Experimental Condition N1a N3: NaOH; N4 a N6: NaOH autoclave

Table 3 presents the results of the normality and homogeneity of variances testes for maximum tensile strength of açaí fibers to the process of alkali mercerization (NaOH and NaOH in autoclave). The results show that the data of maximum tensile strength present normal distribution and equality of variances between the experimental treatment conditions, by presenting in both cases P-value greater than the significance level (0.05), according to the ANOVA model.

Table 3 – Normality and homogeneity of variances tests for the axial tensile strength of the açaí fibers.

Test	P value
Anderson-Darling	0.377
Bartlett	0.485
Levene	0.291

Table 4 presents the results of the maximum tensile strength of açaí fibers analyzed by ANOVA method after alkaline mercerization with and without autoclave. The P-value considered significant (P-value <0.05) was underlined. It appears that only the concentration of NaOH factor significantly influenced the axial tensile strength of açaí fibers, not being significant using the autoclave treatment with NaOH or interaction between factors. Figure 2 shows the effects of NaOH concentration on the maximum axial tensile strength.

Table 4 – Results of the maximum tensile strength of fibers treated with NaOH (with and without autoclaving) analyzed by ANOVA.

FV	GL	SQ	SQ Ajust.	QM Ajust.	F	P-value
NaOH	1	181.91	181.91	181.91	3.12	0.083
%NaOH	2	664.21	664.21	332.10	5.69	<u>0.006</u>
NaOH×%NaOH	2	50.99	50.99	25.49	0.44	0.648
Erro	54	3152.73	3152.73	58.38		
Total	59	4049.83				

SV: source of variation, GL: degrees of freedom. SS: sum of squares, Adj SS: sum of the adjusted squares, QM Adj: the average of the square set, F: F statistic Snedecor and P-value: probability P

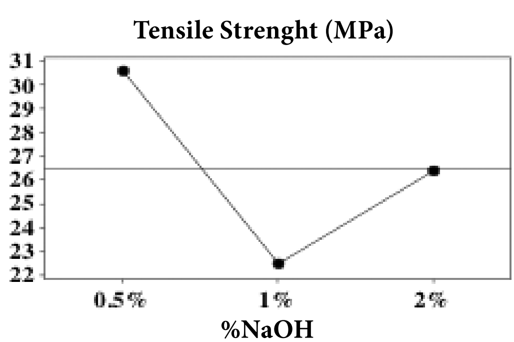


Figure 2 – Concentration of NaOH on the maximum tensile strength of the açaí fiber.

Table 5 presents the results of the Tukey test for maximum tensile strength compared to the levels of concentration of NaOH. Same letters imply in treatments with equivalent mean. The results show that the use of 0.5% NaOH, either with or without an autoclave provides the highest values for maximum axial tensile strength. The concentration of 0.5 wt% NaOH in water yielded the largest values of the maximum tensile strength of the açaí fibers, around 36% and 16% higher than fibers treated with 1% and 2% by weight of NaOH, respectively.

Table 5 – Results of Tukey test for the maximum tensile strength as a function of concentration of NaOH.

Properties	NaOH Concentration		
	0.5%	**1%**	**2%**
Tensile Strength (MPa)	30.59 ^{A}	22.44 ^{B}	26.39 ^{AB}

Means followed by the same letter do not differ significantly by the Tukey test (5% at significance level).

However, regarding the difference in mechanical strength between the fibers treated with NaOH and without autoclaving was not considered significant by ANOVA. With this, we have chosen the autoclave without NaOH treatment for economic reasons, and because of the amount of material available to statistically analyze the fibers in the reference condition.

Table 6 shows the results of the test of normality and homogeneity of variance tests for the maximum tensile strength of the N1 and reference fibers (0.5% NaOH). For the P-value found is below the level of significance (5%), it was found that there is no normal distribution and equality of variances for maximum tensile strength.

Table 6 – Normality and homogeneity of variance tests for axial tensile strength of the açaí fibers N1 (NaOH (0.5%) and reference.

Test	P value
Anderson-Darling	0.042
Bartlett	0.037
Levene	0.039

Thus, to answer to the question of normality and homogeneity of variances required for ANOVA, the values of maximum tensile strength of the treated fibers (N1) and reference were evaluated by means of the Johnson transformation. Results showed that the data of the maximum tensile strength after Johnson transformation presented normal distribution and the variance equivalence (Table 7), which validates the ANOVA results.

Table 7 – Normality and homogeneity of variance tests for the transformed data.

Test	P value
Anderson-Darling	0.711
Bartlett	0.937
Levene	0.771

Table 8 shows the results by ANOVA for maximum tensile strength of the fibers treated (N1) and untreated (reference condition). The P-value found was less than 0.05, resulting in significant differences in the tensile strength of the fibers with and without treatment. Figure 3 shows the main effect plot between the alkaline treatment (N1) with and the reference condition.

Table 8 – ANOVA results from tensile strength test for the treated (N1) and non treated fibers.

FV	GL	SQ	QM	F	P-value
Condition	1	1.3471	1.3471	13.98	0.002
Error	18	1.7343	0.0964		
Total	19	3.0814			

SV: source of variation, GL: degrees of freedom. SS: sum of squares, Adj SS: sum of the adjusted squares, QM Adj: the average of the square set, F: F statistic Snedecor and P-value: probability P

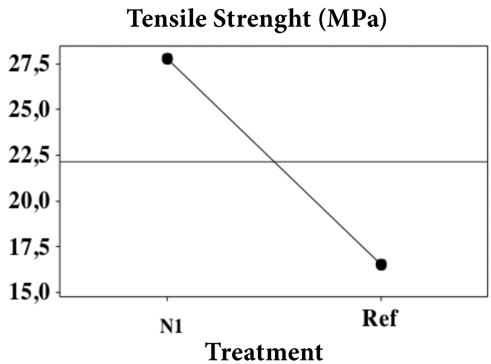


Figure 3 – Main effect plot between the alkaline treatment (N1) with and the reference condition.

The results of the maximum tensile strength of some alkaline mercerizing vegetable fibers (chemical) from other literature sources are shown in Table 9. Indicating tensile strength values that are close to or above the respective reference fiber (16.48 MPa). The results obtained by alkaline mercerizing (NaOH - N1) between the treated fibers without autoclave has an average of 27.79 MPa and 33.40 MPa (N4) between treated with autoclave. These results suggest the same trends of increased tensile strength with respect to the reference fiber, found in the literature.

Table 9 – Results from the literature of the maximum tensile strength of vegetable fibers with alkali treatment.

Author/Year	Fiber	Tensile (MPa)
Rabi et al., 2009	Coco	95
Silva et al., 2006	Sisal	234-28
Goda et al., 2006	Rami	151-661
Gomes et al., 2006	Curauá	523-913

The average value of the maximum tensile strength of the açaí fibers treated with 0.5% NaOH (N1) is 68% higher than the values of the reference condition.

3.1 CONSIDERATIONS AMONG ALKALINE TREATMENTS

The mercerization process of alkaline chemical was responsible for the voids produced on the fiber surface as a result of SiO_2 removal and formation of globular protrusions, leaving the rougher surface of the fiber (Figure 4), which probably facilitate increased adhesion between the fiber and polyurethane resin castor oil based, improving as a consequence, the mechanical properties of the composites.

Figure 4a shows the açaí fiber surface treatment with 0.5% NaOH (N1) and Figure 4b shows the fiber surface treatment with 0.5% NaOH in autoclave (N4). It is observed that both treatments for the numerous microfibrils making up the açaí fiber, along with globular marks are more visible, however, the fiber obtained by treatment with 0.5% NaOH in autoclave present with greater roughness and smaller amount of globular marks, which can improve the adhesion between the fiber and resin in the composite.

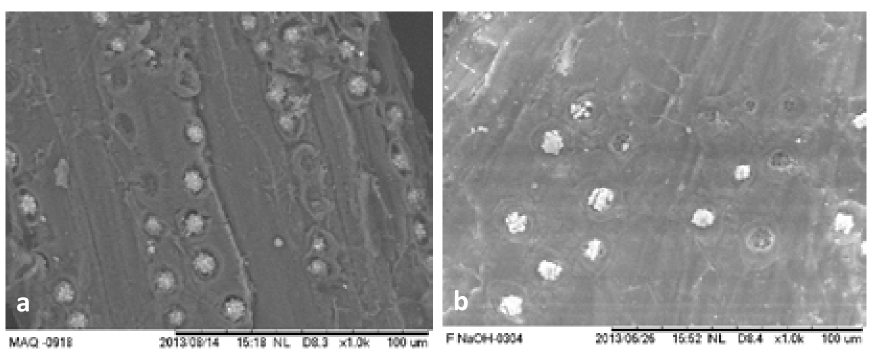


Figure 4 – Globular visible marks microfibril and roughness of the açaí fibers with alkaline mercerization process. a) 0.5% NaOH (N1), b) 0.5 NaOH in autoclave (N4).

The results obtained in this research indicate the potential of the alkaline treatment of the açaí fibers, development of various composite materials, such as promising area of lignocellulosic material panels.

4. CONCLUSIONS

i) The fibers of alkaline NaOH mercerization (0.5%) was selected autoclave process for the manufacture of the composites with the bicomponent polyurethane resin castor oil based;
ii) The process of autoclavable mercerizing alkaline (NaOH 0.5%) contributed to remove hemicellulose, lignin, pectin and waxes, leading to the development of a more rough surface. The fibers showed axial tensile strength 68% higher (in average) then the reference condition (untreated fibers). These results suggest the potential of treated açaí fiber with alkaline solution of NaOH as raw material in the manufacture of eco panels for commercial use;
iii) The results of this study indicate the potential treatment of açaí fibers, by helping to spread its use in the preparation of various composite materials, such as promising area of lignocellulosic material panels.

PERMISSION FOR PUBLICATION

It is the responsibility of the authors the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIALS - ASTM D 3822. **Tensile properties of single fibers.** 1996. 18 p.

ASHORI, A.; NOURBAKHSH, A.; KAREGARFARD, A. Properties of medium density fiberboard based on bagasse fibers. **Journal of Composite Materials**, v. 43, p. 1927-1934, 2009. doi:10.1177/0021998309341099.

BATTISTELLE, R. A. G.; MARCILIO, C.; LAHR, F. A. R. Emprego do bagaço da cana-de-

-açúcar (*saccharum officinarum*) e das folhas caulinares do bambu da espécie *dendrocalamus giganteus* na produção de chapas de partículas. **Revista Minerva**, São Carlos, v.5, n.3, p. 297-305, 2009.

BLEDZKI, A. K.; GASSAN, J. Composites reinforced with cellulose based fibres. **Progress in Polymer Science**, London, n. 24, p 221-274, 1999. doi: 10.1016/S0079-6700(98)00018-5.

BRITO, E. O.; SÁ-ROCHA,JD.; VIDAURRE, G. B.; BATISTA, D. C.; PASSO, P. R.; MARQUES, L. G. C. Propriedades de chapas produzidas com resíduos do fruto de coco e partículas de pinus. **Revista Floresta e Ambiente**, Seropédica, v.11, n.2, p. 1-6, 2004.

CARASCHI, J. C.; LEÃO, A. L.; COIADO CHAMMA, P. V. Painéis produzidos a partir de resíduos sólidos para aplicação na arquitetura. **Polímeros:** Ciência e Tecnologia, São Carlos, v. 19, n. 1, p. 47-53, 2009. doi: 10.1590/S0104-14282009000100012.

CONTRERAS, W. M. OWEN DE C, BALLESTER, C.V.; CONTRERAS M. GARAY J.D. Diseño de Tableros de Partículas de Caña Brava y Adhesivo Fenol – Formaldehído. **Revista Forestal Latinoamericana**, n. 39, p. 39-55, 2006.

FROLLINI, E.; PAIVA J.M.F.; TRINDADE, W. G.; RAZERA A. T.; TITA, S.P. Lignophenolic and phenolic resins as matrix in vegetal fibers reinforced composites. In: WALLENBERGER F.T.; WESTON, N. (editors). **Natural fibers, plastics and composites**. Kluwer Academic Publishers; New York, p. 193-219, 2004.

GARZON, N. ; SARTORI, D. ; ZUANTETTI, I. ; BARBIRATO, G. H. A. ; RAMOS, R. D. ; FIORELLI, J.; SANTOS, S. F.; SAVASTANO JUNIOR, H. Durability evaluation of agroindustrial waste based particle boards using accelerated aging cycling tests. **Key Engineering Materials**, v. 517, p. 628-634, 2012. doi: 10.4028/www.scientific.net/KEM.517.628.

GATANI, M. P. **Utilização de casca de Mani para fabricação de chapas de partículas.** Pirassununga: USP (Relatório de Pesquisa, Laboratório de Construções e Ambiência, FZEA/USP), 2009.

GODA, K.; SREEKALA, M .S; GOMES, A;KAJI, T.; OHGI, J. Improvement of plant based natural fibers for toughening green composites – Effect of load application during mercerization of ramie fibers. **Composites Part A**, p. 2213-2220, 2006. doi: 10.1016/j.compositesa.2005.12.014.

GOMES, E.O. Caracterização do bagaço da cana-de-açúcar. In: CONGRESSO INTERNACIONAL GERAÇÃO DISTRIBUÍDA E ENERGIA NO MEIO RURAL, 6, 2006, Campinas. **Anais...** Campinas: UNICAMP, 2006.

KALIA, S.; KAITH, B.S.; KAUR, I. Pretreatments of Natural Fibers and their Application as Reinforcing Material in Polymer Composites—A Review. **Polymer Engineering and Science**, 2009. doi:10.1002/pen.21328.

KEENER, T. J.; STUART, R. K.; BROWN, T. K. Maleated cooping agents for natural fibre composites. **Composites Part A:** Applied Science and Manufacturing, Kidlington, v. 35, n. 3, p. 357-362, 2004. doi: 10.1016/j.compositesa.2003.09.014.

KHEDARI, J. et al. New insuleting particleboards from durian peel and coconut coir. **Building Scientific Research Center**. Boletin. Bangkok, Thailand, 2004. doi: 10.1016/S0360-1323(02)00030-6.

LEE, S.; SHUPE, T. F.; HSE, C. Y. Utilization of Chinese tallow tree and bagasse for medium density fiberboard. **Forest Products Journal, Madison**, v. 54, n. 12, p. 71-76, 2004.

MWAIKAMBO, L. Y; ANSELL, M. P. Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. **Journal of Applied Polymer Science**, Hoboken, v. 84, p. 2222-2234, 2002. doi:10.1002/app.10460.

PAIVA, J.M.F.; FROLLINI, E. Matriz termofixa fenólica em compósitos reforçados com fibras de bagaço de cana de açúcar. **Polímeros:** ciência e tecnologia, São Carlos, v. 9, n. 2, p. 78-87, 1999. doi: 10.1590/S0104-14281999000200016.

RABI J.A; SANTOS S.F., TONOLI H.D.G., SAVASTANO JR, H. **Agricultural wastes as building materials properties, performance na applications.** Building materials: Properties, performance and applications. Chapter 9, 2009. 44 p.

ROWELL, R. Utilization of natural fibers in plastic composites: problems and opportunities. In: LEÃO, A.; CARVALHO, F. X.; FROLINI, E. (Eds.). **Lignocelluosic: plastic composites.** São Paulo: USP, UNESP, p. 23-25, 1997.

SANTANA A. C.; CRUZ P. J. D.; SANTANA Á. L. **O mercado de açaí e os desafios tecnológicos.** p. 21-39, 2012.

SATYANARAYANA, K. G.; GUIMARÃES, J. L.; WYPYCH, F. Studies on lignocellulosic fibers of Brazil. **Composites Part A:** Applied Science and manufacturing, Kidlington, v. 38, p. 1694-1709, 2007. doi: 10.1016/j.compositesa.2007.02.004.

SILVA, A. J. P.; FRANÇA SANTOS, W. L.; ROCCO LAHR, F. A. Partículas longas e orientadas de bagaço de cana-de-açúcar na produção de painel similar ao OSB. In: XI ENCONTRO BRASILEIRO EM MADEIRA E ESTRUTURAS DE MADEIRA, 2008.

SILVA, R.V., SPINELLI, D.; BOSE, F. W.W.; CLARO, N. S.; CHIERICE, G.O.; TARPANI, J.R. Fracture toughness of natural fibers/castor oil polyurethane composites. **Composites Science and Technology**, v. 66, p. 1328-1335, 2006. doi: 10.1016/j.compscitech.2005.10.012.

SREENIVASAN, S.; BHAMA IYER P.; KRISHNA IYER K. R. Influence of delignification and alkali treatement on the fine sctructure of coir fibres (*cocos nucifera*). **Journal of Material Science**, v. 31, p. 721-726, 1996.

SOUZA, M. A. C.; YUYAMA, L. K. O.; AGUIAR, J.P. L.; PANTOJA, L. Suco de açaí (*Euterpe oleracea* Mart.): avaliação microbiológica, tratamento térmico e vida de prateleira. **Acta Amaz**., vol.36, n.4, p. 497-502, 2006. doi:10.1590/S0044-59672006000400010.

TEIXEIRA, D. E.; COSTA, F.; SANTANA, M. A. E. Aglomerados de bagaço de cana-de--açúcar: resistência natural ao ataque de fungos. **Scientia Forestalis**, Piracicaba, n. 5, p. 29-34, 1997.

WAMBUA, P; IVENS, J.; VERPOEST, I. Natural fibers: can they replace glass in fiber-reinforced plastics. **Composites Science and Technology,** v. 63, p. 1259–64, 2003. doi: 10.1016/S0266-3538(03)00096-4.

WIDYORINI, R.; XU, J.; UMEMURA, K., KAWAI, S. Manufacture and properties of binderless particleboard from bagasse: effects of raw material type, storange methods and manufacturing process. **Journal of Wood Science**, v. 52, n. 6, p. 648-654, 2005. doi:10.1007/s10086-005-0713-z.

LIFE CYCLE ASSESSMENT OF WOOD-BASED COMPOSITES: STATE-OF-THE-ART AND OPPORTUNITIES FOR REDUCING ENVIRONMENTAL IMPACTS

Diogo Aparecido Lopes Silva and **Aldo Roberto Ometto**
University of São Paulo, Department of Production Engineering, São Carlos, Brazil.
E-mail: diogo@sc.usp.br and aometto@sc.usp.br

Rita Pinheiro Garcia and **Fausto Miguel Cereja Seixas Freire**
University of Coimbra, Departament of Mechanical Engineering, Coimbra, Portugal.
E-mail: rita.garcia@dem.uc.pt and fausto.freire@dem.uc.pt

Luciano Donizeti Varanda
University of São Paulo, Department of Materials Engineering, São Carlos, Brazil.
E-mail: lu.varanda@hotmail.com

André Luis Christoforo
Federal University of São Carlos, Department of Civil Engineering, São Carlos, Brazil.
E-mail: alchristoforo@yahoo.com.br

ABSTRACT: Life Cycle Assessment (LCA) is recognized as a complete and effective methodology to identify opportunities for improving the environmental performance of products along their life cycle. In recent years, LCA has been applied to various renewable materials, including wood-based products. In this chapter, we focused on wood-based composites due to their relevance to the furniture and construction sectors. This chapter aims to discuss the state-of-the-art of LCA applied to wood-based composite manufacturing with emphasis on opportunities for reducing environmental impacts. A brief introduction to the LCA methodology is presented followed by a discussion on recent findings of LCA case studies for particleboard produced in Brazil and Portugal. Improvement opportunities for reducing life cycle environmental impacts are identified and recommendations provided, with focus on the substitution of urea-formaldehyde resin and virgin wood particles by alternative materials.

Keywords: Life cycle assessment. Particleboard. Environmental hotspots.

1. INTRODUCTION

In recent years, many studies have focused on the application of the Life Cycle Assessment (LCA) methodology to a wide range of products. Schweinle (2007) pointed out the importance of performing an LCA of wood-based products considering important issues such as: carbon footprint, bioenergy generation and life cycle engineering of new and innovative products from renewable sources (e.g. alternative wood-based composites). This allows a better understanding of the relevant environmental hotspots of wood-based products towards an improved design for environment.

This chapter discusses the state-of-the-art of the LCA of wood-based composites manufacturing, including recent developments on the topic. An in-depth discussion was done for the case of particleboard production in Brazil and Portugal. A benchmark process was adopted in view of suggesting common environmental improvement suggestions for both countries considering the life cycle hotspots identified.

The LCA methodology is detailed in Section 2. A discussion of LCA studies focusing on wood-based panels is documented in Section 3. Section 4 shows improvement opportunities for reducing life cycle environmental impacts and to extend research in the area. The final considerations and future outlook are presented in Section 5.

2. LIFE CYCLE ASSESSMENT (LCA)

2.1 DEFINITION AND MAIN APPLICATIONS

Life Cycle Assessment (LCA) is a methodological framework for the systematic evaluation of the environmental impacts of a product system throughout all stages of its life cycle – from resource extraction, through material production, product manufacturing, use, to end-of-life management, either by reuse, recycling or final disposal (GUINEE, 2001; REBITZER et al., 2004; ISO, 2006a). Environmental impacts assessed in

LCA include climate change, stratospheric ozone depletion, photochemical oxidation, eutrophication, acidification, toxicological stress on human health and ecosystems, depletion of resources, water use, land use, and others (REBITZER et al., 2004). A fundamental feature of LCA is its holistic approach, since it integrates into single framework direct and indirect environmental impacts of a product chain. Furthermore, such approach avoids environmental problem shifting, i.e. shifting impacts between environmental media, regions, or life cycle stages.

The main objectives of performing an LCA include: analyzing the main hotspots of a given product; comparing improvement alternatives for a particular product; designing new products (e.g. eco-design); and comparing functionally-equivalent products. LCA has been widely used to assess the environmental sustainability of both existing and future product systems, in various decision-support contexts, including public policy making (e.g. European Union and USA legislation), product development, and generic consumer information (e.g. environmental product declarations, product carbon footprint, eco-labeling).

2.2 LCA PHASES

The generic LCA methodology was standardized by the International Organization for Standardization, resulting in the ISO 14040 series standards. It is divided in four main phases, presented in Fig. 1: goal and scope definition; life cycle inventory analysis (LCI); life cycle impact assessment (LCIA); and interpretation. It is an iterative process, which means, for instance, that as new information is collected, an adjustment of the scope may be necessary in order to meet the goal of the study. Each of the LCA phases is explained in Sections 2.4.1 to 2.4.4.

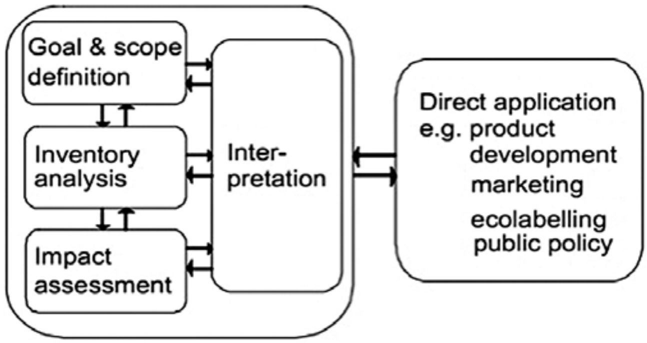


Figure 1 – Phases of LCA according to the ISO 14040:2006 standard. Source: ISO (2006a).

2.2.1 Definition Of Goal And Scope

This phase aims to define the objective of the LCA study. The goal should establish the intended application of the study, the reasons for its development and its target public, while the definition of the scope encompasses the definition of the product system, the function and functional unit, the system boundary, the life cycle impact assessment method chosen, the allocation procedure, and the assumptions and limitations of the study.

The function of a product is defined based on the characteristics it displays during its use phase. According to ISO (2006 a,b), a functional unit should represent qualitative and quantitative aspects of the function that a product fulfills. The functional unit is established to provide a base of reference against which inventoried input and output data are mathematically normalized, and it must therefore be measurable. After defining the functional unit, a reference flow must also be established to measure the quantity of product needed to fulfill the function expressed by the functional unit. Some examples of products, functions, functional units and reference flows are given in Tab. 1.

Table 1 – Examples of products, function, functional unit and reference flow in LCA studies.

Product	Function	Functional unit	Reference flow	Source
Fuel ethanol from sugarcane	• Used as 100% fuel in urban area vehicles.	• 10,000 km run by a car with an engine running on fuel hydrated ethanol.	1,000 kg of ethanol	Ometto et al. (2009)
Medium density particleboard (MDP) from reforest wood	• Used as raw material in the furniture and construction sectors.	• The production of 1 m^3 of uncoated MDP, with nominal thickness of 15 mm, density of 630 kg/m^3 and 8% moisture content.	1 m^3 of MDP	Silva et al. (2013)
Wardrobe made of MDP	• The storage of goods for personal use.	• 40 kg of goods stored per 5 years.	1 wardrobe unit	Iritani et al. (2014)

The system boundary describes the product life cycle and must include all processes and relevant flows considered in the LCA. The system boundary is composed of a set of unit processes, and all of the flows should be classified as inputs and outputs. Inputs may include raw materials, semi-processed materials and finished products, while outputs may be emissions to air and water, waste disposal, and products.

There are several approaches for the system boundary definition as shown in Fig. 2:

i) **Cradle-to-grave:** it represents a complete product life cycle because it encloses all life cycle stages: resource extraction, manufacture, product use and end-of-life strategies for the used product;

ii) **Crade-to-gate:** it is a common perspective adopted when studying intermediate products such as wood-based composites. In this case, the stages of resource extraction and manufacture of products or semi-finished products are considered. All downstream stages (use/end-of-life) are excluded;

iii) **Gate-to-gate:** is another partial LCA, where the system boundary is limited to the manufacture of the product only accounting for activities carried out at this stage. All upstream and downstream life cycle stages are disregarded;

iv) **Gate-to-grave:** this approach only considers the use and end-of-life stages (in some cases only the end-of-life). Prior stages of extraction of resources and manufacturing are not included. Gate-to-grave approaches are common, for instance, when analyzing waste management alternatives (e.g., incineration, landfill, etc.).

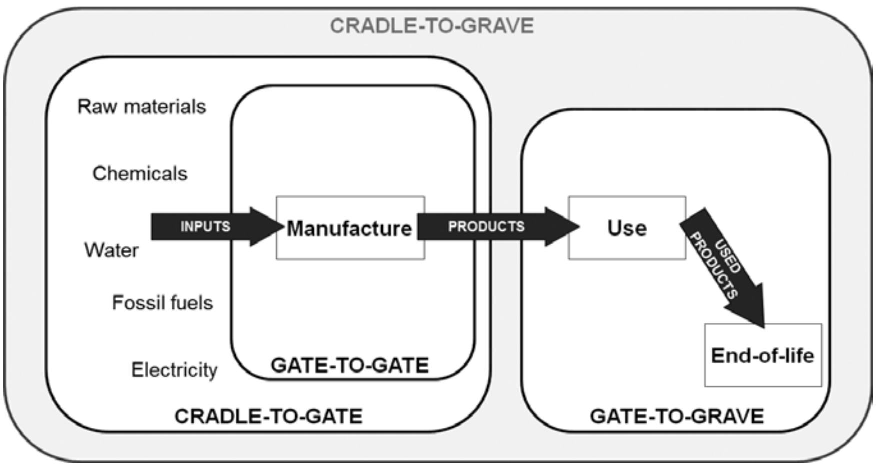


Figure 2 – Different approaches for the system boundary definition in LCA studies.

McDonough and Braungart (2002) proposed another approach called **cradle-to-cradle** or closed loop production, in which the end-of-life phase is focused on **recycling** and **remanufacturing** strategies. The main goal of this approach is to minimize environmental impacts of products by recovering materials that usually would be disposed of in landfill or incinerated.

Fig. 3 shows an example of system boundary definition for the production of MDP in Brazil. MDP is an intermediate product and its system boundary encloses two life cycle stages (forest and industrial production) in a **cradle-to-gate** approach. Each life cycle stage includes several unit processes and transportation activities. More specifically, the forest production stage starts with the seedlings cultivation and ends when wood is harvested and transported to the MDP factory; the MDP industrial production stage involves unit processes from wood storage until finishing activities. For each unit process in Fig. 3, it is necessary to quantify all inputs and outputs considering the established functional unit as exemplified in Tab. 1.

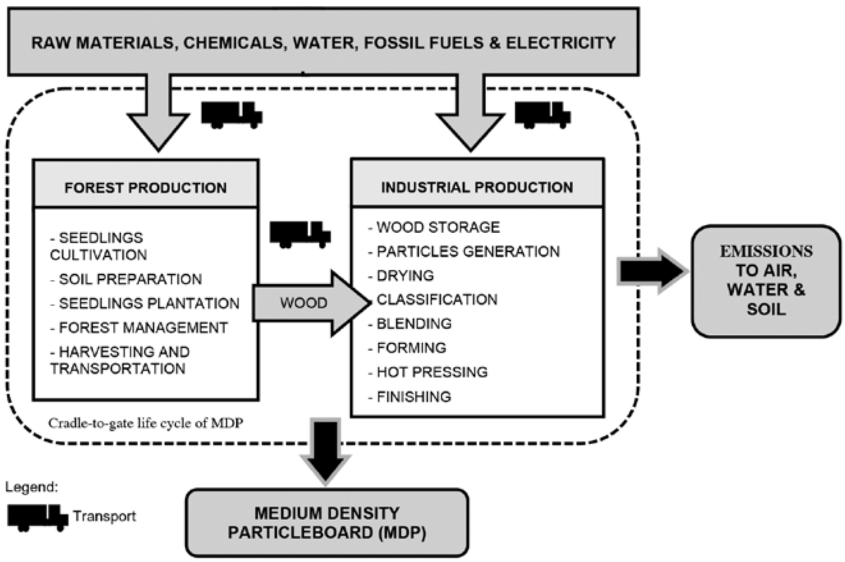


Figure 3 – System boundary of the MDP life cycle production. Source: Silva et al. (2013).

2.2.2. Life Cycle Inventory (LCI)

The LCI phase encloses data collection and calculation in order to quantify inputs (energy, raw and ancillary materials and other physical inputs) and outputs (products, emissions and waste) for the system boundary under analysis. Input/output data are collected for each unit process (with principles of conservation of matter being applied) as illustrated on the generic system shown in Fig. 4.

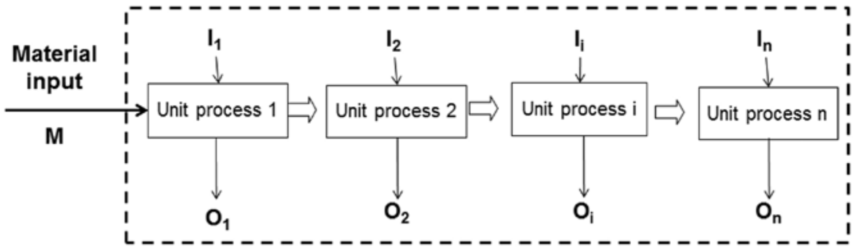


Figure 4 – A generic system boundary representation for a linear chain of unit processes. Source: adapted from Reich-Weiser et al. (2013).

The system shown in Fig. 4 comprises ***n*** unit processes with a total quantity of material input ***M***. Each unit process ***i*** consumes a number of inputs $\boldsymbol{I_i}$ and generates a number of outputs $\boldsymbol{O_i}$ according to Eq. 1:

$$M = \sum_{i}^{n} I_i + \sum_{i}^{n} O_i \tag{1}$$

Eq. 1 represents a balance of material assuming only a single material input ***M*** and its flow within the system boundary. However, a system boundary usually comprises multiple material inputs, especially when considering a complete product life cycle, i.e. a cradle-to-grave assessment. For a comprehensive analysis of material flows within a system boundary, Eq. 1 must be applied for each type of input.

The main activities to consolidate the LCI are organized bellow according to the ISO (2006a) standard:

i) **Data collection:** inventory flows can number in the hundreds depending on the system boundary. Data collection can be the most time consuming task when conducting an LCI because it usually involves the collection of a large number of direct and indirect flows associated with each unit process. Indirect flows are usually obtained from LCA software and databases, and direct flows may be collected from primary and secondary data sources. For example, during the collection process of direct input/output data, semi-structured or survey questionnaires, data collection sheets, can be used, while indirect flows associated to the direct flows can be obtained from international databases such as Ecoinvent (http://www.ecoinvent.ch/) and by using LCA software tools like GaBi (http://www.gabi-software.com/) and SimaPro (http://www.pre-sustainability.com/simapro);

ii) **Data calculation:** calculation procedures are applied to validate the collected raw data. In general, for wood-based products, such as the MDP in Fig. 3, input/output data from the forest production stages are usually represented in terms of cultivated area (e.g. mass of input per hectare (ha) of cultivated area). However, since the functional unit adopted for MDP is usually 1 m^3 of produced panel (e.g. Silva et al., 2013; Garcia and Freire, 2012), it is necessary to further calculate data expressed per ha of cultivated area to the reference basis of 1 m^3 of MDP. This is usually done using an LCA software, in which the activity levels of the various unit processes are calculated in terms of the functional unit selected. Another step is to check material and energy balances for each unit process, and Eq. 1 can be used for that. The mass-balance principle is used as a tool for verification in LCI, as it states that at each physical transformation process, the mass of inputs must equal the mass of outputs, including wastes;

iii) **Allocation:** if necessary, allocation procedure should be applied to the unit processes where there is multifunctionality (i.e. multiple-input or -output processes).

2.2.3 Life cycle impact assessment (LCIA)

LCIA evaluates the significance of environmental impacts by characterizing LCI data into a set of specific environmental categories and indicators. This phase of LCA includes three mandatory elements:

i) **Selection:** choice of impact categories, category indicators, and characterization models;

ii) **Classification:** assignment of the inventory dataset (expressed by the emission of substance ***s***, $\boldsymbol{E_s}$) to a set of specific impact categories (***k***);

iii) **Characterization:** calculation of category indicators results using characterization factors ($\boldsymbol{CF_{k,s}}$), which involves the multiplication of $\boldsymbol{E_s}$ and $\boldsymbol{CF_{k,s}}$ values for each impact category ***k***.

For each impact category ***k***, Eq. 2 can be used to calculate environmental impact potential ($\boldsymbol{EIP_{(k)}}$) of a product system.

$$EIP_{(k)} = \sum \left(CF_{k,s} \times E_s\right) \tag{2}$$

There are also some optional elements when conducting an LCIA, such as:

i) **Normalization:** calculation of the magnitude of category indicator results relative to a reference (e.g. the total impacts in a region of interest);

ii) **Weighting:** conversion of indicator results calculated for different impact categories using numerical factors based on value choices (ISO, 2006b). The different environmental impacts are weighted relative to each other and may be aggregated to get a single value for the total environmental impact. Weighting is a controversial step among LCA practitioners. Furthermore, according to the ISO standards, it "shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public." (ISO, 2006b, section 4.4.5, p.23). Unfortunately, this is often ignored (including in the scientific literature), which results in a misunderstanding of the high degree of subjectivity associated with weighting and its role in LCA studies;

iii) **Grouping:** sorting and possibly ranking the impact categories based on predefined priorities.

A schematic representation of the three mandatory LCIA steps (with the characterization step focusing on the **acidification** category) is illustrated in Fig. 5 using the LCIA method EDIP97 (proposed by WENZEL et al., 1997), with impact categories typically assessed in LCA studies, namely:

i) **Acidification:** can be caused by pollutant emissions into air, water and soil, mainly from combustion processes in electricity and heat generation, and in transport systems. For a substance to be considered a contributor to acidification it must introduce or release hydrogen ions into the environment, and anions (that accompany hydrogen ions) must be leached or washed out from the system (Wenzel et al., 1997);

ii) **Ecotoxicity:** chemicals emitted through anthropogenic activities contribute to ecotoxicity if they negatively affect the function of ecosystems – by exerting toxic effects on the organisms that live in them (WENZEL et al., 1997);

iii) **Eutrophication:** also called nutrient enrichment, it represents an impact on ecosystems from substances containing nitrogen or phosphorus in a biologically available form. According to Wenzel et al. (1997), eutrophication impacts can be caused by emissions into air (e.g. nitrogen oxides from combustion processes), water (e.g. nitrogen in the aquatic environment originating from the use of fertilizers in agriculture) and soil (e.g. emissions of phosphorus leaching into the soil from agricultural sources);

iv) **Global warming:** the main anthropogenic contributions to global warming derive from the combustion of fossil fuels agro-industrial processes, land use and land use changes. Substances that are contributors to global warming absorb infrared radiation and remain stable in the atmosphere, with a residence time of years to centuries (IPCC, 2007);

v) **Ozone layer depletion:** is caused by the breakdown of stratospheric ozone as a result of man-made emissions of halocarbons (e.g., CFCs, HCFCs). The main contributors are gases at normal atmospheric temperatures, which contain chlorine or bromine such as refrigerant substances, solvents and foaming agents (WENZEL et al., 1997).

In addition, other impact categories may also be assessed, such as human toxicity, abiotic resources depletion, particulate matter formation, ionizing radiation, photochemical oxidant formation, etc, depending on the goal of the study.

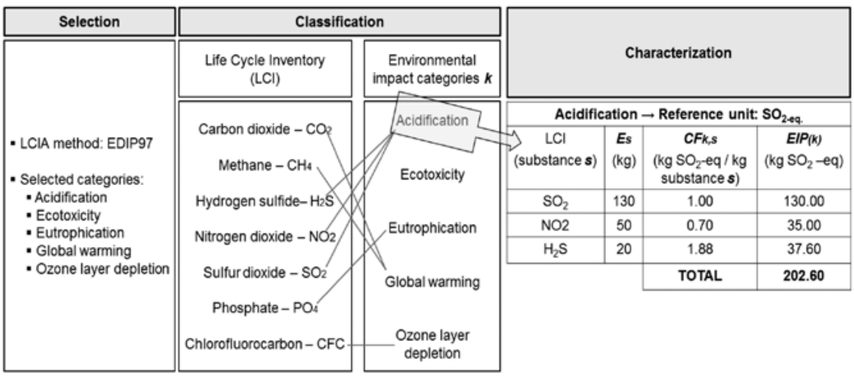


Figure 5 – Schematic representation of the three mandatory LCIA steps.

2.2.4 Interpretation

The life cycle interpretation phase occurs in every phase of the LCA and involves drawing the main conclusions, making recommendations and identifying the limitations of a study based on LCI and LCIA results. Additionally, according to ISO (2006a) the interpretation phase can include evaluation of the study considering completeness, sensitivity, uncertainty and consistency analyses.

2.3 CRITICAL MODELING ISSUES IN THE LCA OF WOOD-BASED PRODUCTS

There are a number of critical issues associated with the LCA of wood-based products. These include how to account for the biogenic carbon which is temporarily stored in biomass and how to deal with multifunctionality in the biomass supply chain. Other important methodological difficulties encountered in the LCA of wood-based products is how to inventory and assess land use and land use change impacts, such as those related to different forest management practices, impacts on biodiversity and on the hydrological cycle (WERNWE; NEBEL, 2007). The definition of the functional unit and the system boundary and the incorporation of uncertainty in LCA studies are also critical issues, which are common to all LCA studies. The following sections focus on biogenic carbon accounting and multifunctionality in the biomass supply chain, due to their relevance for wood-based composites.

2.3.1 Biogenic Carbon

Wood-based products are generally perceived as a potentially carbon-neutral material since they incorporate carbon, although emissions related to its production can have a high contribution to its environmental profile (WERNER; RICHTER, 2007). The way biogenic carbon is accounted in LCA studies of wood-based products is a critical issue since it can lead to completely different results (GARCIA; FREIRE, 2014), in particular when wood-based products are compared with fossil-based products (e.g. plastics).

The carbon stored in wood-based products during biomass growth may be re-emitted to the atmosphere during the life cycle of products (e.g. as biogenic CO_2) or be indefinitely stored as a result of waste management (e.g. in landfill). LCA studies often exclude biogenic CO_2 emissions from the assessment, as it is assumed that the same amount of CO_2 was previously sequestered by biomass, giving a net zero emission (GUINEÉ et al., 2009; HISCHIER et al., 2010). However, not explicitly considering biogenic CO_2 may lead to accounting errors (SEARCHINGER et al., 2009; BIRD et al., 2010).

Moreover, wood-based products may have a relatively long service life, therefore, understanding the dynamics related to storage and delayed carbon emissions in both use and disposal phases is of key importance. There are several approaches to account for temporary storage and delayed emission of biogenic carbon (e.g. MOURA-COSTA; WILSON, 2000; LEVASSEUR et al., 2010, 2012; EC JRC, 2010; MÜLLER-WENK; BRANDÃO, 2010; BSI, 2011; KENDALL, 2012) However, there is no consensus neither on whether temporary carbon storage should be accounted for nor which is the best approach to assess it (BRANDÃO; LEVASSEUR, 2011; BRANDÃO et al., 2013). Additionally, different methods may lead to very different results, as demonstrated by Garcia and Freire (2014) in an application to particleboard produced in Portugal.

2.3.2 Multifunctionality

Other important aspect in the wood-based product life cycle is the fact that biomass-based production chains are often multifunctional, i.e. they are associated to more than one co-product (JUNGMEIER et al., 2002; MALÇA; FREIRE, 2006). Since LCA studies usually focus on only one function, it is necessary to allocate the burdens to the product under analysis. The majority of LCA of wood-based products allocates the burdens to the different co-products based on physical properties (e.g. mass, energy content, carbon content) or other characteristics (economic value). Results from LCA studies of wood-based products are, nevertheless, very sensitive to the selection of the allocation procedure, as demonstrated by Jungmeier et al. (2002), Werner et al. (2007), and Garcia and Freire (2014).

3. LCA APPLIED TO WOOD-BASED PRODUCTS

3.1 WOOD-BASED COMPOSITES

There is a wide variety of products made from wood, ranging from timber and lumber to engineered products (e.g., wood pulp and paper, furniture, panels, etc.). Planted forests are the main source of raw material for the production of such products, particularly Eucalyptus and Pine. Among the wide range of applications for wood, Biazus et al. (2010) highlighted the wood-based panels sector, which is very dynamic and competitive due to the quality and wide acceptance of products in the market. The market for wood panels has grown in recent years due to the growth of the furniture and construction sectors (RESEARCH AND MARKETS, 2013).

Thoemen et al. (2010) classified the main types of wood panels into two categories:

i) **Solid wood:** represented by plywood, laminated veneer lumber (LVL) and glued laminated timber (GLT) – all of them widely used in the construction sector;
ii) **Reconstituted:** industrialized panels made with particles or fibers, in particular: particleboards / medium density particleboard (MDP), oriented strand board (OSB), medium density fiberboard (MDF), hard density fiberboard (HDF). This category also encompasses other composites, such as wood-cement, wood-plastic and other lignocellulosic materials.

Tab. 2 presents a summary of the main LCA publications regarding these two categories of wood-based panels in the last 10 years. In general, these studies concern LCA case studies focusing on the LCI, identification of hotspots and assessment of environmental improvements in the product life cycle. The largest number of publications assessed wood-based panels produced in the United States, most of them performed by the Consortium for Research on Renewable Industrial Materials (CORRIM) (PUETTMANN et al., 2010). Other studies focused on wood panels produced in Brazil and Europe.

Table 2 – Published LCA studies of wood-based panels.

Product	Nation	Reference
GLT	United States	Puettmann and Wilson (2004)
Hardboard	Austria	González-García et al. (2009)
Hardboard	Austria	González-García et al. (2011)
LVL	United States	Wilson and Dancer (2004)
MDF	Spain	Rivela et al. (2007)
MDF	United States	Wilson (2010a)
MDF	Germany	Mitchell and Stevens (2009)
OSB	Luxembourg	Benetto et al. (2009)
OSB	United States	Earles et al. (2011)
OSB	United States	Kline (2005)
Particleboard	Spain	Rivela et al. (2006)
Particleboard	United States	Wilson (2010b)
Particleboard	Portugal	Garcia and Freire (2014)
Particleboard	Brazil	Silva et al. (2013)
Particleboard	Brazil	Iritani (2014)
Particleboard	Brazil	Santos et al. (2014)
Particleboard	Brazil	Silva et al. (2014)
Plywood	Brazil	Teixeira et al. (2010)
Plywood	United States	Wilson and Sakimoto (2005)

The majority of publications in Tab. 2 focused on engineered panels (i.e., MDP, MDF, OSB, HDF) because the industries in this segment are important suppliers of the furniture segment. In particular, there is currently a high demand for particleboard and MDF for furniture production (IRITANI et al., 2014; SILVA et al., 2014). MDP/particleboard is the reconstituted wood panel most produced and consumed worldwide. It was also the wood based product with more LCA studies (see Tab. 2). Particleboard is applied on the manufacture of straight line furniture components, such as tabletops, bedside cabinets, shelves and partitions (BIAZUS et al., 2010; SILVA et al., 2013; IRITANI et al., 2014; SILVA et al., 2014). The next sections address the LCA of particleboard manufactured in Brazil and Portugal.

3.2 THE CASE OF PARTICLEBOARD MANUFACTURE IN BRAZIL AND PORTUGAL

Particleboard is a lignocellulosic composite made of a synthetic adhesive matrix and a reinforcing phase represented by wood particles (THOEMEN *et al,*. 2010). The matrix and reinforcing phases are combined by the application of heat and pressure for the consolidation of the panel. The wood particles are arranged in three layers and, in general, are from Eucalyptus or Pine species. The synthetic adhesive is composed of a thermoset resin, usually urea–formaldehyde (UF), which is the binding agent; other common additives applied to the resin are paraffin emulsion and a catalyst (ammonium chloride/sulfate).

The Brazilian particleboard is different from the one produced in Europe and the United States (US). The most important differences can be organized in two perspectives.

i) While in Brazil (IRITANI et al., 2014; SILVA et al., 2013; SILVA et al., 2014) biomass to particleboard manufacturing is provided by forests planted specifically for that purpose, in the US (Wilson 2010b) and Europe (e.g. Portugal – GARCIA; FREIRE 2014; and Spain - RIVIELA et al., 2006; GONZÁLES; GARCIA et al., 2009; 2011), waste wood is mainly used (pre-consumer, e.g., from sawmills and forest operations, and post-consumer);
ii) In Brazil, according to Silva et al. (2014), lignocellulosic residues such as sugarcane bagasse are most used to provide power and heat through cogeneration processes at industries. However, in particleboard manufacture, Brazilian producers are still not aware of the benefits of cogeneration of local wood waste to produce both electrical and thermal energy. Currently, they use such residues only to generate heat for the drying process of wood particles. Other secondary applications include selling the surplus of wood residues to other industries as biomass source. On the other hand, in Europe, such as in Portugal and Spain, cogeneration of wood waste is very common. Rivela et al. (2006) explained that wood particles are dried through direct contact with hot flue gas from a

cogeneration unit that also supplies electricity to the panel manufacturing plant. As a result, the power demand from the national grid is reduced.

Considering these two bullet points, the production of particleboards in Brazil and Portugal is different. In this sense, Sections 3.2.1 to 3.2.4 assess and discuss the environmental life cycle performance of particleboards following Silva et al. (2013) and Garcia and Freire (2012; 2014). Silva et al. (2013) performed a LCA of MDP produced in Brazil form a cradle-to-gate perspective and assessed environmental impacts in both toxicological and non-toxicological categories.

They discussed alternative scenarios in order to improve the environmental performance of particleboard production in Brazil. Garcia and Freire (2012) assessed the life cycle environmental impacts of particleboard produced in Portugal from a cradle-to-grave perspective including different end-of-life scenarios. They also compared different life cycle-based tools such as environmental product declarations and the PAS 2050:2008 -Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI, 2008). Garcia and Freire (2014) built on the model and inventory from Garcia and Freire (2012) and focused on assessing the carbon footprint of particleboard by comparing different methodologies (ISO/TS 14067; GHG Protocol Product Standard, PAS 2050:2011 and Climate Declaration). For the next sections, only the cradle-to-gate results from Garcia and Freire (2012); 2014) are discussed.

3.2.1 Functional Unit And System Boundary

First, as reported in the ISO 14040 and 14044 standards, the functional unit must be defined. In general, most papers adopted 1 m^3 of panel as the basis for the functional unit definition. However, further technical characteristics can also be integrated in the functional unit definition, for instance, density, moisture content, nominal thickness, or others. For example, in Brazil, the LCA study of Silva et al. (2013) assumed the production of 1 m^3 of particleboard, with nominal thickness of 15 mm, average density of 630 kg/m^3, and 8% moisture content.

Fig. 6 shows the system boundary for the two particleboard production life cycles – “green dashed line” represents the system boundary for the Brazilian particleboard production and “black dashed line” limits the system boundary of the Portuguese particleboard production. Three subsystems are considered: forest production, wood waste generation and industrial production, each of them supplied by ancillary subsystems according to their specific activities.

As shown in Fig. 6, the particleboard production is characterized by the use of wood coming from two possible sources – forest production and wood waste generation. The Brazilian particleboard only uses virgin wood from the forest production subsystem (details regarding each forest activity are available in Silva et al. (2013). The wood waste generation subsystem supplies biomass to particleboard produced in Portugal. As previously explained, biomass used in Portugal is mainly wood waste from pre-consumer and post-consumer activities, as detailed in Garcia and Freire (2014).

In particleboard industrial production, there is one main technological difference between Brazil and Europe: the process of cogeneration of biomass. In European plants, such as in Portugal, cogeneration units supply part of the heat and electricity requirements for the industrial particleboard manufacture. The remaining energy requirements are supplied by natural gas combustion (thermal energy) and electricity (from the national grid). In Brazil, there is no cogeneration of biomass. Heat is provided by the combustion of biomass and heavy fuel oil. Electricity is provided from the national grid. The remaining industrial process is similar to both countries.

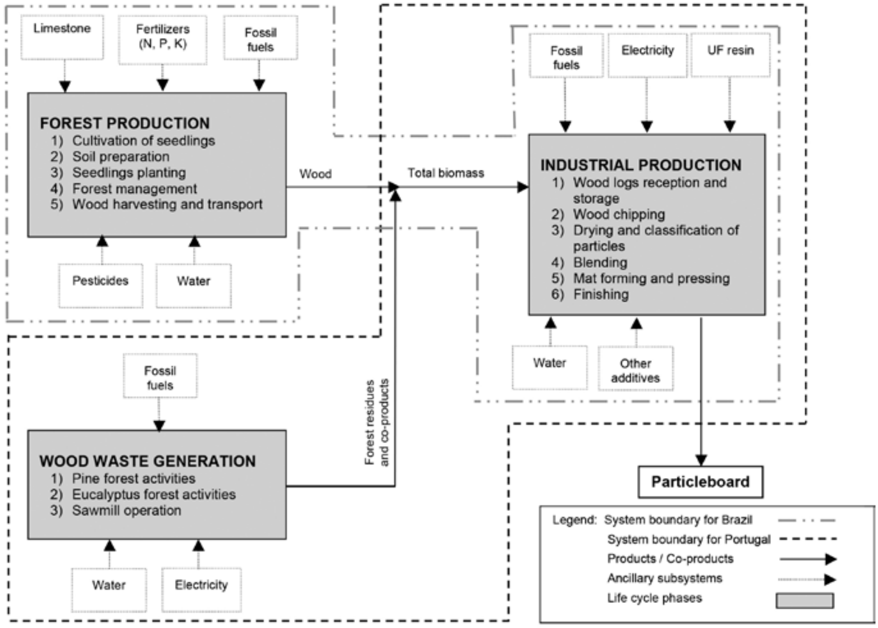


Figure 6 – System boundary of production of particleboards in Brazil and Portugal.

3.2.2 Data sources and life cycle inventory

Inventory data for the Brazilian particleboard production was obtained from Silva et al. (2013). These authors collected average input/output data from particleboard manufacturing companies in Brazil. Data for three companies, located in the States of São Paulo and Minas Gerais, representing 57% of the Brazilian particleboard production (1,733,785 m^3 in 2011), was collected covering both forest and industrial production stages.

Primary data for Portugal was collected in the context of research projects and thesis at the Center for Industrial Ecology, University of Coimbra. Some of this data is available in Nunes (2008); Nunes and Freire (2007); Garcia (2010); Garcia and Freire (2012). The main sources of secondary data were peer-reviewed literature and databases (mainly Ecoinvent v.2, Ecoinvent, 2012). More details on data sources can be found in Garcia and Freire (2014).

Tab. 3 shows a comparative gate-to-gate inventory between Brazil and Portugal for the industrial production of particleboards. All inventories are based on 1 m^3 of particleboard and LCI results available at Silva et al. (2013) and Garcia and Freire (2012; 2014) studies.

Table 3 – Comparative gate-to-gate particleboard industrial production in Brazil and Portugal.

Inputs/Outputs	**Unit**	**Silva** et al. **(2013) (unit/m³)**	**Garcia and Freire (2012; 2014)**[;] **(unit/m³)**
INPUTS			
Materials consumption			
Eucalyptus forest residues	kg	-	111
Pine forest residues	kg	-	185
Wood co-products	kg	-	444
Virgin wood (as logs)a	kg	687.2	-
Lubricants (oil and grease)	g	18	-
Ammonium sulfate	kg	1.38	0.73
Paraffin emulsion[b]	kg	5.47	2.3
Urea formaldehyde resin[c]	kg	71.7	68
Eucalyptus forest residues	kg	-	111
Urea (scavenger)	kg	-	2.9
Water	kg	90.4	304
Energy consumption			
Electricity from national grid	MJ	507	94
Electricity from cogeneration	MJ	-	230
Natural gas	MJ	-	490
Wooden residues	kg	38.5	55
Heavy fuel oil	kg	13.7	-
Diesel	kg	1.72	-
OUTPUTS			
Particleboard	kg	630	640
Co-products			
Wooden residues	kg	97.2	-

continued on next page

Inputs/Outputs	Unit	**Silva** et al. (2013) (unit/m³)	Garcia and Freire (2012; 2014)[*] (unit/m³)
Emissions to air			
Ash (from wood residue)	kg	0.39	-
Carbon dioxide (from fossil fuels)[d]	kg	48	58
Carbon monoxide	kg	0.19	1.31
Formaldehyde	kg	0.15	0.06
Hydrocarbons	g	1.64	-
Methane	g	1.69	-
Methanol	g		30
Nitrogen dioxide	kg		0.04
Nitrogen oxides	kg	0.18	-
Nitrogen monoxide	kg		0.12
Particulate material (no specified)	kg	0.18	0.31
Sulfur dioxide	kg	-	0.0005
Sulfur oxides	kg	1.32	-
VOC (not specified)*	kg	0.36	0.36
VOCNM*	g	9.48E-04	-
Emissions to water			
Ammonia	g	0.121	-
BOD*	g	0.616	-
Effluent (not specified)	kg	6	-
Formaldehyde	g	7.29E-02	-
Suspended solids	g	24.4	-
Emissions to soil			
Lubricant residues	g	15.9	-

a Wood (as logs): average density of 474 kg/m³ (oven dry) or 1.45 m³/m³ of MDP.
b Paraffin emulsion: weight at 100% solids (solid content of 60%).
c UF resin: weight at 100% solids (solid content of 67%); molar ratio formaldehyde/urea of 1.38.
d Biogenic carbon dioxide emission to air was not included in the inventory.
* BOD – Biochemical oxygen demand; VOC – Volatile organic compounds; VOCNM – Volatile organic compounds non methane.

3.2.3 Life cycle impact assessment: main hotspots

This section discusses the life cycle impact assessment of particleboard considering the CML2001 (GUINEÉ, 2001) and the USETox (HAUSCHILD et al., 2008; ROSENBAUM et al., 2008) LCIA methods. Results of LCIA for the Brazilian and Portuguese particleboards are summarized in Tab. 4. Higher impacts in AC, GW and POC were calculated for the particleboard produced in Brazil. For AC, this is due to the combustion of heavy fuel oil in Brazilian manufacturing plants. Electricity and heavy fuel oil, are responsible for the large GW of the Brazilian particleboard. On the other hand, the Portuguese particleboard presents higher impacts in AD, EP and EC mainly due to the production of urea for UF resin production. The large impacts on HT are mainly due to production of heat by cogeneration of wood.

Biogenic carbon storage is not included in the value presented for the GW impact, but amounts 1,272 kg $CO_{2\text{-eq.}}/m^3$ for the Brazilian particleboard and 1,098 kg $CO_{2\text{-eq.}}/m^3$, for the Portuguese one. It is important to report the amount of carbon stored in the product explicitly in cradle-to-gate assessments in order to avoid misleading comparisons with other products, since the embodied carbon at gate may be released later during use or end-of-life phase (i.e. through incineration) (GARCIA; FREIRE, 2014).

Table 4 – LCIA results for the production of 1m3 of particleboard in Brazil and Portugal.

Impact category	LCIA method	Unit	Silva et al. (2013)	Garcia and Freire (2012; 2014)
Abiotic depletion (ADe)	CML	kg Sb_{eq}	0.98	1.60[b]
Acidification (AC)	CML	kg SO_{2eq}	2.40	0.68
Eutrophication (EP)	CML	kg $PO_4^{-3}{}_{eq}$	0.13	0.21
Global warming (GW)	CML	kg CO_{2eq}	333.28[c]	188[d]
Photochemical oxidation (POC)	CML	kg C_2H_{2eq}	0.28	0.05
Ecotoxicity (EC)	USEtox	PAF.m³.day	82.80	56.87[b]
Human toxicity (HT)	USEtox	Cases	6.71E-07	2.07E-05

a Results using economic allocation.
b Calculated for this publication.
c Carbon storage is 1,272 kg $CO_{2\text{-eq.}}/m^3$ (not included).
d Carbon storage is 1,098 kg $CO_{2\text{-eq.}}/m^3$ (not included).

Tab. 5 shows the main hotspots identified for each impact category. The UF resin production represents the major hotspot for all impact categories, except EC in Brazil and HT in Portugal. For the Brazilian particleboard, heavy fuel oil production is also an important hotspot in AD, AC and GW. The production of glyphosate herbicide is the main contributor to the impacts in EC. For the Portuguese particleboard, natural gas combustion and cogeneration of biomass in the manufacturing plant have also an important contribution to the environmental impacts. In general, most of the impacts occur in the industrial production subsystem. For the Brazilian particleboard, impacts in EC occur mainly in the forestry subsystem while for EP both subsystems are important contributors to the impacts.

Table 5 – Environmental hotspots for the production of particleboards in Brazil and Portugal.

Impact category	Silva et al. (2013)	Garcia and Freire (2012; 2014)
Abiotic depletion (AD)	Heavy fuel oil / UF resin	UF resin
Acidification (AC)	Heavy fuel oil / UF resin	UF resin
Eutrophication (EP)	Diesel / Fertilizers / UF resin	UF resin
Global warming (GW)	Electricity / Heavy fuel oil / UF resin	UF resin / Natural gas combustion
Photochemical oxidation (POC)	UF resin	UF resin
Ecotoxicity (EC)	Glyphosate herbicide	UF resin
Human toxicity (HT)	UF resin	Biomass cogeneration

3.2.4 General opportunities for reducing environmental impacts

For Brazil, based on the main hotspots identified in the cradle-to-gate assessment of MDP (Tab. 5), some general improvement suggestions can be identified:

i) The substitution of heavy fuel oil (HFO) by alternative fuels (e.g. diesel, wood residues or other biomass sources) in the manufacturing process;
ii) The substitution of UF resin for other types of synthetic resins or renewable compounds from trees and plants. (Section 4 shows a comparative LCA study of UF resin with other formaldehyde-based resins);
iii) The production of particleboards considering the addition of other lignocellulosic materials because it could reduce impacts during the forest production, such as EP and EC (a LCA case study which evaluated the production of particleboard made with sugarcane bagasse waste addition is described in Section 4);

For the Portuguese case, the substitution of UF resin by other resins produced with lower environmental impacts could lead to significant improvements in the overall environmental performance of particleboard. Nevertheless, a full life cycle assessment should be conducted in order to avoid environmental problem shifting.

The next section addresses some of the options to reduce environmental impacts of particleboard with focus on UF resin and virgin wood substitution by other technological alternatives.

4. ASSESSMENT OF ALTERNATIVES FOR REDUCING ENVIRONMENTAL IMPACTS

Concerning reducing impacts from UF resin, Silva et al. (2015) proposed to use melamine-urea-formaldehyde (MUF) resin to reduce environmental impacts, as shown in Fig. 7. They performed a scenario analysis considering the addition of up to 10% of melamine to the UF resin for the particleboard produced in Brazil, concluding that MUF can replace UF resin because of its lower contribution to PO and HT. The particleboard made with UF resin was the reference scenario for the comparative LCA.

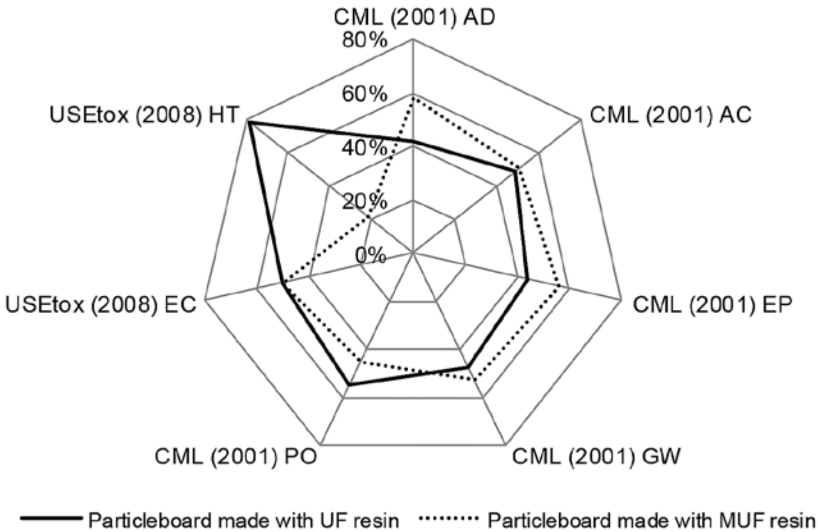


Figure 7 – Comparative LCA of particleboards made with MUF and UF resins.
Source: Silva et al. (2015).

Other options to reduce impacts could be to substitute the UF resin with alternative resins, manufactured using renewable sources. The use of natural tannin (KIM, 2009) and cashew nutshell liquid (CNSL) (KIM, 2010) were highlighted as satisfactory adhesives for wood-based flooring as they reduce formaldehyde and VOCs emissions during the resin use phase and also as they tend to release less free formaldehyde emissions than UF resins. Another study by González-García et al. (2011) introduced a laccase system in the hardboard production by substituting phenol-formaldehyde resin for a two-component adhesive with a wood-based phenolic material and a phenol-oxidizing enzyme (i.e. laccase activated lignin). The results showed that the laccase system had a small contribution to the AC and EP categories. Further research is needed in view of investigating the environmental performance of resins made from renewable resources to produce wood panels.

Concerning using renewable resources other than virgin wood, important amounts of residues are originated from the agro-industrial sector, which could be used to produce wood-based panels. The production of particleboards using such residues proved to be a technically good alternative when compared to conventional particleboards, as reported by many papers on the area: Amin (2011), Barros Filho et al. (2011), Belini et al. (2012), Madurwar et al. (2013) Pinto et al. (2012), and Varanda et al. (2013). On the other hand, the environmental consequences of producing such kind of particleboards are less studied, especially in Brazil, as only virgin wood is still applied as raw material. However, Santos et al. (2014) and Silva et al. (2014) recently evaluated the addition of residues to produce particleboards in Brazil.

Santos et al. (2014) conducted a comparative LCA of particleboards made with residues from sugarcane bagasse and pine wood shavings. The results indicated that bagasse particleboard had lower environmental impacts than pine particleboard. Nevertheless, the investigation reported was at laboratory scale and, therefore, cannot reflect the results of the industrial scale. To extend research on the topic, Silva et al. (2014) analyzed the life cycle impacts of bagasse particleboard manufacture at industrial level. The main results are shown in Fig. 8. They analyzed five scenarios, as follows:

i) Scenario 0: baseline representing a consumption of 50 % bagasse and 50 % wood;
ii) Scenario 1: consumption of 0% bagasse and 100% wood;
iii) Scenario 2: consumption of 25% bagasse and 75 % wood;
iv) Scenario 3: consumption of 75% bagasse and 25% wood;
v) Scenario 4: consumption of 100% bagasse and 0% wood

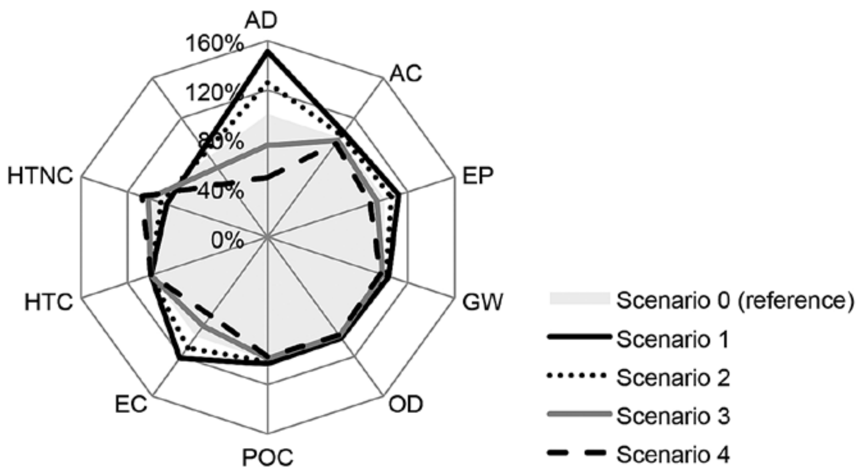


Figure 8 – Influence of addition of sugarcane bagasse to produce particleboards.
Source: Silva et al. (2014).

Fig. 8 shows that the displacing of wood with bagasse leads to reduction of impacts mainly in the categories of AD, EP, EC, and HTNC (human toxicity non cancer effects). Silva et al. (2014) suggested mixing sugarcane bagasse up to 75% (Scenario 2) to produce particleboards in order to obtain particleboards with technical quality and better environmental profile than those produced with 100% virgin wood (Scenario 1). Similar conclusions were also observed by Iritani et al. (2014), which evaluated a wardrobe made with particleboards made with wood waste. LCA results showed that the use of wood waste as raw material can present environmental advantages to the overall environmental profile of furniture components (Iritani et al. 2014).

5. FINAL CONSIDERATIONS AND FUTURE OUTLOOK

Life cycle assessment has been applied to a wide-range of wood-based composites, aiming at identifying the main hotspots in their supply chain and assessing different options for reducing environmental impacts. This chapter revised LCA studies of particleboard production, focusing in two main regions: Brazil (SILVA et al., 2013); and Portugal (GARCIA; FREIRE 2012; 2014). The main areas of concern were identified: utilization of UF resin in the particleboard manufacture, energy use in the industrial plant, and biomass production. The utilization of MUF resin and other options made from renewable resources, such as natural tannin and cashew nut-shell liquid, was found to improve the environmental performance of particleboard. Another option for environmental improvement of wood-based composites assessed in the literature is the substitution of virgin wood by commonly available biomass residues. Further research is, however, needed in view of assessing other technically available options, such as other alternatives of resins from renewable resources (e.g. castor oil resin), while also considering the inclusion of economic and social aspects in the life cycle assessment.

ACKNOWLEDGEMENT

Diogo A. L. Silva, Francisco A. Rocco Lahr, and Aldo R. Ometto are grateful for the financial support provided by two Brazilian Governmental Funding Agencies: Coordination for the Improvement of Higher Education Personnel (“Coordenação de Aperfeiçoamento de Pessoas de Nível Superior”, CAPES – 9331/13-1); and São Paulo Research Foundation (“Fundação de Amparo à Pesquisa do Estado de São Paulo”, FAPESP - 2011/03816-6 and 2013/06736-9). Rita P. Garcia and Fausto M. C. S. Freire are grateful for the financial support provided by “Fundação para a Ciência e a Tecnologia” (FCT) under projects MIT/SET/0014/2009, MIT/MCA/0066/2009, PTDC/SEN-TRA/117251/2010, and PTDC/EMS-ENE/1839/2012. Rita P. Garcia also thanks FCT for Doctoral grant SFRH/BD/51299/2010. This work has been framed under the Energy for Sustainability Initiative of the University of Coimbra and the MIT-Portugal Program and supported by the R&D Project EMSURE (CENTRO-07-0224-FEDER-002004).

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

AMIN, N. Use of bagasse ash in concrete and its impact on the strength and chloride resistivity. **Journal of Materials in Civil Engineering**, v. 23, p. 717-720, 2011. doi:10.1061/(ASCE)MT.1943-5533.0000227.

BARROS FILHO, R. M.; MENDES, L. M.; NOVACK, K. M; APRELINI, L. O.; BOTARO, V. R. Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin. **Industrial Crops and Products**, v. 33, p. 369-373, 2011. doi:10.1016/j.indcrop.2010.11.007.

BELINI, U. L.; TOMAZELLO FILHO, M.; LOUZADA, J. L. P. C.; RODRIGUES, J. C. C.; ASTOLPHI, J. R. S. Pilot study for MDF manufacture from sugarcane bagasse and eucalyptus fibers. **European Journal of Wood and Wood Products,** v. 70, p. 537-539, 2012. doi:10.1007/s00107-011-0577-4.

BENETTO, E.; BECKER, M.; WELFRING, J. Life-cycle assessment of oriented strand boards (OSB): from process innovation to ecodesign. **Environmental Science & Technology**, v. 43, n. 15, p. 6003-6009, 2009. doi:10.1021/es900707u.

BIAZUS, A.; HORA, A. B.; LEITE, B. G. P. Panorama de mercado: painéis de madeira. **BNDES setorial**, Rio de Janeiro, v. 32, p. 49-90, 2010.

BIRD, D. N.; COWIE, A.; FRIEDEN, D.; GUSTAVSSON, L.; PENA, N.; PINGOUD, K.; RUETER, S.; SATHRE, R.; SOIMAKALLIO, S.; TUERK, A.; WOESS-GALLASCH, S.; ZANCHI, G. Emissions from bioenergy: improved accounting options and new policy needs. In: 18th EUROPEAN BIOMASS CONFERENCE EXHIBITION, 18, Lyon, France, 2010. **Proceedings...** Lyon, 2010. p. 98-102.

BRANDÃO, M.; LEVASSEUR, A. **Assessing temporary carbon storage in life cycle assessment and carbon footprinting: outcomes of an expert workshop.** Luxembourg: Publications Office of the European Union, 2011.

BRANDÃO, M.; LEVASSEUR, A.; KIRSCHBAUM, M. U. F.; WEIDEMA, B. P.; COWIE,

A. L.; JØRGENSEN, S. V.; HAUSCHILD, M. Z.; PENNINGTON, D. W.; CHOMKHAMSRI, K. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. **The International Journal of Life Cycle Assessment**, v. 18, p. 230-240, 2013. doi:10.1007/s11367-012-0451-6.

BSI. **Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.** London: British Standards Institution, 2008. PAS 2050:2008.

______. **Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.** London: British Standards Institution, 2011. PAS 2050:2011.

EARLES, J. M.; HALOG, A.; SHALER, S. Improving the environmental profile of wood panels via co-production of ethanol and acetic acid. **Environmental Science & Technology**, v. 45, n. 22, p. 3743-3749, 2011. doi:10.1021/es202180m.

EC JRC. **International reference life cycle data system handbook.** European Commission Joint Research Centre and the Institute for Environment and Sustainability. Available at: <http://lct.jrc.ec.europa.eu/assessment/publications>. Accessed on: 2010.

ECOINVENT. **Ecoinvent Database,** v2.2. Available at: <http://www.ecoinvent.ch>. Accessed on: May 03, 2012.

INTERNATIONAL ORGANIZATION OF STANDARDIZATION. **14040: environmental management – life cycle assessment - principles and framework**. Geneva, 2006a

______. **14044: environmental management – life cycle assessment – requirements and guidelines**. Geneva, 2006b.

INTERNATIONAL PANEL ON CLIMATE CHANGE. **Climate change 2007***:* the physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change, 2007.

IRITANI, D. R.; SILVA, D. A. L.; SAAVEDRA, Y. M. B.; GRAEL, P. F.; OMETTO, A.R. Sustainable strategies analysis through life cycle assessment: a case study in a furniture industry. **Journal of Cleaner Production** (in press), 2015.

GARCIA, R. **Avaliação comparativa de instrumentos de ciclo de vida aplicados a dois sistemas com biomassa: painéis e electricidade**. Dissertation - University of Coimbra, 2010.

GARCIA, R.; FREIRE, F. Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. **Journal of Cleaner Production**, v. 66, p. 199-209, 2014. doi:10.1016/j.jclepro.2013.11.073.

______. Environmental assessment of wood-based panels: a comparison of life-cycle-based tools. **International Journal of Sustainable Construction**, v. 1, n. 1, p. 63-71, 2012.

GONZÁLEZ-GARCÍA, S.; FEIJOO, G.; HEATHCOTE, C.; KANDELBAUER, A.; MOREIRA, M. T. Environmental assessment of green hardboard production coupled with a laccase activated system. **Journal of Cleaner Production**, v. 19, n. 5, p. 445–453, 2011. doi: 10.1016/j.jclepro.2010.10.016.

GONZÁLEZ-GARCÍA, S.; FEIJOO, G.; WIDSTEN, P.; KANDELBAUER, A.; ZIKULNIG-RUSCH, E.; MOREIRA, M. T. Environmental performance assessment of hardboard manufacture. **The International Journal of Life Cycle Assessment**, v. 14, p. 456-466, 2009. doi: 10.1007/s11367-009-0099-z.

GUINEÉ, J. B. **Life cycle assessment: an operational guide to the ISO standards**. LCA in perspective – operational annex to guide. Netherlands: Centre for Environmental Science, 2001.

GUINEÉ, J. B.; HEIJUNS, R.; VOET, E. A greenhouse gas indicator for bioenergy: some theoretical issues with practical implications. **The International Journal of Life Cycle Assessment**, v. 14, p. 328-339, 2009. doi:10.1007/s11367-009-0080-x.

HAUSCHILD, M. Z.; HUIJBREGTS, M.; JOLLIET, O.; MACLEOD, M.; MARGNI, M.; VAN DE MEENT, D.; ROSENBAUM, R. K.; MCKONE, T. Building a model based on scientific consensus for life cycle impact assessment of chemicals: the search for harmony and parsimony. **Environmental Science and Technology**, v. 42, p. 7032-7037, 2008. doi: 10.1021/es703145t.

HISCHIER, R.; WEIDEMA, B.; ALTHAUS, H.-J.; BAUER, C.; DOKA, G.; DONES, R.; FRISCHKNECHT, R.; HELLWEG, S.; HUMBERT, S.; JUNGBLUTH, N.; KÖLLNER, T.; LOERINCIK, Y.; MARGNI, M.; NEMECEK, T. Implementation of life cycle impact assessment methods. **Final report ecoinvent**, Swiss Centre for Life Cycle Inventories, v2. 2, n. 3, Dübendorf, 2010.

JUNGMEIER, G.; WERNER, F.; JARNEHAMMAR, A. C.; HOHENTHAL, C.; RICHTER, K. Allocation in LCA of wood-based products, experiences of cost action E9, part II. Examples. **The International Journal of Life Cycle Assessment**, v. 7, n. 6, p. 369-375, 2002. doi: 10.1007/BF02978686.

KENDALL, A. Time-adjusted global warming potentials for LCA and carbon footprints. **The International Journal of Life Cycle Assessment**, v. 17, n. 8, p. 1042-1049, 2012. P. 1042–1049. doi: 10.1007/s11367-012-0436-5.

KIM, S. Environment-friendly adhesives for surface bonding of wood-based flooring using natural tannin to reduce formaldehyde and TVOC emission. **Bioresource Technology**, v. 100, p. 744-748, 2009. doi: 10.1016/j.biortech.2008.06.062.

______. The reduction of formaldehyde and VOCs emission from wood-based flooring by green adhesive using cashew nutshell liquid (CNSL). **Journal of Hazardous Materials**, v.

182, p. 919-922, 2010. doi: 10.1016/j.jhazmat.2010.03.003.

KLINE, E. D. Gate-to-gate life inventory of oriented strand board. **Wood and Fiber Science**, v. 37, p 74-84, 2005.

LEVASSEUR, A.; LESAGE, P.; MARGNI, M.; DESCHÊNES, L.; SAMSON, R. Considering time in LCA: dynamic LCA and its application to global warming impact assessments. **Environmental Science & Technology**, v. 44, p. 3169-3174, 2010. doi:10.1021/es9030003.

LEVASSEUR, A.; LESAGE, P.; MARGNI, M.; SAMSON, R. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. **Journal of Industrial Ecology**, v. 17, n. 1, p. 117-128, 2012. doi:10.1111/j.1530-9290.2012.00503.x.

MADURWAR, M. V.; RALEGAONKAR, R. V.; MANDAVGANE, S. A. Application of agro-waste for sustainable construction materials: a review. **Construction and Building Materials**, v. 38, p. 872-878, 2013. doi: 10.1016/j.conbuildmat.2012.09.011.

MALÇA, J.; FREIRE, F. Renewability and life-cycle energy efficiency of bioethanol and bio--ethyl tertiary butyl ether (bioETBE): Assessing the implications of allocation. **Energy**, v. 31, p. 3362-3380, 2006. doi:10.1016/j.energy.2006.03.013.

______. Life-cycle studies of biodiesel in Europe: a review addressing the variability of results and modeling issues. **Renewable and Sustainable Energy Reviews**, v. 15, p. 338-351, 2011. doi:10.1016/j.rser.2010.09.013.

MCDONOUGH, W.; BRAUNGAR, M. **Cradle to cradle: remaking the way we make things.** United States: North Point Press, 2002. 193p.

MITCHELL, A.; STEVENS, G. **Life-cycle assessment of closed loop MDF recycling: microrelease trial – final report.** Material change for a better environment, 2009.

MOURA-COSTA, P.; WILSON, C. An equivalence factor between CO_2 avoided emissions and sequestration–description and applications in forestry. **Mitigation and Adaptation Strategies for Global Change**, v. 5, p. 51-60, 2000.

MÜLLER-WENK, R.; BRANDÃO, M. Climatic impact of land use in LCA – carbon transfers between vegetation/soil and air. **International Journal of Life Cycle Assessment**, v. 15, n. 2, p. 172-182, 2010. doi:10.1007/s11367-009-0144-y.

NUNES, J. **Avaliação Integrada da produção de electricidade com base em biomassa lenho-celulósica em Portugal:** emissões de GEE, análise tecnológica e energética de ciclo de vida. MSc. Dissertation, University of Coimbra, 2008.

NUNES, J.; FREIRE, F. Tecnologias avançadas para a produção de electricidade com base em biomassa lenho-celulósica. **Jornal de Engenharia Química**, v. 6, p. 34-41, 2007.

OMETTO A. R.; HAUSCHILD M. Z.; ROMA W. N. L. Lifecycle assessment of fuel ethanol from sugarcane in Brazil. **The International Journal of Life Cycle Assessment**, v. 14, n. 3, p. 236-247, 2009. doi:10.1007/s11367-009-0065-9.

PINTO, J.; CRUZ, D.; PAIVA, A.; PEREIRA, S.; TAVARES, P.; FERNANDES, L.; VARUM, H. Characterization of corn cob as a possible raw building material. **Construction and Building Materials**, v. 34, p. 28-33, 2012. doi:10.1016/j.conbuildmat.2012.02.014.

PUETTMANN, M. E.; RICHARD, B.; HUBBARD, S.; JOHNSON, L.; LIPPKE, B.; ONEIL, E.; WAGNER, F. G. Cradle-to-gate life-cycle inventory of US wood products production: CORRIM phase I and phase II products. **Wood and Fiber Science**, v. 42, p. 15-28, 2010.

PUETTMANN, M. E.; WILSON, J. B. **Glued laminated beams-Pacific Northwest and Southeast**. Phase I final report. Consortium for Research on Renewable Industrial Materials. CORRIM, Inc. Seattle: University of Washington, 2004.

REBTIZER, G.; EKVAL, T.; FRIESCHKNECHT, R.; HUNKELER, D.; NORRIS, G.; RYDBERG, T.; SCHMIDT, W-P.; SUH, S.; WEIDEMA, B. P.; PENNINGTON, D. W. Life cycle assessment, Part1: Framework, goal and scope definition, inventory analysis, and applications. **Environmental International**, 30, p. 721-739, 2003. doi:10.1016/j.envint.2003.11.005.

REICH-WEISER, R.; SIMON, T.; FLESCHUTZ, C.; YUAN, A.; Vijayaraghavan, H.; Onsrud. Metrics for green manufacturing. In: DORNFLED, D.A. (Ed.). **Green manufacturing: fundamentals and applications**. Springer, 2013.

RESEARCH AND MARKETS. **Amino resin market - by types (urea formaldehyde, melamine formaldehyde, melamine urea formaldehyde), applications (particle board, MDF, plywood, laminates, coatings) & geography – global trends & forecasts to 2018**. Markets and Markets, 2013. 268 p.

RIVELA, B.; MOREIRA, M. T.; FEIJOO, G. Life-cycle inventory of medium density fiberboard. **The International Journal of Life Cycle Assessment**, v. 12, p. 143-150, 2007. doi:10.1065/lca2006.12.290.

RIVELA, B.; HOSPIDO, A.; MOREIRA, T.; FEIJOO, G. Life cycle inventory of particleboard: a case study in the wood sector. **The International Journal of Life cycle Assessment**, v. 11, p. 106-113, 2006. doi: 10.1065/lca2005.05.206.

SANTOS, M. F. N.; BATTISTELLE, R. A. R.; BEZERRA, B. S.; VARUM, H. S. A. Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse (*Saccharum* spp.) and pine wood shavings (*Pinus Elliottii*). **Journal of Cleaner Production**, v. 64, p. 345-355, 2014. doi:10.1016/j.jclepro.2013.06.039.

ROSENBAUM, R. K.; BACHMANN, T. M.; GOLD, L. S.; HUIJBREGTS, M. A. J.; JOLLIET, O.; JURASKE, R.; KOEHLER, A.; LARSEN, H. F.; MACLEOD, M.; MARGNI, M.; MCKO-

NE, T. E.; PAYET, J.; SCHUHMACHER, M.; VAN DE MEENT, D.; HAUSCHILD, M. Z. USEtox — the UNEP/SETAC – consensus model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. **The International Journal of Life Cycle Assessment**, v. 13, p. 532-546, 2008. doi: 10.1007/s11367-008-0038-4.

SCHWINLE, J. Wood & other renewable resources: a challenge for LCA. **The International Journal of Life Cycle Assessment**, v. 3, p. 141-142, 2007. doi:10.1065/lca2007.04.326.

SEARCHINGER, T. D.; HAMBURG, S. P.; MELILLO, J.; CHAMEIDES, W.; HAVLIK, P.; KAMMEN, D. M.; LIKENS, G. E.; LUBOWSKI, R. N.; OBERSTEINER, M.; OPPENHEIMER, M.; ROBERTSON, G. P.; SCHLESINGER, W. H.; TILMAN, G. D. Fixing a critical climate accounting error. **Science**, v. 326, n. 5952, p. 527-528, 2009. doi:10.1126/science.1178797.

SILVA, D. A. L.; ROCCO LAHR, F. A.; GARCIA, R. P.; FREIRE, F. M. C. S.; OMETTO, A. R. Life cycle assessment of medium density particleboard (MDP) produced in Brazil. **The International Journal of Life Cycle Assessmen**t, v. 18, n. 7, p. 1404-1411, 2013. doi: 10.1007/s11367-013-0583-3.

SILVA, D. A. L.; ROCCO LAHR, F. A.; PAVAN, A. L. R.; SAAVEDRA, Y. M. B.; MENDES, N. C.; SOUSA, S. R.; SANCHES, R.; OMETTO, A. R. Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particleboard manufacturing. **The International Journal of Life Cycle Assessment**, v. 19, n. 10, p. 1767-1778, 2014. doi: 10.1007/s11367-014-0776-4.

SILVA, D. A. L.; ROCCO LAHR, F. A.; VARANDA, L. D.; CHRISTOFORO, A. L.; OMETTO, A. R. Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil. **Journal of Cleaner Production** (in press), 2015. doi:10.1016/j.jclepro.2014.03.007.

TEIXEIRA, C. E.; SARTORI, L.; FINOTTI, A. R. Comparative environmental performance of semi-trailer load boxes for grain transport made of different materials. **The International Journal of Life Cycle Assessment**, v. 15, p. 212-220, 2010. doi:10.1007/s11367-009-0138-9.

THOEMEN, H.; IRLE, M.; SERNEK, M. **Wood-based panels: an introduction for specialists.** London: Brunel University Press, 2010.

VARANDA, L. D.; NASCIMENTO, M. F.; CHRISTOFORO, A. L.; SILVA, D. A. L.; ROCCO LAHR, F. A. Oat hulls as addition to high density panels production. **Materials Research**, v. 16, p. 1355-1361, 2013. doi:10.1590/S1516-14392013005000131.

WENZEL, H.; HAUSCHILD, M. Z.; ALTING, A. **Environmental assessment of products. Methodology, tools and case studies in product development**. Dordrecht: Kluwer Academic. V.1, 1997.

WERNER, F.; ALTHAUS, H-J.; RICHTER, K.; SCHOLZ, R. W. Post-consumer waste wood in attributive product LCA: context-specific evaluation of allocation procedures in a functionalistic conception of LCA. **The International Journal of Life Cycle Assessment**, v. 12, n. 3, p. 160-172, 2007. doi:10.1065/lca2006.05.249.

WERNER, F.; NEBEL, B. Wood & other renewable resources. **The International Journal of Life Cycle Assessment**, v. 12, n. 7, p. 462-463, 2007. doi:10.1065/lca2007.10.362.

WERNER, F.; RICHTER, K. Wooden building products in comparative LCA. **The International Journal of Life Cycle Assessmen**t, v. 12, p. 470-479, 2007. doi:10.1065/lca2007.04.317.

WILSON, J. B. Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. **Wood and Fiber Science**, v. 42, 2010.

WILSON, J. B.; DANCER, E. R. **Laminated veneer lumber - Pacific Northwest and Southeast.** Phase II final report. Consortium for Research on Renewable Industrial Materials. CORRIM, Inc. Seattle: University of Washington, 2004.

WILSON, J. B.; SAKIMOTO, E. T. Gate-to-gate life-cycle inventory of softwood plywood production. **Wood and Fiber Science**, v. 37, p. 58-73, 2005.

NON-CONVENTIONAL PANELS PRODUCTS BASED ON AGRO-WASTES

Bwire Sturmius Ndazi
University of Dar es Salaam, Department of Mechanical and Industrial Engineering, Dar es Salaam, Tanzania.
E-mail: bndazi@udsm.ac.tz

Wilson Otieno Ogola
The Technical University of Kenya, Department of Mechanical and Mechatronics Engineering, Nairobi, Kenya.
E-mail: wilsonogola@hotmail.com

Joseph Varelian Tesha
University of Dar es Salaam, Department of Mechanical and Industrial Engineering, Dar es Salaam, Tanzania.
E-mail: jumapili.tesha@gmail.com

Elifas Tozo Bisanda
The Open University of Tanzania, Department of Physical Sciences, Dar es Salaam, Tanzania.
E-mail: bisanda56@gmail.com

ABSTRACT: The rising demand for wood-like construction materials, brought about by increasing concerns on the environment and the need to use renewable materials, has seen increasing research activities in the development of ligno-cellullosic materials based on agricultural wastes. Most agricultural activities produce wastes and residues that have potential as reinforcement and fillers to polymer and mineral based matrices. These materials exhibit wood-like properties with superior properties. Various crop residues, including rice hulls (husks), coffee husks, coir, sisal, and saw dust have been used to produce composite panels, their adoption have attracted applications in the construction and furniture industry, where, unlike timber, they can be moulded to any desired shape and size. The paper looks at recent trends in the development of these materials, and their potential to replace timber products as well as other non-degradable composite panels. Rice husks and coffee husks have been used as examples. The physical and mechanical properties of panels made from them have been tested, and most of their properties found to meet minimum requirements of standard particleboards.

Keywords: Agro-wastes. Characteristics. Panels. Properties.

1. INTRODUCTION

Agriculture is among the most vital economic activities in different parts of the world. This activity generates a considerable amount of crop residues or agro-wastes every year from cereals such as maize, rice, wheat, and other crops such as sugar cane, coffee, cotton, sisal, groundnuts, and coconut. Most of these residues and agro-wastes have traditionally been considered a nuisance to the public and the environment. Various disposal options to manage some of these residues have been considered. However, among the most prevalent practices include use of some of the residues or wastes as biomass energy and in particular cases some of it has been used for firing bricks. The largest portion of this renewable biomass is usually burnt in farms or public spaces causing environmental pollution and emission of toxic gases. Farm burning has led to extinction of some important biological macro and micro-organisms from the soil (TANGJUANK, 2011). In exceptional cases, the crop residues and agro-wastes generated annually also have been turned to compost manure or fed to animals.

Rapid increase of the world population coupled with high demand for wood consumption, wood scarcity and its vast applications, have made man to think of other alternative sources of raw materials for the furniture and construction industries. This is due to growing concerns over the sustainability of forest resources and impending extinction of thousands of tropical forest species. Use of crop residues and agro-wastes in producing non-conventional bio-composite materials is therefore geared to address these concerns by supplementing wood-based products in the construction industry. It is an opportunity where the shortage of wood products is addressed by producing large panels that cannot be readily obtained from existing solid wood while at the same time being efforts to add commercial value to crop residues and agro-wastes. Like any other lignocellulosic products, most of crop residues and agro-wastes are readily compostable (biodegradable), and so will their products be once they are no longer needed. The fact that most crop residues and agro-wastes are extracted from annual crops, which have very short maturity cycles, their use as feedstock for production of materials for construction not only creates additional revenue to famers but also reduces pollution and global warming that is generated by open air burning.

Being ligno-cellulosic, most crop residues and agro-wastes contain cellular components such as cellulose, hemicelluloses and lignin, like wooden materials. They can therefore be processed similar to wood-based materials into useful commercial products in the form of particleboards, insulation boards, and fibreboards for the construction sector. The fact that most of the crop residues and agro-wastes have low bulk density, products derived from them have better properties per unit weight than most of conventional materials like steel, bricks and glass (NDAZI, 2001; NDAZI; TESHA; BISANDA; 2006) Some of the residues and wastes, which have so far demonstrated this potential include rice husks (NDAZI et al., 2006; NDAZI et al., 2007; SHUKLA; OHJA; GUPTA, 1985; VASISHTH, 1974) coffee husk (BEKALO; REINHARDT, 2010; BISANDA; OGOLA; TESHA, 2003; OGOLA, 1997) bagasse (TABARSAA; ASHORIB; GHOLAMZADEHA, 2011) pineapple leaves (TANGJUANK, 2011), maize cobs (SCATOLINO; SILVA; MENDES, 2013), maize stalks (BABATUNDE, 2011; KARGARFARD; JAHAN-LATIBARI, 2011) rice straw (WANG; SUN, 2002), cotton stalks (KARGARFARD; JAHAN-LATIBARI, 2011). Wastes from other crops such as coir fibre (VAN DAM; MARTIEN; VAN DEN OEVER; KEIJSERS, 2004), coir pith (VISWANATHAN; GOTHANDAPANI, 1999), coconut husks (OLORUNNISOLA, 2009), oil palm residues (HASHI et al., 2012; LAEMSAK; OKUM, 2000) and many more others have also been reported. Sampathrajan et al. (1991) reported the properties of various crop residues such as rice straw, coconut pith, maize cobs, maize husks and ground nuts bonded by urea formaldehyde resin. Most of the boards were found to have properties suitable for interior applications.

Despite the above listed efforts in the processing of crop residues and agro-wastes into composite materials for construction, there are still a number of challenges that require attention in order to attain perfect utilization of these resources. The main requirement is to ensure that the products meet the minimum standard of quality level (YOUNGQUIST et al., 1997). One of the key challenging facts is that most crop residues and agro-wastes are heterogeneous and hence their physical and chemical characteristics vary significantly among different types depending on several factors such as agricultural practice and season, harvesting practice and season, geographical area, and rainfall pattern (ROWELL; HAN; ROWELL, 2000). Thus, the resulting properties are also influenced by the type of residue used (SAMPATHRAJAN; VIJAYARAGHAVAN; SWAMINATHAN, 1991) and more interestingly even by species of the same type of residue (SUEMATSU; OKUMA, 1993). This is why the type or form of residues and wastes used is important due to its significant impact on the properties and quality of resulting products (NDAZI; TESHA; BISANDA, 2006). Resource base availability amid competing demands for the same resource (KOOPMANS; KOPPEJAN, 1997) is another important aspect to be considered. The fact that some of the crop residues and agro-wastes have low bulk densities makes their transportation and storage difficult. More importantly, compatibility and interfacial properties requirement between the crop residues or agro-wastes in mineral or polymer matrices are of paramount importance in order to successfully produce products that meet at least the minimum quality and standards of comparable commercial wood-based products.

The earliest record of using non-conventional resources for construction dates back to the ancient Egyptians, 3000 BC, where straw was added to clay to produce bricks which were stronger and more durable for construction of Pyramids (NDAZI; TESHA; BISANDA, 2006). In recent years, large wood composite panels have been produced from sawmill wastes as a response to address two main challenges; disposal problem of large quantities of sawmill wastes which were generated and shortage of large diameter solid timbers (KOLLMANN; KUENZI; STAMM, 1975; KUBLER, 1977). This breakthrough has set a foundation for further research and development in the use of crop residues and agro-wastes for production of large composite panels.

This chapter briefly explains the opportunities and challenges of producing non-conventional composite panels from crop residues and agro-wastes as supplement to wood for the construction industry. It also presents the methodologies used for preparations and production of the composite panels and their standard tests. Composite panels developed from rice hull (or husks) and coffee husks have been presented as examples.

2. CHALLENGES IN THE APPLICABILITY OF AGRO-WASTES

2.1. RESOURCES AVAILABILITY

Wood as a conventional material for construction cannot survive longer the current human consumption pressure and demand due to rapid population increase. This has made man to think of other alternative sources of raw materials. Several research and development have revealed that non-wood crops residues and agro-wastes have the potential of supplementing wood where it has been prevalent. These light weight renewable sources have become important for production of composite materials for the building and construction industry. However, among the greatest challenges is the assurance of availability of resources in the midst of competing demands (KOOPMANS; KOPPEJAN, 1997). This brings the question on whether or not crop residues and agro-wastes generated are adequate enough to supplement wood in these potential areas. According to Bolton (1995), availability of crop residues and agro-wastes for any application depends on the use pattern of other available resources. The use patterns of crop residues and agro-wastes vary among countries depending on the most dominant factors among them being socio-economic, technological development, or political factors. According to Bolton (1995), these factors influence the amount of residues and wastes consummed and needed by each country to a large extent.

Along with the availability of resources there is also a challenge of scattered and unreliable information and database on actual quantities of annual crop and agro-wastes produced. Absence of this vital information has derailed efforts in quantifying how much resource is available to supplement wood for construction. According to the World Bank (2010), lack of the reliable crops production statistics is associated with the failure of many developing countries to have the capacity of collecting and disseminating the most basic production statistics, which existed in the 1970s. The available data may therefore be fragmented or fail to reveal the correct quantities of crop residues and agro-wastes that may be available. Table 1 shows the estimated world generation of major crops and their coresponding residues and wastes.

Table 1 – Estimated annual world generation of major agro-industrial wastes

Crop	Annual Production Quantity ($\times 10^3$ tonnes)	Type of Residue	Waste Factor (residue to product ratio)	Potential Quanity of Wastes Available ($\times 10^3$ tonnes)
Wood fibre	1,750,000	-	-	
Rice (Paddy)	568,914	Straw	1.757	999,587
		Hull	0.267	151,900
Wheat	65,000	Straw	1.750	113,750
Maize	70,893	Stalk	2.00	141,786
		Cob	0.273	19,354
		Hull	0.200	14,179
Coconut +copra	*40,000	Shell	0.650	26,000
		Husk	0.419	16,760
		Pith	0.700	11,732
		Fibre	0.300	5,028
Sugar cane	265,865	Bagasse	0.300	79,759
		Tops	0.290	77,101
Coffee	8,280	Hull	0.250	2,070
Cotton	20,000	Stalks	2.200	44,000
Pineaple	19,488	Fibre	1.8	35,075

van Dam et al., 2004 c CIMMYT mega-environment database; C.R. Dowswell, R.L. Paliwal and R.P. Cantrell, Maize in the Third World, Boulder, Colorado, Westview Press, 1996.

The availability of crop residues and agro-wastes can be estimated from the amount of crop produced as shown in Table 1. The residue to product ratio method (RPR) has been used by previous authors to quantify the amount of residues generated available from annual crops as indicated in Akinbomi et al., (2014). Despite the limitation of this method, which may be associated with variations in crop varieties, weather, crop type, water availability, soil fertility and farming practices, it can be applicable in multi-cropping systems (KOOPMANS; KOPPEJAN, 1997).

2.2 CHARACTERISTICS OF CROP RESIDUES AND AGRO-WASTES

In order to produce products that meet minimum quality and standard of materials for construction, both the residues and agro-wastes together with binding materials must be able to interact physically and more importantly chemically in order to generate strong bonds at the fibre-matrix interfaces of the composite materials. The interface properties determine most of the properties of any composite materials because this is where stresses are shared and transferred among the reinforcing or filler components while propagating through the matrices. Effective bonding at the interface is thus vital and can be influenced to large extent by physical and chemical characteristics of the crop residues and agro-wastes as well as the processing conditions.

2.2.1 Chemical Characteristics

Most crop residues and agro-wastes, like wood, contain cellulose, lignin and hemicelluloses as their major cell wall components. Variations in chemical characteristics of agricultural fibres have been reported by different authors. The most challenging fact is that the chemical characteristics of any agricultural fibres, whether wood or non-wood resources, not only vary among different types but also vary within the same type of resource and species due to many factors including the agricultural practice and season, harvesting season, geographical area and rainfall pattern (ROWELL; HAN; ROWEL, 2000). Table 2 shows the range of chemical compositions of some crop-residues and agro-wastes reported by various authors.

Table 2 – Major chemical compositions (%) of selected non-wood agrofibres

Fibre Source	Cellulose	Lignin	Pentosan	Ash	Silica
Rice straw	32-47	5-24	-	12.4	9.7
Rice hull	28 - 48	12 – 17.2	23 - 28	15.0 - 20	9 - 14
Wheat straw	29 - 51	8 - 21	26 - 32	4.5 – 10.1	3 - 7
Cotton fibre	89 - 96	0.7- 1.6	1 - 3	0.8 – 2.0	-
Cotton stalks	31.1- 45	8.2 - 30.1	22.1	4.3 - 6.0	2.5
Oat	31 - 48	16 - 19	27 - 30	2 - 5	0.5 – 4.0
Baggase	32 - 48	19 - 24	27 - 23	1.7 – 5.0	0.7
Banana/abaca	56 - 63	7 - 9	15 - 17	1 - 3	-
Sisal	43 - 62	7 - 9	21 - 24	0.6 – 1.0	-
Hemp	57 - 77	9 - 13	14 - 17	0.8	-
Ramie	87 - 91	-	5 - 9	-	-
Coir (fibre)	36 - 43	41 - 45	-	-	-
Coniferous	40 -45	26 -34	7 -14	< 1	-
Deciduous	38 -49	23 -30	19 - 26	< 1	-

Cited by Corradini et al. (2006); Ndazi et al. (2006); Sarkar et al. (2012); Tutus et al. (2010).

2.2.2 Physical Characteristics

Physical characteristics such as moisture content, morphology and surface characteristics of crop residues and agro-wastes are very important when considering their applications in construction. A moisture content ranging between 5 and 12% is recommended (KOLLMANN; KUENZI; STAMM, 1975) to avoid generation of excessive moisture which can detrimental to the interface bonding process (DINWOODIE, 1997). Crop residues and agro-wastes exist as particles and fibres. Particles include all kinds of non-fibrous crop residues and agro-wastes such as flakes, strands, wafer, strands or chips which may be natural or formed by pre-processing. The most important geometrical characteristics of crop residues and agro-wastes are particle size and particle shape. The particle size and shape not only define the type of composite panels produced but also determine their quality. Names like strandboards, fiberboards, flakeboards, waferboards, chipboards and particleboards explain the form of furnish particulate used to produce them. Fine particles have a tendency to absorb considerable amounts of binders compared to course particles. Oversized particles increase porosity due to large inter-particle distances especially when the mat is imperfectly coated by the resin and it has not been consolidated effectively. The proportion of fine particles should be limited to around 6% (KOLLMANN; KUENZ; STAMM, 1975) to avoid agglomeration and inhomogeneous distribution of matrix within the particles (DINWOODIE, 1997) and thus generate large quantity of voids within the composite panels. Smaller particles are preferred for smooth surface when used on the top while larger particles are used in the core to enhance strength. Volumetric content of voids in composite panels can be estimated from Equation 1.

$$V_o = 1 - \varrho_c \left(\frac{W_m}{\varrho_m} - \frac{W_f}{\varrho_f} \right) (\%) \tag{1}$$

where:

V_o = voids in %;

ρ = density kg/m^3, subscripts c, f and m stand for composite, fibre and matrix respectively

W = weight (kg).

Particle geometry, orientation, and packing have significant influence on board properties (BODIG; JAYNE, 1982). The particle geometry has been reported to have remarkable contribution to the properties of composite panels. For example, flaked particles (high flake length) have significant influence on maximum strength of composite panels as it is for fibres with higher aspect ratio (NISHIMULA; AMIN; ANSELL, 2001). The orientation of the particles affect the isotropy of the system especially for irregular particles during processing at which there is a possibility of inducing orientations of the particles. The modulus of rupture (MOR) and the modulus of elasticity (MOE) of flakeboards and the waferboards have been improved by aligning the surface flakes in the direction of the applied stress. However, the internal bond strength and thickness swelling are not affected (MCNATT; BACH; WELLWOOD, 1992).

The surface texture and characteristics of crop residues and agro-wastes play vital roles on physical interactions between the matrix and reinforcement or filler. Some mechanical bonding has been proposed between rough surfaces of fillers or reinforcements and matrices (BISANDA; ANSELL, 1991). However, the ultimate contribution of properties of reinforcing components to the overall quality and performance of the products is more attributed to chemical interaction with the matrix than to physical interactions.

2.3 PREPARATION, INTERACTION AND PRODUCTION CONDITIONS AND TECHNIQUES

In order to produce quality panel products that meet minimum standards similar to conventional wood-based products, crop residues and agro-wastes as well as the binding materials must be chemically and physically compatible in order to produce strong bonds at their interfaces. Other important factors are structure, processing and composition. Youngquist et al. (1997) illustrated this relation diagrammatically as shown in Figure 1. The mechanisms of interfacial bonding and the measures to improve it have been the main focus of all efforts directed to produce composite materials. Loads absorbed by matrices are shared among fillers or reinforcing components through the interface. Processing of composite panels therefore involves facilitating formation of efficient mechanical and chemical bonds at the interfaces.The most important factors influencing interfacial bonding are:

i) Chemical affinity between the binding material and the reinforcing phase or filler,
ii) Physical properties and surface condition of the reinforcing phase or filler,
iii) Preparations of the reinforcing phase
iv) Processing methods and conditions.

2.3.1 Feedstock Preparations

Preparations of crop residues and agro-wastes can involve change of their geometry, surface topography and surface chemistry. The geometrical and chemical characteristics of crop residues and agro-wastes determine the preparation method required. Geometry can be changed by cutting, milling, shredding, steam explosion, or by chemical treatment depending on physical change desired. For example, steam treatment (NDAZI et al., 2007; GERARDI; MINELLIN; VIGGIANO, 1998) and thermo-chemical treatments such as soda cooking (NDAZI; KARLSSON, 2010) have been found to be effective in producing remarkable physical and chemical changes including the bulk structure (NDAZI; KARLSSON, 2010) as shown in Figure 2. A series of processes may be carried out to produce materials with much more improved properties. For example, combined mechanical and steam treatments of cotton and maize stalk were observed to improve the properties of medium density fibreboards (MDF) to the level of standard MDF (KARGARFARD; JAHAN-LATIBARI, 2011). In other studies combined preparations including milling and steam explosion of various products such as oil palm front (HASHIM et al., 2012; LAEMSAK; OKUMA, 2000) and coconut husk (VAN DAM et al., 2004) were observed to enhance chemical reactivity of biomass feedstock. Through these combined treatments it was possible to produce products with properties exceeding the minimum requirement of standard panel.

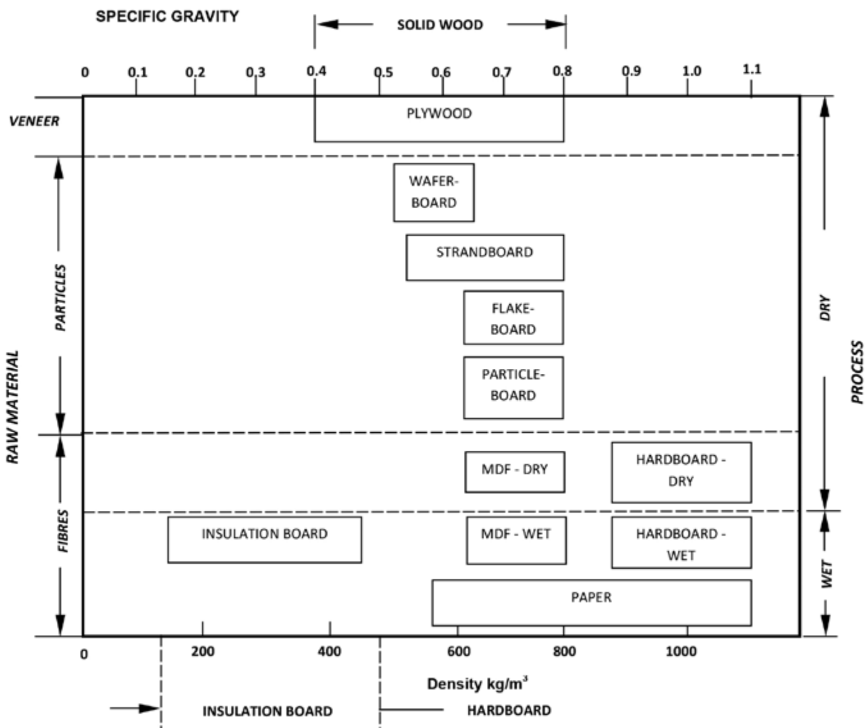


Figure 1 – Properties-structure (particle size) - process relation: Youngquist et al. (1997)

2.3.2 Compatibility and Interactions

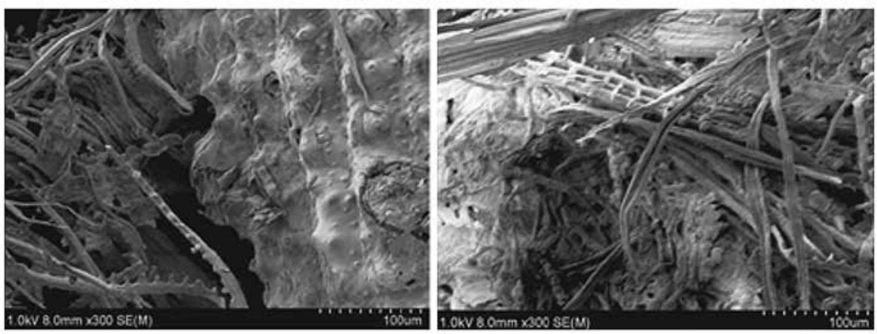
The requirements of the substrate and matrix for effective bonding depend on the type of substrates and binder used as well as the interaction between them. According to previous studies (NDAZI; TESHA; BISANDA, 2006), the binder should cover a large area so as to resist any internal stresses resulting from moisture stress change. More importantly, the chemistry and topography of surfaces should facilitate the formation of strong interface bonding when the binder penetrates to produce stronger bonds. Binder penetration therefore depends on many factors including viscosity, chemical compatibility, and physical condition of the surface (DINWOODIE, 1997; DUNKY, 2000)

The quality of bond formed in polymer bonded panel products depends on the amount of binder used, resin viscosity and flowability, surface wettability, surface roughness and compatibility with the resin. In order to achieve better interaction, the binder should also be physically compatible with the surfaces. Sometimes rough surfaces have been believed to contribute to chemical reaction (HOUWINK; SALOMON, 1965) apart from supporting mechanical interlock. Where wood furnishes has been partly added to replace part of the non-wood furnish like cotton (KARGARFARD; JAHAN-LATIBARI, 2011) and rice hull (NDAZI, 2001) improvement of some properties has been reported.

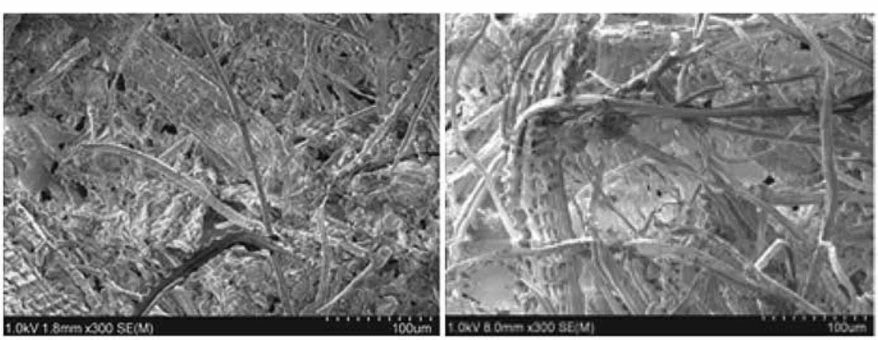
2.3.3 Production Methods and Conditions

Production conditions have very significant impact on the quality of the composite panel produced. Most of crop residues and agro-fibres have low bulk density. They therefore require high compaction pressure during consolidation in order to reduce porosity in the product. They require pressing at different pressures with (KOLLMANN; KUENZII; STAMM, 1975) or without temperatures (BABATUNDE, 2011) depending on the matrix used, sometimes for longer duration in order to enhance the completion of the interface binding process. These pressing variables have been found to be interdependent and closely related to the density of composite panels (GRAHAM; HIZIROGULU, 1998). When composite panels are produced from non-mineral binders such as liquid resin and plastics, they require sufficient pressure and heat for a specified duration to meet the required properties. A combination of these parameters is very crucial due their different influences on the interface bonding process during curing. Higher temperatures facilitate thermo-chemical reaction and enhances complete cure especially for thermosetting binders. High pressure enhances binding stresses at the interface (SHUKLA; OHJA; GUPTA, 1985). However, with liquid binders such phenol formaldehyde, urea formaldehyde and tannin formaldehyde when consolidated at high pressure and high temperature the trapped steam in the locked-in internal stresses can lead to a catastrophic delamination of interface bonds upon releasing the pressure (DUNKY, 2000). In that regard the amount of moisture in the particle–resin mixture must be limited for an effective hot-pressing process (KOLLMANN; KUENZI; STAMM, 1975; DUNKY, 2000).

Most common methods of producing composite materials for construction from crop residues and agro-wastes include compression moulding and casting techniques especially when mineral and thermosetting binders are used. Other reported methods include extrusion, which is most applicable to thermoplastic matrices. When different profiles of products are required, for example production of corrugated roofing sheets, special moulds may be prepared to suit the needs.



(a)



(b)

Figure 2 – SEM of the soda cooked rice husk 170°C with (a) 5% and 7.5% NaOH (b) 10% and 13 %NaOH, respectively: Ndazi and Sigbrit (2010)

3. CHARACTERIZATION METHODS AND PROPERTY REQUIREMENTS

In order to determine whether or not the composite panels produced meet or pass minimum performance and quality requirements of existing conventional products like particleboards, waferboards, fiberboards medium density fiberboards, hardboards, ceiling boards and strandboards, standard tests are conducted in additional to any other complementary and confirmatory tests. Three major categories of standard tests for evaluating performances of composite panels for construction are dimensional tests, physical property tests, and mechanical property tests. These tests have been well described in various standards and literature on composite products from wood and non-wood fibres (YOUNGQUIST et al., 1997; ROWELL; HAN; ROWELL, 2000). Other tests which can be categorized as application tests such as nail and screw holding tests, and chemical tests can also be conducted.

3.1 DIMENSIONAL TESTS

Several standards have developed requirements for measuring dimensional properties and requirements for composite panels. They define size, thickness, squareness, and straightness tolerance limits.

3.2 PHYSICAL PROPERTY TESTS

Standard tests for physical properties include moisture content tests, density, and water absorption tests. Linear expansion and other tests such as thermal insulation properties can also be conducted if the application requires so.

3.2.1 Moisture Content

This test is aimed at establishing whether the produced composite panel meets the recommended minimum moisture content. Different composite panels have different minimum moisture requirement content. Important part of this the test specimen preparation requirement. This information is normally spelt out in a particular standard, which is in use by the person conducting the test. The basic formula for determining moisture content M (%) is:

$$M = \frac{W_e - W_i}{W_i} \ (\%) \tag{2}$$

where:
M = moisture content in %;
W = weight (kg);
Subscripts e and i stand for final and initial, respectively.

3.2.2 Density

Densities are also evaluated based on existing standards. It one of the most important test that should be conducted due to the fact that density virtually affects all properties of the material. The density is determined using the full thickness of the composite with the dimensions and weights measured to an accuracy specified in a particular reference standard based on the dry weight of the sample. The basic formula for density evaluation is:

$$\rho_c = \frac{W_c}{V_c} \ (kg / m^3) \tag{3}$$

where:
V = volume of in m^3;
W = weight in kg;
Subscript c stands for composite panel.

3.2.3 Water Soak Tests

Water soak also known as water immersion tests are used for evaluating physical stability of the product against water uptake, the fact that products produced contain hydrophilic components and can also be porous. Standard tests are usually conducted for 1 hr, 2 hrs and 24 hrs but can be extended if the interest is to study the water uptake kinetics. The test also permits evaluation of dimensional stability due to water absorption. Test specimen sizes and required preparations and maximum values for each product are usually specified in a particular reference standard used.

Determination of weight changes and dimensional stability also known as thickness swelling (TS) in other standards uses Equation 4.

$$TS = \frac{T_e - T_i}{T_i}\ (\%) \tag{4}$$

where:
T = thickness (mm) or weight (g);

3.3 STATIC MECHANICAL PROPERTIES TESTING

Mechanical properties requirements and testing procedure have been well developed in various standards for composite panels. Mechanical tests can be dynamic or static properties tests. Since these products are highly susceptible to moisture absorption, their mechanical properties are significantly influenced by moisture content. In order to control the influence of moisture content on the mechanical properties, test specimens are usually prepared and conditioned to constant moisture content in conditioned chambers of constant temperature and relative humidity. The tests can be extended to a range of moisture content and humidity if the goal is to evaluate their influence on the mechanical properties.

When it is required to test the stability against exposure to aggressive conditions, accelerated aging tests can be conducted for recommended aging cycles. One method includes the boil water test where a specimen is submerged into the boiling water prior to testing. The basic static mechanical properties investigated under this test are static bending, tensile strength, dent and impact resistance.

3.3.1 Static Bending

This test is conducted to determine the strength (modulus of rupture, MOR) and the stiffness also known as the modulus of elasticity (MOE) of a composite specimen subjected to a three or four point bending configuration. Important to this test configuration is the span to thickness ratio of the test specimen. Various standards specify a fixed the span (L) to thickness (T) ratio L/T in order to avoid significant error in the computation of the apparent stiffness from the test (NDAZI, 2001). For example ASTM recommended 24 while in BS it is 25. The MOE and MOR are determined using Equations 5 and 6.

$$MOR = \frac{3PL}{2BT^2} \left(N / mm^2\right) \tag{5}$$

where:
P = applied bending load N;
B = composite panel width in mm.

$$MOE = \frac{\Delta PL^3}{4BT^3 \Delta Y} \left(N / mm^2\right) \tag{6}$$

where:
ΔP = load at the proportionality limit N;
ΔY = slope at the proportionality limit.

3.3.2 Tensile Strength

There are two types of tensile strength tests set-up: one is measured parallel to the face of the specimen and the other perpendicular to the face. The latter is also known as the internal bond strength test. Specimens considered in the evaluation are those which did not fail within the grips.

The tensile strength tests evaluate indirectly the interfacial properties and can tell the bonding properties of composite panels.

Tensile strength parallel-to-face measures the resistance of a composite panel when pulled apart parallel to its surface. Maximum tensile strength is evaluated by dividing the maximum fracture load by the cross-sectional area (width × thickness) of the test specimen of specified dimensions.

Tensile strength perpendicular-to-face measures the internal bond strength or the resistance of a composite panel to fracture when it is pulled apart in the direction perpendicular to its flat surfaces. The recommended square specimen is bonded with an appropriate adhesive between two steel plates or appropriate blocks of equal dimensions to the specimen. The internal bond strength is calculated by dividing the maximum fracture load by the cross-sectional area of the surface perpendicular to the direction of the pull (Equation 7).

$$IB = \frac{P_{max}}{A} \left(N / mm^2\right) \tag{7}$$

where:
P_{max}= maximum load N;
A = area in mm^2.

3.4 SUPPLEMENTARY/COMPLEMENTARY AND APPLICATION TESTS

These are tests required to evaluate other properties that are relevant to composite panels during use in different environment or for different purposes. They include hardness and impact resistance tests, fasteners holding strength and withdraw resistance tests and chemical tests.

3.4.1 Face Hardness and Impact Resistance

These tests are conducted to evaluate the resistance of composite panels against indentation or damage in service struck by moving objects. Details about these tests can be found in a particular reference standard that will be used.

3.4.2 Fastener Holding Strength and Withdraw Resistance

Test procedures for fastener holding strength and withdrawal resistance have been described in various standards. The test is important for applications where a composite panel requires screw and nail fastening. It is intended to measure the capability of the composite panel to be fastened by screws and nails and the withdraw resistance. It is the test which is required for composite panels that are used in structural applications. Specimen preparations and evaluation procedures can be obtained from relevant standards in use. The tests under this group include edge and face screw holding tests which are aimed at determining the capacity of the composite panel to hold the screw firmly. Other similar tests determine the capacity of the composite panel to resist nail withdrawal without shattering. Specific test requirement and procedures have been described in various standards and literatures.

3.4.3 Chemical Tests

Chemical tests are conducted to evaluate chemical characteristics and emission of composite panels that may be relevant to particular applications. They include procedure to determine the amount of extractives when the panel is in use. The test is more relevant for formaldehyde bonded panels where a long-term exposure and the amount of formaldehyde released can affect end users of the products.

4. PROPERTIES OF SELECTED COMPOSITE PANELS

4.1 COMPOSITE PANELS PRODUCED FROM RICE HUSK

The composite panels were produced from modified and unmodified rice husk bonded with different types of binders. Tannin formaldehyde PF was used as base resins and resins. The rice husks feedstock was prepared by crushing, chemical treatment using NaOH at different concentrations and steam treatment. All the panel boards were produced by compression moulding at high pressure and high temperatures. The quality and performance of the products were evaluated against BS standards using standard testing procedures of basic physical and static mechanical tests described in Section 3.

4.1.1 Influence of Density and Sawdust

Figures 3 to 5 show the influence of density on the impact strength and flexural properties of the rice husk composite panels bonded with 16% tannin-formaldehyde based resin. The results show a good linear correlation (R=0.9) between the impact strength and the density of the three types of composite panels produced from crushed rice husk (BRH), untreated rice husk (URH) and URH containing + 30% sawdust (SD). The increase in the impact strength with respect to the density of the panel was attributed to improved binding stresses at the interface during pressing the composite panels at higher densities as explained in previous studies (SHUKLA; OHJA; GUPTA, 1985). The panel products were produced from rice husk bonded with tannin-formaldehyde based resin. Similar trends are depicted by the flexural strength (MOR) and flexural stiffness (MOE), which also explain further the influence of increased binding stresses at higher densities during pressing on the flexural properties.

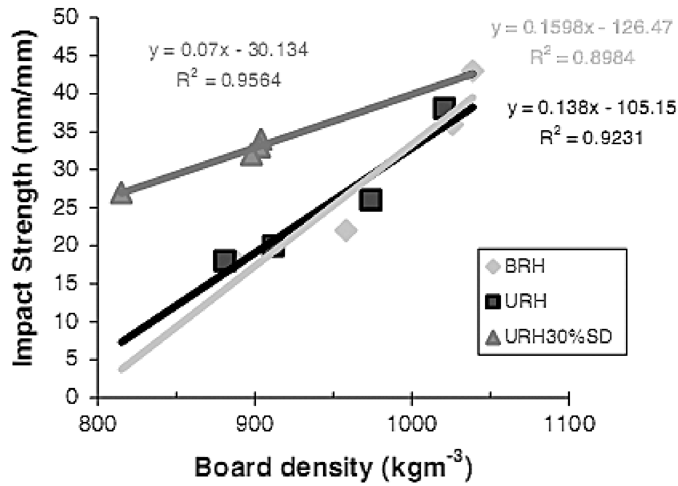


Figure 3 – Impact strength as a function of board density for broken rice husk (BRH), untreated rice husk (URH) and untreated rice board husks with 30% sawdust (URH + 30%SD).
Ndazi et al. (2006)

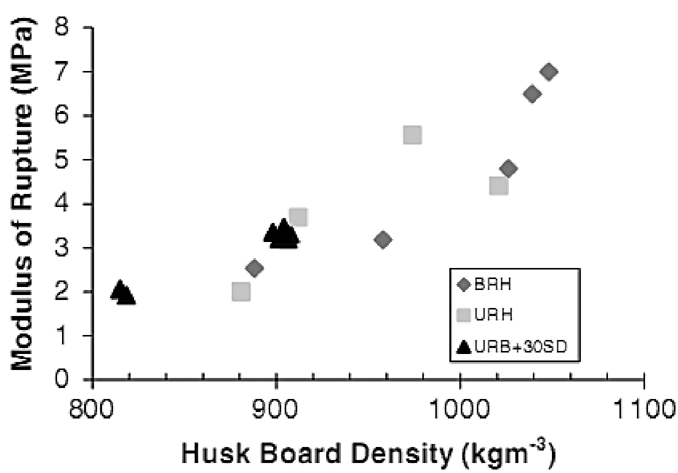


Figure 4 – Flexural strength (MOR) as a function of board density for broken rice husks (BRH), untreated rice husks (URH) and untreated rice husks with 30% sawdust (URB + 30%SD).
Ndazi et al. (2006).

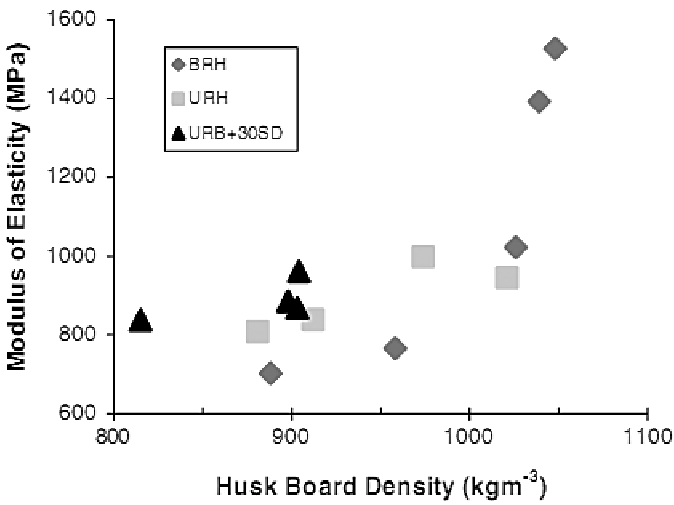


Figure 5 – Flexural stiffness (MOE) as a function of board density for broken rice husks (BRH), untreated rice husks (URH) and untreated rice husks with 30% sawdust (URB + 30%SD). Ndazi et al. (2006).

A summary of the mechanical and physical properties of crushed rice husks composite panels bonded with 16% tannin-formaldehyde based resin with respect density variation is given in Table 3 below. The results have been compared with equivalent particleboard standards in Table 4, which demonstrate that pressing at higher densities than 1000 kgm^{-3} is necessary to attain the minimum quality and standard of conventional wood boards.

Table 3 – Influence of composite panel density on internal bond (IB) strength and impact strength (IS)

Property	Actual Board Density (kgm^{-3})				
	739	**958**	**1026**	**1050**	**1079**
IB (MPa)	0.07	0.07	0.07	0.11	0.20
IS (mm/mm)	16	22	28	34	43

Table 4 – Average mechanical properties of the best rice husks composite panels bonded with tannin-formaldehyde resin

Composite Panel Type	Fexural Strength, MOR (MPa)	Flexural Modulus, MOE (MPa)	IB Strength (MPa)	Impact Strength (mm/mm)
Untreated rice husks (URH)	5.41	1039	0.04	36
Untreated rice husks with 30% sawdust (URH + 30%SD).	3.40	989	0.04	34
Crushed rice husks (BRH),	7.00	1527	0.20	43
Minimum as per BS5569: Part 2 1989	13.00	2500	0.34	34

4.1.2 Influence of Chemical and Physical Modifications

In this study steam curing, alkali treatment and crushing of the rice husks were employed to improve the surface characteritsics of the rice husks and their subsequent interaction with phenol formaldehyde (PF) resin with ultimate goal of improving the performance of the composite panels. The rice husk was collected from rice grain millers in Tanzania. Steam curing was accomplished by passing saturated steam heated at 110, 120, 130 and 140°C through the rice husks in the steam reactor for 1 hr. Limited alkali treatment was done using 1%, 2%, 45, 6% and 8% NaOH at room temperature for 24 hrs. Physical modification was accomplished by crushing the rice husks in a hammer mill to give the particle size distribution as shown in Table 5.

Table 5 – Particle size distribution type of crushed rice husks

Type of Rice Husk	Particle Size Range (%)			
	≥ 2.0 mm	2.0 – 1.0 mm	1.0 – 0.5 mm	≤ 0.5 mm
Untreated (URH)	77.8	16.2	4.2	1.8
Crushed (BRH-A)	37.6	37.6	15.3	9.5
Crushed (BRH-B)	3.2	51.6	23.2	22.0

Alkali treatment of cellulosic fibres with sodium hydroxide (NaOH) has been employed widely for improving the fiber–matrix interface bonding (MOHANTY; KHAN; HINRICHSEN, 2000; MWAIKAMBO; ANSELL, 2002). It is believed to remove natural surface fats and waxes on cellulose fibres, thus exposing physically active and chemically reactive surfaces with chemical groups suggested previously (MOHANTY; KHAN; HINRICHSEN, 2000; SREEKALA; THOMAS, 2003).

The composite panels were prepared by spraying PF resin on the rice husk followed by pressed at on a 50-ton hot-hydraulic press for 13 min at 170°C to produce composite panels of 300 mm by 300 mm, with a target density of 1000 kg and thickness of 6 mm.

4.1.2.1 Effect of Treatment on Composite Panel Properties

Partial removal of carbonyl and silica groups from the surface of rice husks by alkali treatment improved the rice husks-PF resin interfacial bonding as revealed by an increase in the modulus of elasticity to 2.76 ± 0.28GPa, which is slightly above the minimum value of 2.1GPa for particleboards recommended in EN312-3 standard. This improvement was attributed to improved chemical and physical interaction at the interface leading strong interfcial bonding between the treated rice husks surfaces and the PF resin as shown in Table 6 below. The internal bond strength fell below the recommended minimum value in EN312-2 for general purpose boards. However, the flexural strength (MOR) met the recommended minimum value in EN312-2. Thickness swelling after 2 hours soak could not pass the recommend value in EN312-5.

Table 6 – Average properties of composite panel from alkali treated rice husks

Property	NaOH Treatment (%)						Min per EN312	
	Untreated	1	2	4	6	8		
IB (MPa)	0.07	0.22	0.26	0.23	0.22	0.09	0.28	EN312-2
MOR (MPa)	9.3	14.9	20.3	20. 9	24.1	18.1	12.5	EN312-2
MOE (MPa)	2070	2342	2763	2546	2702	2096	2100	EN312-3
TS -2hr (%)	11.9	14.5	26.1	24.1	20.1	76.3	16.0	EN312-5

Analysis of variance indicated that the modification methods had significant influence on all the properties of particleboards (NDAZI, 2006). Although steam curing did not reaveal any remarkable changes on surface chemistry and surface topography of rice husks like alkali treatment as revealed in Figures 6 and 7, it demonstrated the best mechanical properties with respect to an increase in steam curing temperatures (NDAZI, 2006). PF-bonded composite panels which were produced from rice husks cured at 140°C passed the minimum standard values recommended in EN312 as shown in Table 7. However, unlike the NaOH treated rice husks which exhibited lower thermal stability, steam treated rice husks had higher thermal stability a clear indication that the rice husks did not undergo chemical and physical degradation like the NaOH treated rice husk (NDAZI, 2006). These complementary tests provided useful corelation on structure–property relation in understanding the performance of the modified rice husks.

Table 7 – Average properties of composite panel from steam cured rice husks

Property	Steam Curing Temperature (°C)					Min. per EN312	
	Untreated	110	120	130	140		
IB (MPa)	0.07	0.22	0.24	0.24	0.31	0.28	EN312-2
MOR (MPa)	9.3	12.6	13.5	14.4	13.7	12.5	EN312-2
MOE (MPa)	2070	2411	2635	2934	2746	2100	EN312-3
TS -2hr (%)	11.9	9.6	22.8	20.9	9.2	16.0	EN312-5

Crushing of rice husks can improve the properties of rice husk feedstock, e.g. the bulk density (NDAZI, 2001), in the manufacture of composite panels as shown in Section 4.1.1. Among its advantages is the remarkable reduction of residual expansion of rice husk after compression (NDAZI, 2006). This reduction of the residual expansion (spring back) minimizes delamination or debonding at the fiber–matrix (DINWOODIE, 1997). Since denser particles require lower compaction they have been found to exhibit higher dimensional stability after compression (NDAZI, 2006). The only major drawback of crushed rice husk is when there is a high proportion of fine particles (BRH-B), which can lead to disproportionate distribution and consuption of resin within the particles (VASISHTH,

1974) and thus affecting the quality of the product as shown in Table 8. The summary results in Table 8 indaictes that some of the composite panel passed the standard values of EN312.

Table 8 – Average properties of composite panel from crushed rice husks

Property	Particle Size Distribution Type			Min per EN312	
	Untreated	BRH-A	BRH-B		
IB (MPa)	0.07	0.20	0.24	0.28	EN312-2
MOR (MPa)	9.3	10.5	12.6	12.5	EN312-2
MOE (MPa)	2070	2337	2201	2100	EN312-3
TS -2hr (%)	12.0	14.0	19.5	16.0	EN312-5

4.1.3 Conclusions

Rice husks have the potential for production of panels for construction industry and furniture application. However, in order to effectivey use this potential it has been observed that the rice husks must be modified physically, chemically or both using mechanical methods, chemica treatment and thermal processes. Physical, chemical and steam curing can improved the interaction of rice husks when used for production of composite panels using phenolic and tannin resins. The enhanced interaction improves the physical and mechanical properties of the resulting panels making them comparable to some of the standard partiboards specifies in BS5569: Part 2 1989 and EN312.

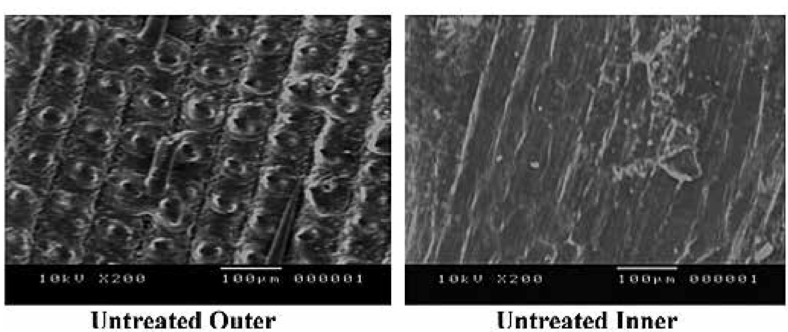


Figure 6 – SEM of the outer an inners surfaces of untreated rice husks

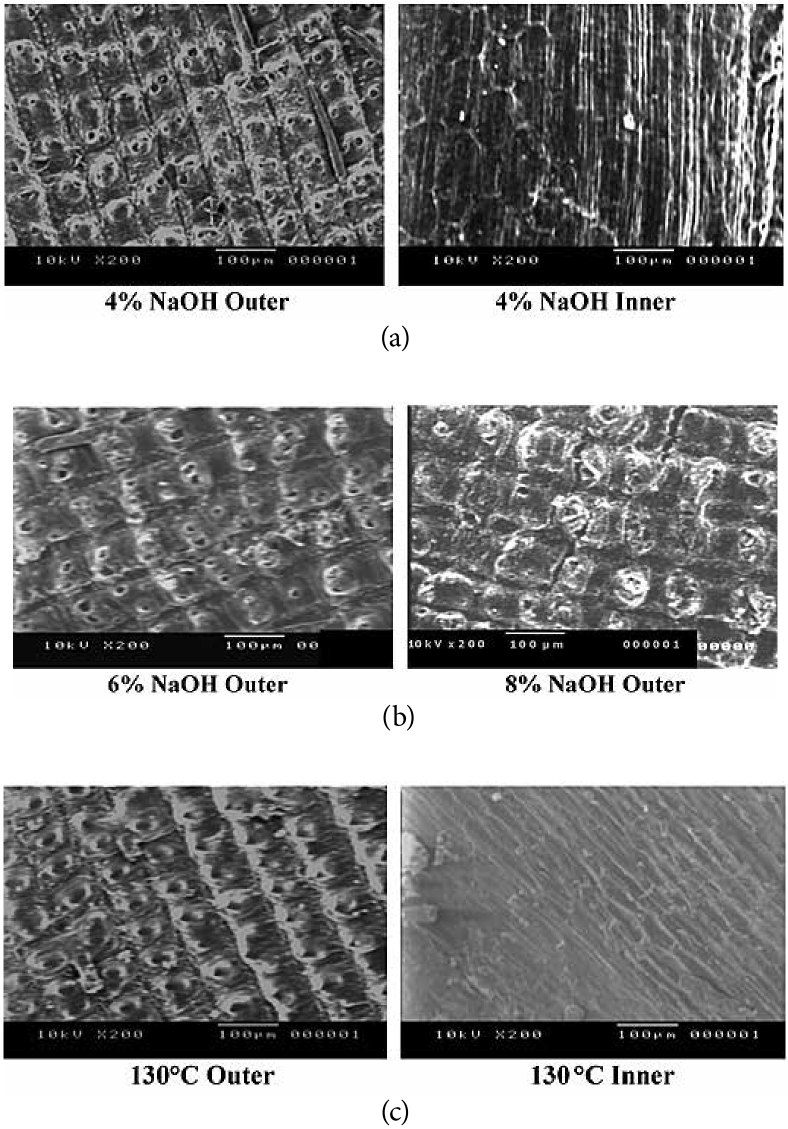


Figure 7 – SEM of the outer an inners surfaces of treated rice husks (a) and (b) alkali treated (c) steam cured: Ndazi et al. (2007).

4.2 COMPOSITE PANELS FROM COFFEE HUSKS

4.2.1 Introduction

Coffee is one of the export crops grown in many developing countries. Tanzania produces two types of coffee, namely *Coffea Arabica* commonly known as Arabian or Arabica coffee and *Coffea Canephora* commonly known as Robusta coffee (OGOLA, 1997). The external soft cover of the coffee fruit is removed mechanically, the bean is then fermented, cleaned and dried to a moisture content of 12%. The husks removal is done at the factory and the dry beans are usually packed and graded before being sold for export. Regular application of coffee husks as fertilizer is now being discouraged because of the risk of raising the potassium content of the soil to such an extent that coffee quality can be reduced (OGOLA, 1997). In most cases coffee husks has been traditionally used as an animal feed, fuel source, as a fertilizer and recently for production of particleboard (BEKALO; REINHARDT, 2010; OGOLA, 1997). While synthetic resins have remained expensive, tannin, a naturally occurring resin, has demonstrated the potentail of being used as particleboard adhesive (BISANDA; OGOLA; TESHA, 2003; OGOLA, 1997). The use of non-wood fibres to reinforce thermoplastic and thermosetting resins is now possible for such end applications such as roofing, panelling, food grain silos, low cost housing units, particleboards etc.

The objective of this research was to produce and characterize particle boards from coffee husks, a by-product from coffee processing, using the naturally occuring hydrolized tannin adhesive and urea formaldehyde and phenol formaldehyde resins. The physical and mechanical properties of the resulting panels were compared with other apnel products and standard particleboards indicated in BS 5669 standards.

4.2.2 Coffee Parchment Processing

There are two methods of coffee processing namely the dry and wet methods as summarized in Figure 8. The beans are either peeled or hulled according to the type of coffee being processed. The shelled or peeled coffee is then winnowed by passing it through a blower.

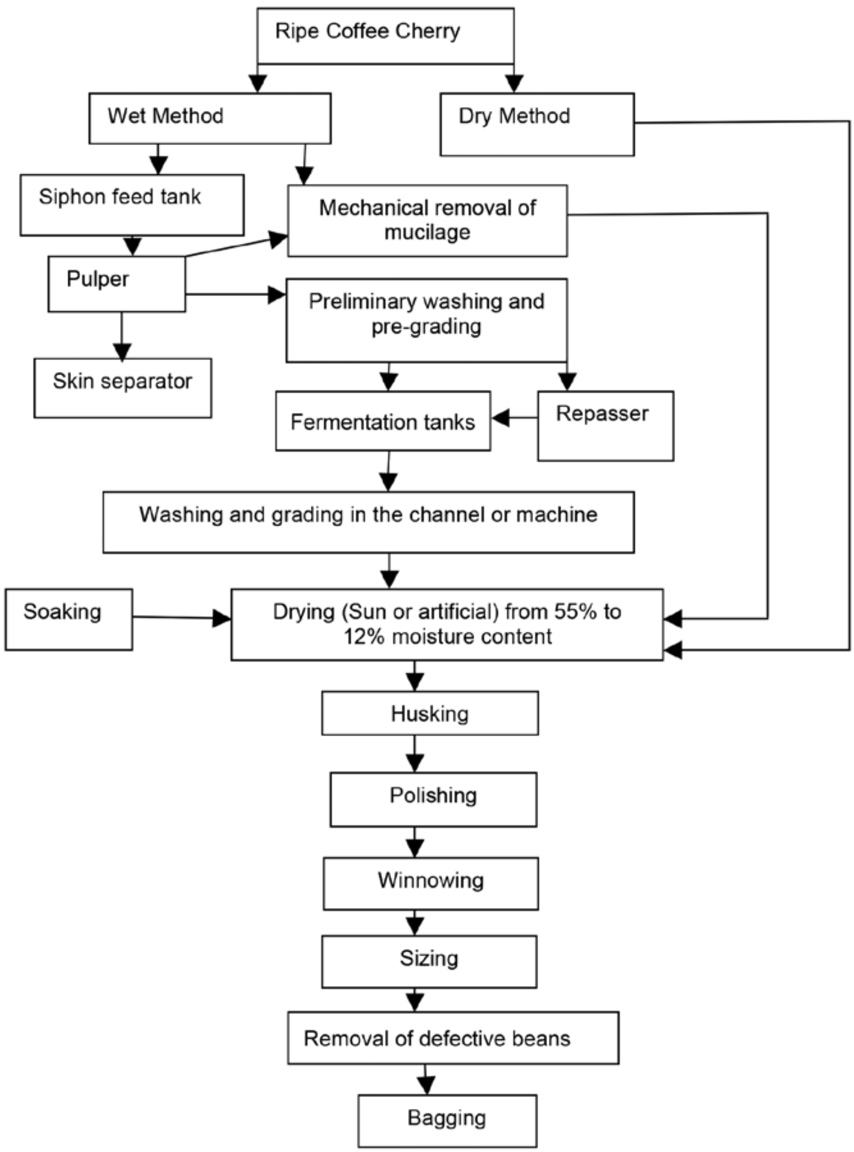


Figure 8 – Coffee processing methods. Source: Ogola (1997)

4.2.3 Experimental Methods

Coffee husks was obtained from coffee curing companies in Tanzania. The hydrolyzed tannin, urea formaldehyde powder, and wood particles from white spruce wood (*Picea Glauca[Moench]Voss*) were all obtained from the Tanzania Industrial Research and Development Organisation (TIRDO), Dar es salaam, Tanzania where particleboard processing and testing was also done.

The coffee husks particle sizes were determined by passing them through test sieves ranging from 850 μm – 475mm. The amount necessary for a given targeted board was then weighed and loaded onto the blender. While the wood particles with 355 μm sieve was used for surface layer and 3.34mm sieve for the core layer. The amount necessary for a given targeted board density based on a given ratio for core and surface particles was weighed and the appropriate amount of resin required.

The tannin-based resin was prepared by hydrolyzing spray dried tannin powder to acceptable level suitable for the manufacture of composite panels. This was performed at the Tanzania Industrial Research and Development Organization (TIRDO) laboratories following a technique established by Clave et al. (1995). Urea formaldehyde powder was weighed and mixed with water at 35% solid contents and stirred manually to obtain a uniform mixture with a viscosity of 180-350 centipoises suitable for pumping and spraying.

The phenol formaldehyde used was in liquid form and 3% by weight of the hardener was added to the phenol and the mixture thoroughly stirred. The resin was then weighed and manually mixed with the coffee husks. The furnish was used to make particleboards in the press with targeted densities ranging between 1000-1400 kg/m^3. Pressing was varied between 150˚C and 200˚C for the press time of between 3 minutes and 6 minutes, and resin content ranging between 4 and 14% until optmum conditions were obtained.

4.2.4 Results and Discussion

Table 9 shows the results of moisture contents in coffee husks, wood chips and the composite panels obtained by using the Karl Fischer method.

The values of moisture content that fell within the theoretical values for coffee husks quoted as 9-13% (OGOLA, 1997). It was found that coffee husk/tannin composite panels contained the minimum moisture content of 7.5% compared with the composite panels produced from wood chips. The moisture content of the composite panels was less than that of the coffee husks suggesting that tannin resin improved slightly the moisture absorption resistance of the hydrophilic coffee husks, an advantage given the humdid environment where the these products may be exposed to.

Table 9 – Moisture content using the Karl Fischer method

Sample type	Average moisture content (%)
Coffee husks	9.1
Coffee husks/tannin composite panels	7.5
Wood/tannin composite panels	7.7

Source: Ogola (1997)

Table 10 shows the comparison of actual densities of composite panels made from coffee husks against those of wood chips. Coffee husks composite panel were generally denser than wood chips composite panels, suggesting better moisture absorption and wetting by the coffee during blending.

Table 10 – Comparison of actual density of various particleboards

Target Density (kgm^{-3})	Actual density (kgm^{-3})	
	Coffee husks/tannin	Wood/tannin
1000	873.1	810.4
1100	923.5	853.4
1150	950.3	896.4
1200	988.8	915.6
1300	1034.8	962.5
1400	1050.5	1007.9

Source: Ogola (1997)

Table 11 shows the mechanical properties of the coffee husks/tannin and wood/tannin composite panels for the target density of 1300 kgm^{-3}. It is shown that composite panels made from wood chips has superior mechanical properties compared with those of coffee husks. However, it is only the internal bond strength of the wood chips tannin composite panel that passed the recommended minimum value in BS 5669 Part 2. If tannin should be used as alternative resin to bind coffee husks then further processing of the coffee husks, the resin or both may be required.

Table 11 – Comparison of MOE, MOR, I.B. Strength of various particleboards

Particleboard	Target density (kg/m^3)	MOE (MPa)	MOR (MPa)	I.B. Strength (MPa)
Coffee husks/tannin	1000	1216	6.5	0.12
Wood/tannin	1000	1332	12.9	0.60
BS 5669: Part 2	-	1920	13.0	0.32

Source: Ogola (1997)

The nail and screw withdrawal tests of the composite panels are shown in Table 12. Coffee husks/tannin composite panel exhibited better nail withdrawal than the wood chips.

Table 12 – Screw and nail withdrawal strength of the various particleboards

Particleboard	Density (kg/m^3)	Screw withdrawal force (N)		Nail withdrawal force (N)		
		Face	Edge	Face	Edge	Head pull
Coffee husks/tannin	1034.8	2300	638	497	283	1787
Wood/tannin	700	-	-	191	230	-
BS 5669 Part 2	-	-	335	-	-	-

Table 13 – Thickness swelling and specific heat capacities.

Particleboard	Density (kg/m^3)	Thickness swelling (%)			Specific Heat (J/kg°C)
		1hr	2hrs	2hrs Boil test	
Coffee husks/tannin	1034.8	6.0	7.6	42.4	1670
Wood/tannin	1007.9	12.0	15.0	66.0	1651
BS 5669 Part 2	-	8.4	-	-	-

4.2.5 Conclusions

It is possible to make coffee husks particleboards from hydrolyzed tannin.

The coffee husks/particleboards are dimensionally stable at room temperature. Coffee husks/tannin particleboards could be suitable for thermal insulation application from the specific heat capacity results.

Wood/tannin particleboards had superior mechanical properties compared to coffee husks/tannin particleboards.

A summary of the mechanical and physical properties for the various particleboard systems indicate that coffee husks particleboards had both mechanical and physical properties that were partly comparable to standard particleboards. They can therefore be used for general applications where high density and low bending loads are expected.

ACKNOWLEDGEMENT

The authors wish to expresses there sincere thanks to their host institutions for enabling them to prepare this work. Special thanks go to DAAD, Sida, Swedish Institute, University of Dar es salaam, the Royal Institute of Technology (KTH) for supporting various research activities consolidated in this report. Lastly, to the editor for allowing this chapter to be published in their book.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

AKINBOMI, J.; BRANDERG, T.; SANNI, S. A.; TAHERZADEH, M. J. Development and dissemination strategies for accelerating biogas production in Nigeria. **BioResources**, v. 9, issue 3 (in press), 2014.

BABATUNDE, A. Durability characteristics of cement-bonded particleboards manufactured from maize stalk residue. **Journal of Forestry Research**, v. 22, issue 1, p. 111-115, 2011. doi:10.1007/s11676-011-0135-2.

BEKALO, S. A.; REINHARDT, H. W. Fibers of coffee husk and hulls for the production of particleboard. **Materials and Structures**, v. 43, Issue 8, p. 1049-1060, 2010. doi:10.1617/s11527-009-9565-0.

BISANDA, E. T. N.; ANSELL, M. P. Effects of Silane Treatment on the Mechanical and Physical Properties of Sisal Epoxy Composites. **Composite Science and Technology**, v. 41(2), p. 165-178, 1991. doi:10.1016/0266-3538(91)90026-L.

BISANDA, E. T. N.; OGOLA, W. O.; TESHA, J. V. Characterization of tannin resin blends for particle board applications. **Cement and Concrete Composites**, v. 25, Issue 6, p. 593-598, 2003. doi:10.1016/S0958-9465(02)00072-0.

BODIG, J.; JAYNE, B. A. **Mechanics of Wood Composites**. New York: Van Nostrand Reinhold Company Inc., 1982.

BOLTON, A. J. The potential of plant fibres as crops for industrial use. **Outlook on Agriculture**, v. 24, n.2, p. 85-89, 1995.

CALVÉ, L.; MWALONGO, G. C. J.; MWINGIRA, B. A.; RIEDL, B.; SHIELDS, J. A. Characterization of Wattle Tannin Based Adhesives for Tanzania. **Holzforschung**, v. 49, p. 259-268, 1995. doi:10.1515/hfsg.1995.49.3.259.

CORRADINI, E.; DE MORAIS, L. C.; DE ROSA, M. F.; MAZZETTO, S. E.; MATTOSO L. H. C.; AGNELLI, J. A. M. A preliminary study for the use of natural fibers as reinforcement in starch-gluten-glycerol matrix. **Macromolecular Symposia**, v. 245-246, p. 558-564, 2006. doi:10.1002/masy.200651380.

DINWOODIE, J. M. The Nature and Behaviour of Wood-Based Composites. In: 1ST EUROPEAN PANEL PRODUCTS SYMPOSIUM, 9–10, October, 1997, University of Wales. **Proceedings...** Llandudno, Wales, p. 1-9, 1997.

DUNKY M. Optimised Bonding Solutions for the New Millennium. In: PROCEEDINGS OF THE 4TH EUROPEAN PANEL PRODUCTS SYMPOSIUM, October, 2000, University of Wales. **Proceedings...** Llandudno, Wales, p. 1-14, 2000.

GERARDI, V.; MINELLIN, F.; VIGGIANO, D. Steam Treated Rice Industry Residue as an Alternative Feedstock for Wood-Based Particleboards Industry in Italy. **Biomass and Bioenergy**, v. 4, n. 3, p. 295-299, 1998. doi:10.1016/S0961-9534(97)10042-3.

GRAHAM, M.; HIZIROGULU, S. Effect of press closing time and target thickness on surface roughness of particleboard. **Forest Products Journal**, v. 48, n. 3, p. 50-54, 1998.

HASHIM, R.; NADHARI, W. N. A.W.; SULAIMAN, O.; SATO, M.; HIZIROGULU, S.; KAWAMURA, F.; SUGIMOTO, T.; SENG, T. G.; TANAKA, R. Properties of binderless particleboard panel manufactured from oil palm biomass. **BioResources**, v. 7, n. 1, p. 1352-1365, 2012.

HOUWINK, R.; SALOMON, G. **Adhesion and Adhesives**. 2 ed., v. 1 Adhesion. Elsevier Publishing Company, 1965.

KARGARFARD, A.; JAHAN-LATIBARI, A. The Performance of corn and cotton stalks for medium density fiberboard production. **BioResources**, v. 6, n. 2, p. 1147-1157, 2011.

KOLLMANN, F. P.; KUENZI, W. E.; STAMM A. J. **Principles of wood science and technology: II Wood based materials**. Springer Verlag, 1975.

KOOPMANS, A.; KOPPEJAN, J. Agricultural and forest residues generation, utilization and availability. In: THE REGIONAL CONSULTATION ON MODERN APPLICATIONS OF BIOMASS ENERGY, 6-10 January 1997, Kuala Lumpur, Malaysia (see FAO, 1998).

KUBLER, H. **Wood as a Building and Hobby Material**. Canada: Wiley and Sons Inc, 1977.

LAEMSAK, N.; OKUMA, M. Development of boards made from oil palm frond properties of binderless boards from steam-exploded fibers of oil palm frond. **Journal of Wood Science**, v. 46, p. 322-326, 2000. doi:10.1007/BF00766224.

MCNATT, J. D.; BACH, L.; WELLWOOD, R. W. Contribution of flake alignment to performance of strand board. **Forest Product Journal**, v. 42, n. 3, p. 45-50, 1992.

MOHANTY, A. K.; KHAN, M.A.; HINRICHSEN, G. Surface modification of jute and its influence on performance of biodegradable jute-fabric/Biopol composites. **Composite Science Technology**, v. 60, p. 1115-1124, 2000. doi:10.1016/S0266-3538(00)00012-9.

MWAIKAMBO, L. Y.; ANSELL, M. P. Chemical Modification of Jute, Sisal, Hemp and Kapok Fibres by Alkalization. **Journal of Applied Polymer Science**, v. 84, p. 2222-2234, 2002. doi:10.1002/app.10460.

NDAZI, B. **Performance of hydrolyzed tannin-CNSL resin rice husk particleboards.** Thesis – (M.Sc.) University of Dar es Salaam, 2001.

______. **Effects of rice husks modifications on the performance of particleboards.** Ph.D. Thesis. University of Dar es Salaam, 2006.

NDAZI, B.; KARLSSON, S. Characterization of the Potential of Soda Cooking to Extract Fibrous Residues From Rice Hulls. **Polymers from Renewable Resources**, v. 1, n. 3, p. 143-160, 2010.

NDAZI, B.; TESHA, J.V.; BISANDA, E. T. N. Some opportunities and challenges of producing bio-composites from non-wood residues. **Journal of Materials Science**, v. 41, p. 6984-6990, 2006. doi:10.1007/s10853-006-0216-3.

NDAZI, B.; TESHA, J. V.; KARLSSON, S.; BISANDA, E. T. N. Production of rice husks composites with *Acacia mimosa* tannin-based resin. **Journal of Materials Science**, v. 41, p. 6978-6983, 2006. doi:10.1007/s10853-006-0220-7.

NDAZI, B.; TESHA, J. V.; KARLSSON, S.; BISANDA, E. T. N.; NYAHUMWA, C.W. Chemical and physical modifications of rice husks for use as composite panels. **Composites Part A Applied Science and Manufacturing**, v. 38, n. 3, p. 925-935, 2007. doi:10.1016/j.compositesa.2006.07.004 2007.

NISHIMULA, T.; AMIN, J.; ANSELL, M. Image Analysis of the Shape and Size of Strands in Model OSB Panels and Correlation with MOE and MOR. In: THE 5TH EUROPEAN PANEL PRODUCTS SYMPOSIUM, October, 2001, University of Wales, Llandudno. **Proceedings...** Wales, p. 155-166, 2001.

OLORUNNISOLA, A. O. Effects of husk particle size and calcium chloride on strength and sorption properties of coconut husk–cement composites. **Industrial Crops and Products**, v. 29, n. 2–3, p. 495-501, 2009. doi:10.1016/j.indcrop.2008.09.009.

OGOLA, W. O. **Production and characterization of coffee husks particleboards.** Thesis (Ph.D), University of Dar es Salaam, 1997.

ROWELL, R. M.; HAN, J. S.; ROWELL, J. S. Characterization and Factors Effecting Fiber Properties. In: **Natural Polymers and Agrofibers Composites**, FROLLINI, E., A.L. LEAO and L.H.C. MATTOSO (Eds.). São Carlos, Brazil, p. 115-134, 2000.

SAMPATHRAJAN, A.; VIJAYARAGHAVAN, N. C.; SWAMINATHAN, K. R. Mechanical and thermal properties particle boards made from farm residues. **Bioresource Technology,** v. 40, n. 3, p. 249-251, 1992. doi:10.1016/0960-8524(92)90151-M.

SARKAR, N.; GHOSH, S. K.; BANNERJEE, S.; AIKAT, K. Bioethanol production from agricultural wastes: An overview. **Renewable Energy**, v. 37, p. 19-27, 2012. doi:10.1016/j.renene.2011.06.045.

SCATOLINO, M. V.; SILVA, D. W.; MENDES, R. F.; MENDES L. M. Use of maize cob for production of particleboard. **Ciência e Agrotecnologia**, Lavras, v. 37, n. 4, p. 330-337, 2013. doi: 10.1590/S1413-70542013000400006.

SHUKLA, B. D.; OHJA, T. P.; GUPTA, C.P. Measurement of properties of rice husk boards: Part I physical and mechanical properties. **Agricultural Mechanization in Asia, Africa and Latin America**, v. 16, n. 1, p. 72-82, 1985.

SREEKALA, M. S.; THOMAS, S. Effects of Fibre Surface Modification on Water-Sorption Characteristics of Oil Palm Fibres. **Composites Science Technology**, v. 63, n. 6, p. 861-869, 2003. doi: 10.1016/S0266-3538(02)00270-1.

SUEMATSU, A; OKUMA, M. Mechanical properties of low density particle board. Modulus of rigidity and lateral nail resistance. **Journal of the Japan Wood Research Society**, v. 37, n. 3, p. 293-300, 1993.

TABARSAA, T.; ASHORIB, A.; GHOLAMZADEHA, M. Evaluation of surface roughness and mechanical properties of particleboard panels made from bagasse. **Composites Part B: Engineering**, v. 42, n. 5, p. 1330-1335, 2011. doi: 10.1016/j.compositesb.2010.12.018.

TANGJUANK, S. Thermal insulation and physical properties of particleboards from pineapple leaves. **International Journal of Physical Sciences**, v. 6, n. 19, p. 4528-4532, 2011. doi: 10.5897/IJPS11.1057.

THE WORLD BANK. **Global strategy to improve agricultural and rural statistics, REPORT OF THE FRIENDS OF THE CHAIR ON AGRICULTURAL STATISTICS.** United Nations Economic and Social Council Statistical Commission 41st session 23-26 February 2010.

TUTUS, A.; EZICI, A. C.; ATES, S. Chemical, morphological and anatomical properties and evaluation of cotton stalks (*Gossypium hirsutum* l.) in pulp industry. **Scientific Research and Essays**, v. 5, n. 12, p. 1553-1560, 2010.

VAN DAM, J. E. G.; MARTIEN, J. A.; VAN DEN OEVER, M. J. A.; KEIJSERS, E.R.P. Production process for high performance binderless boards from whole coconut husk. **Industrial Crops and Products**, v. 20, p. 97-101, 2004. doi: 10.1016/j.indcrop.2003.12.017.

VASISHTH, R.C. **Assignee**: Cor Tech Research Ltd. Patent, P.N. US 3850677, and I.D.: 741126, 1974.

VISWANATHAN, R.; GOTHANDAPANI, L. Mechanical properties of coir pith particle board. **Bioresource Technology,** v. 67, n. 1, p. 93-95, 1999. doi:10.1016/S0960-8524(99)00065-6.

WANG, D.; SUN, X. S. Low density particleboard from wheat straw and corn pith. **Industrial Crops and Products**, v. 15, n. 1, p. 43-50, 2002. doi: 10.1016/S0926-6690(01)00094-2.

YOUNGQUIST, J. A.; KRZYSIK, A. M.; CHOW, P.;MEIMBAN, R. Properties of composite panels. In: ROWELL, R. M., YOUNG, R. A.; ROWELL, J. K. (eds.) **Paper and composites from agro-based resources**. Boca Raton, FL: CRC Lewis Publishers, 1997.

PARTICLEBOARDS BASED ON AGROINDUSTRIAL WASTE

Sergio Luis de Castro Junior
University of São Paulo, Faculty of Animal Science and Food Engineering, Undergraduate Student, Pirassununga, Brazil

Diogo de Lucca Sartori
University of São Paulo, Faculty of Animal Science and Food Engineering, Postgraduate students, Pirassununga, Brazil

Mariana Pilar Gatani
Consejo Nacional de Investigaciones Cientificas y Tecnológicas (CONICET), Centro Experimental de Vivienda Economica (CEVE), Córdoba, Argentina.

Francisco Antonio Rocco Lahr
University of São Paulo, São Carlos Engineering School, Structure Engineering Department, São Carlos, Brazil.

Valdemir dos Santos and Juliano Fiorelli
University of São Paulo, Faculty of Animal Science and Food Engineering, Biosysten Engineering Department, Pirassununga, Brazil.

ABSTRACT: This work presents a study on the potential use of agroindustrial waste (sugarcane bagasse and *Pinus sp.* wood waste) to produce particleboards, using castor oil-based polyurethane adhesive. Particleboards were produced using mass proportions: 20, 40, 60% and 100% of sugarcane bagasse as addition to *Pinus sp*. particles (density 500 kg.m^{-3}) and castor oil-based polyurethane resin as adhesive. Products quality was evaluated according to NBR 14810:2006 and ANSI A208.1-1999 codes requirements. Panels density, thickness swell (TS), water absorption, modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending were determined. Results indicated that: (a) particleboard with 40% of sugarcane bagasse and 60% of wood residues of *Pinus sp* and particleboard with 100% of sugarcane bagasse presented better physical and mechanical properties and (b) castor oil-based polyurethane adhesive particleboards demonstrated to be a new option of resin to produce particleboards.

Keywords: Sugarcane bagasse. Sustainability. Composites.

1. INTRODUCTION

Agricultural sector depends directly or indirectly on environment as a source of raw materials for its development, as well as on areas as “dumping sites” for byproducts and waste generated in productive cycles. Waste disposal, once quantified, monitored and treated, becomes easily bearable for the environment in a given time. Otherwise, degradation of such residue can take thousands of years or even fail to occur as there are no natural specific mechanisms for this.

One proposed alternative for waste destination is using to produce particulate composites. These panels are generally manufactured with wood particles bonded by synthetic adhesive or other binders, pressed under heat long enough to adhesive curing (IWAKIRI et al., 2004).

Basically, these panels can be produced from any lignocellulosic material which gives pre-determined specific weight and convenient properties, since chemical composition of lignocellulosic materials is similar to wood, especially hardwoods with smaller lignin content and higher pentosan hemicelluloses content Okino et al. (1997); Brito et al. (2004); Khedari et al. (2004); Contreras (2006); Chama and Leão (2008); Barros Filho et al. (2011); Fiorelli et al. (2012).

In recent years, efforts have intensified to study the best use of lignocellulosic residues for new products, such as particleboards (CHAMMA; LEÃO, 2008). This is due to the fact that using lignocellulosic residues contributes to mitigate environmental impacts, featuring new products with sustainable appeal.

Barros Filho et al. (2011) conducted a study on particleboards made with sugarcane bagasse using urea formaldehyde (UF) and melamine formaldehyde (MF) resins. Particleboards were produced with a mixture of sugarcane bagasse and pine or eucalyptus particles, with and without paraffin in the formulation. Nine different types of particleboards, all containing 9% of resin in the mix, were produced at a temperature of 160°C and under 4.0 MPa pressure. Physical properties of these particleboards complied with the ASTM CS 236-66 standard requirements for medium density chipboards, and in most cases, showed better results than others reported in literature. However, when subjected to mechanical testing, these particleboards did not comply with the aforementioned code and, in most cases, results were close to or worse than those reported in literature.

Xu et al. (2009) studied sugarcane bagasse particleboards (BPBs) using polymeric methylene diphenyl diisocyanate (pMDI) resin as binder and wax emulsion as dimension stabilizer. A factorial experiment was conducted to measure effects of wax and pMDI resin content on particleboard's dimensional stability and mechanical properties. Results were compared with corresponding properties specified in American standard ANSI A208.1:1999 - Particleboard for commercial M3 grade wood-based particleboard. Wax-sizing improved linear expansion (LE) of particleboards produced with different pMDI resin proportions tested in their research, and all LE values remained below requirement of 0.35%. Using wax significantly reduced 24-h water absorption and thickness swelling compared to the control particleboards (without wax). Moderate levels of wax-sizing also proved to have a positive effect on properties of long-term water absorption and thickness swelling. Mechanical properties of all particleboards far exceeded the minimum values specified in ANSI A208.1:1999 standard. As expected, the overall properties of 5% pMDI BPBs were better than those of 3% pMDI particleboards.

Fiorelli et al. (2013) evaluated sugarcane bagasse particleboards with two different fiber lengths (5 mm and 8 mm), of the same density, as a raw material for particleboard production, using castor oil-based bi-component polyurethane adhesive. Results revealed a significant difference between particleboards made with 5-mm-long fibers and those made with 8-mm-long fibers. An analysis by scanning electron microscopy (SEM) indicates that interparticle spaces are filled with resin, contributing to improve particleboards physicomechanical properties.

Urea formaldehyde and phenol formaldehyde based adhesives have noticeable homogeneity (MENDES et al., 2010). However, there is a global trend towards biodegradable, non pollutant and renewable products. This trend led to further research, resulting in castor oil-based polyurethane adhesive (ARAÚJO, 1992), among others.

This work aimed to demonstrate the feasibility of producing panels of agroindustrial waste of sugarcane bagasse, residues of *Pinus spp* and castor oil-based polyurethane adhesive.

2. AGROINDUSTRIAL WASTE PARTICLEBOARDS PRODUCTION PROCESS

Panels with agroindustrial wastes were prepared using a heated automatic press with load capacity of 100 T, following detailed recommendations from Maloney (1996). Process began by collecting wastes and natural fiber (Fig. 1A). Waste was dried to a moisture content around 8 and 12%. To particleboards manufacture, 12% castor oil-based bi-component polyurethane adhesive was used. Particles were mixed with adhesive in a planetary mixer (Fig. 1 B). After, the material was placed into a mold (Fig. 1 C) and inserted into the thermo-hydraulic press (Fig. 1D), under 5 MPa and temperature up to 100°C. Particleboards with nominal dimensions of 40 x 40 cm and 10 mm thickness and density of 500 $kg.m^{-3}$ were made. From these particleboards, 10 specimens were taken for each physicomechanical test, as recommended by Brazilian standard ABNT NBR 14810:2006 - *Chapas de madeira aglomerada*. This standard was chosen due to its similarity between sugarcane bagasse particleboards produced in this study and wood panels.

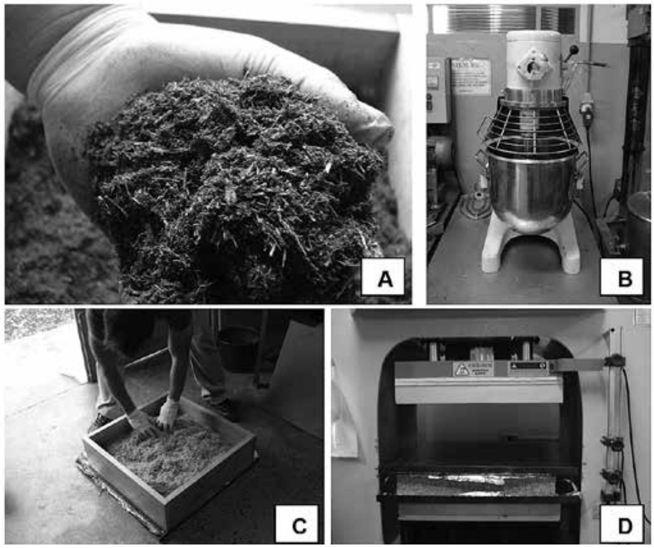


Figure 1 – Particleboard production steps. A) Particles of agroindustrial waste. B) Mixture of adhesive and waste. C) Transfer of the particles to the mold-forming panel. D) Particles insert in hydraulic press.

3. MATERIALS AND METHODS

3.1 CHARACTERIZATION - AGROINDUSTRIAL WASTE

Performance of the agroindustrial wastes (residues of sugarcane bagasse and *Pinus spp*) was evaluated by physical, chemical and anatomical tests. To determine wastes real density a pycnometer helium gas was employed; pH was evaluated by method of Vital (1973). Anatomic analysis was carried out by Scanning Electron Microscopy (SEM).

3.2 CHARACTERIZATION – PARTICLEBOARDS

Physicomechanical performance of particleboards was evaluated according to the Brazilian standard NBR 14810:2006 requirements. A completely random design (CRD) was used with four treatments (Tab. 1). Properties determined were: thickness swelling (TS), water absorption (WA), modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending. Average values were compared by a multiple comparison test (Tukey) when ANOVA showed a significance level with $P \leq 0.05$.

Table 1 – Experimental program for sugarcane bagasse particleboard.

Treatment	Density ($kg.m^{-3}$)	*Pinus* sp. wood waste (%)	Sugarcane bagasse (%)
B20	500	80	20
B40	500	60	40
B60	500	40	60
B100	500	0	100

3.2.1 Thickness Swelling (TS)

Thickness swelling was calculated from the difference in a specimen's thickness before and after soaking in water for 2 h and 24 h. Specimen´s linear dimensions were measured using a digital caliper, 0.01 mm sensibility. Percentage of thickness swelling was calculated using eq. 1:

$$TS(\%) = \left[\frac{Tf - Ti}{Ti}\right] \cdot 100 \qquad (1)$$

where:
T*f* = final thickness after soaking for 2 h and 24 h;
T*i* = initial thickness.

3.2.2 Water Absorption (WA)

Samples to determine water absorption were soaked in water for 2 h and 24 h. Water absorption was calculated using eq. 2.

$$WA(\%) = \left[\frac{Wf - Wi}{Wi}\right] \cdot 100 \qquad (2)$$

where:
W*f* = final weight after soaking for 2 h and 24 h;
W*i* = initial weight.

3.2.3 Mechanical Testing

Static bending tests were carried out by means of a universal test machine at room temperature. The loading rate for the bending strength was controlled at 4 mm/min. Modulus of rupture (MOR) and modulus of elasticity (MOE) were determined by a three-point bending test with a load cell capacity of 5 kN. A total of ten specimens were made and tested.

4. RESULTS

This section presents results of physical and chemical characterization of agroindustrial wastes and physicomechanical properties of the produced particleboards (treatments B20, B40, B60 and B100). Results were compared with those recommended by NBR 14810:2006 and ANSI A208.1:1999 standards.

4.1 AGROINDUSTRIAL WASTE – PHYSICAL, CHEMICAL AND ANATOMICAL PROPERTIES

Tab. 2 shows physical and chemical properties. Fig. 2 presents properties anatomical specificities (surface and transversal SEM with different increases of sugarcane bagasse and *Pinus spp* wood waste).

Table 2 – Physical and chemical properties.

Agroindustrial waste	Real density ($kg.m^{-3}$)	pH
Sugarcane bagasse	1.40	5.11
Pinus sp. wood waste	1.24	4.48

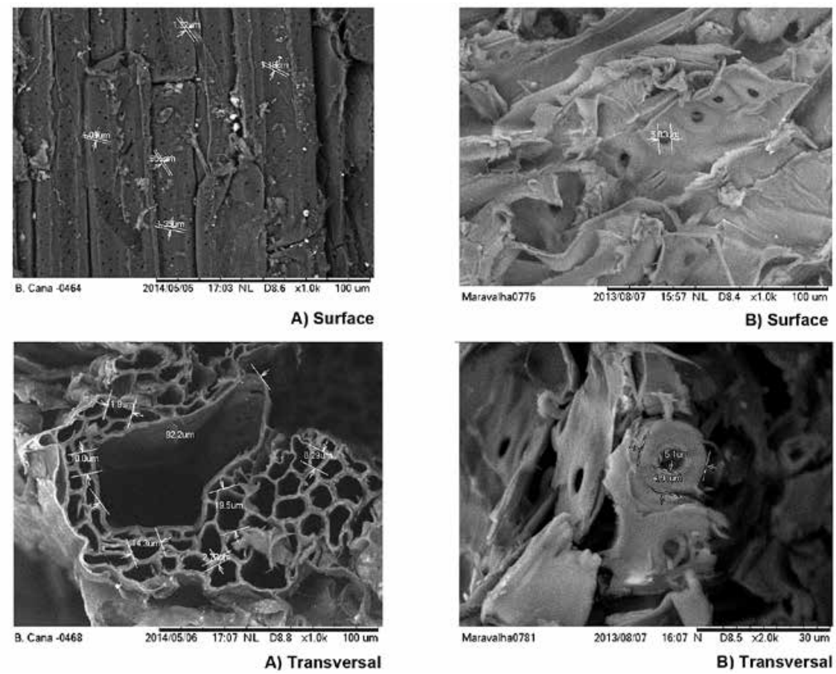


Figure 2 – Surface and transversal SEM. A) Sugarcane bagasse. B) *Pinus spp* Wood wastes, with different magnification.

Sugarcane bagasse´s real density is superior to that of *Pinus spp* residues, these results are similar that Oliveira et al. (2003). The pH is similar (5.11 and 4.48). This value of pH indicates that the same wastes show effective potential for particleboard production, once an acid pH helps adhesion among particles (IWAKIRI, 2005).

SEM image indicates that the surface of particles presents pores that facility adhesive dispersion among particles. Fibril thickness (3 – 5 μm) is also similar between sugarcane bagasse and *Pinus spp* wood waste.

4.2 PARTICLEBOARDS – PHYSICAL AND MECHANICAL PROPERTIES

Tab. 3 shows physical and mechanical properties of the produced particleboards. The particleboards belonging to this study presented density around 500 kg.m^{-3} and they can be classified as low-density, according to ANSI A208.1-1999 standard. Statistical analysis indicated a significant difference ($P<0.05$) to the studied variables.

Table 3 – Results of physical and mechanical tests.

Treatment	Density (kg.m^{-3})	TS		WA		MOR	MOE
		2h(%)	24h(%)	2h(%)	24h(%)	MPa	MPa
B20	560±37	7.83±0.63 a	9.68±1.20 a	36.24±7.84 a	73.80±9.20 a	7.6±2.1 a	797±272 ab
B40	520±38	8.22±1.15 b	11.19±1.30 b	26.29±7.45 ab	55.61±3.83 b	12.0±2.9 ab	1207±345 bc
B60	510±53	9.22±1.25 bc	12.97±1.15 b	17.00±2.36 b	34.66±5.04 c	10.1±2.4 b	1065±223 c
B100	520±85	6.43±1.06 c	11.32±1.10 c	16.42±2.06 b	54.71±7.48 b	18.5±2.6 c	1702±206 d

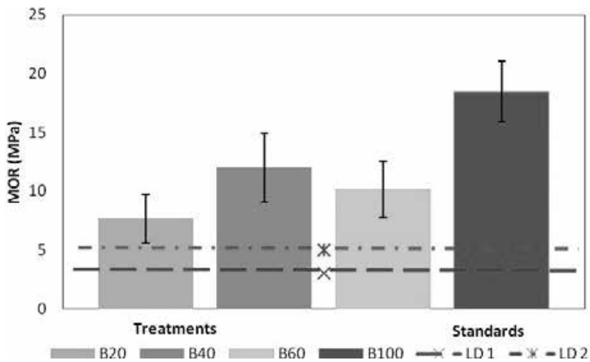
* Same letter in the column do not differ statistically ($P>0.05$)

Particleboards with greater quantity of sugarcane bagasse (B100) present lowest percentage of thickness swell in 2 h and 24 h, but decrease of water absorption in 2 h and 24 h. This result can be associated with the agglomeration of the particles and pores in the surface of the particleboards.

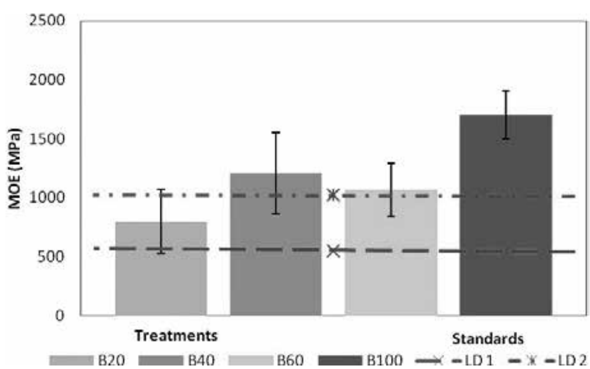
Treatments B40 and B60 don't have a significant statistical difference ($P<0.05$) for properties TS and WA.

Mechanical properties increased with the quantity of sugarcane bagasse. Treatments B40 and B60 do not perform a significant statistical difference ($P<0.05$) for properties MOR and MOE as well.

Results shown in Tab. 3 were compared with ANSI A208.1-1999 requirements (Fig. 3). Particleboards obtained by treatments (B20 – B100) can be classified as Low Density (LD) category (less that 640 kg.m^{-3}). Treatments (B20 – B100) presented values of MOR and MOE above LD-1 and LD-2, according to the standard A208.1:1999. Treatment B20 presented MOE average below the recommended for LD-2. These results demonstrated that (a) panels density meet the standard's requirements; (b) production process here proposed is consistent; (c) castor-oil based polyurethane resin is a viable alternative adhesive for manufacturing sugarcane bagasse and wood waste form *Pinus spp* particleboards. Treatment B40 can be indicated as option to particleboard production with different agroindustrial wastes.



(a)



(b)

Figure 3 – Average values. A) MOR. B) MOE - Treatments and Codes.

4.3 SCANNING ELECTRON MICROSCOPY ANALYSES (SEM)

Fig. 4 presents a microstructure analysis SEM of specimens representing treatments B20, B40, B60 and B100. A homogeneous dispersion of resin among particles can be observed, essential to ensure a uniform load distribution in composite (CALLISTER, 2002). Different particles shapes (sugarcane bagasse and *Pinus spp* wood waste) induce pores formation and differences in values of TS; WA; MOR and MOE.

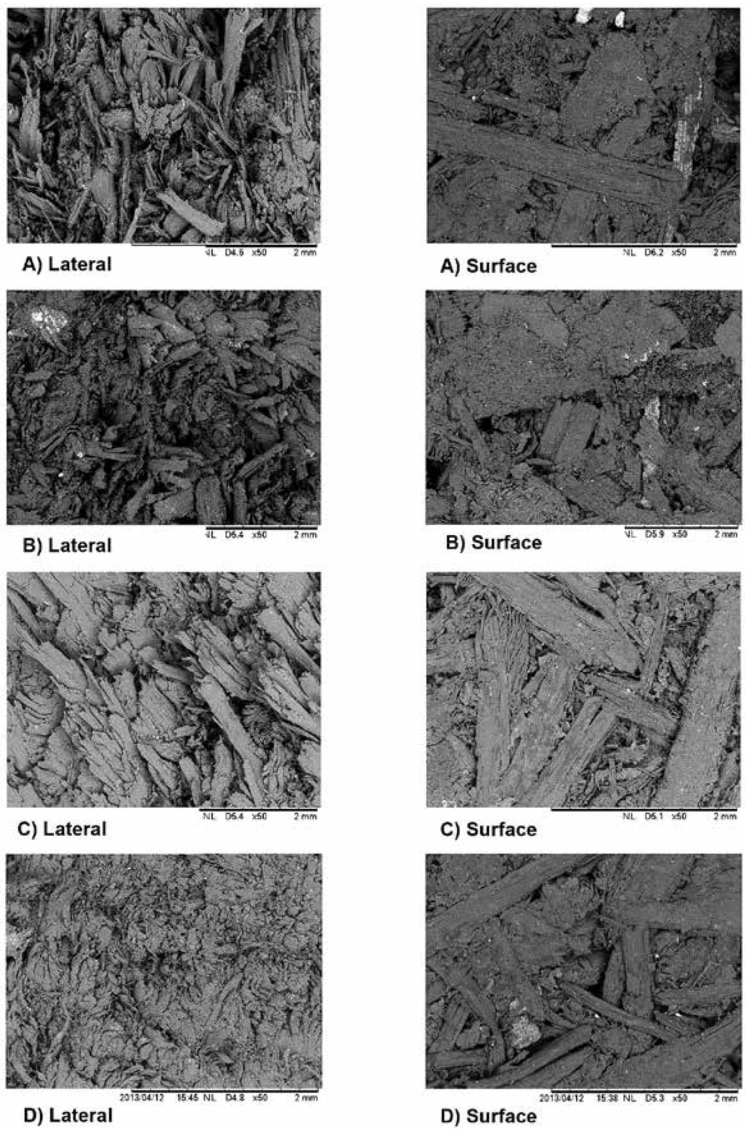


Figura 4 – SEM image - Panel with agroindustrial waste and castor oil resin. A) B20, B) B40, C) B60 and D) B100, with magnification (x50).

5. CONCLUSION AND FUTURE PERSPECTIVE

Sugarcane bagasse and *Pinus spp* wood waste are agroindustrial wastes and a promising material for particleboard manufacturing. Based on the conducted tests, the panels made of sugarcane bagasse and *Pinus spp* wood waste and castor oil-based polyurethane adhesive (B40), with density 500 kg.m^{-3}, presented sufficient mechanical properties for use in civil and agricultural constructions. Scanning electron microscopy (SEM) indicated that castor oil-based polyurethane adhesive helps particle agglomeration, a factor that contributes to improved particleboard´s physical and mechanical properties. In the future, this panel could be produced in several areas around the world, in regions that generate a great volume of agricultural wastes, and used in multiple applications.

ACKNOWLEDGEMENT

FAPESP, CNPq and FINEP - Brazilian Agency Research.

Technical team of the Construction and Ambience Laboratory – Faculty of Animal Sciences and Food Engineering, University of São Paulo, Pirassununga, Brazil.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text

REFERENCES

AMERICAN NATIONAL STANDARDS INSTITUTE. **ANSI A208.1** - Particleboard. Gaithersburg, 1999. 13p.

ARAÚJO, L.C.R. **Caracterização química e mecânica de poliuretanas elastoméricas baseadas em materiais oleoquímicos**. 1992. Dissertação (Mestrado) - Instituto de Física e Química de São Carlos, Universidade de São Paulo, São Carlos, 1992.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 14810** - Chapas de madeira aglomerada. Rio de Janeiro, 2006. 32p.

BARROS FILHO, R.M.; MENDES, L.M.; NOVACK, K.M.; APRELINI, L.O.; BOTARO, V.R. Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin. **Industrial Crops and Products**, v. 33, n. 2, p. 369-373, 2011. doi:10.1016/j.indcrop.2010.11.007.

BRITO, E.O.; SÁ-ROCHA, J.D.; VIDAURRE, G.B.; BATISTA, D.C.; PASSO, P.R.; MARQUES, L.G.C. Propriedades de chapas produzidas com resíduos do fruto de coco e partículas de pinus. **Revista Floresta e Ambiente**, v. 11, n. 2, p. 1-6, 2004.

CALLISTER, W.D. **Ciência e Engenharia de Materiais: Uma Introdução.** 5.ed. São Paulo: LTC, 2002.

CHAMMA, P. V. C.; LEÃO, A. L. Aproveitamento de resíduos sólidos na produção de painéis para aplicações arquitetônicas. **Revista Energia na Agricultura**, v. 23, p. 73-87, 2008.

COMMERCIAL STANDARD. **CS 236-66** - Mat formed wood particleboard. 1968.

CONTRERAS, W. M.; OWEN, M. E C.; BALLESTER, V. C.; CONTRERAS, Y. M.; GARAY, D. J. Diseño de tableros de partículas de caña brava y adhesivo fenol-formaldehído (R 10% / R 13%). **Revista Forestal Latinoamericana**, n. 39, p. 39-55, 2006.

FIORELLI J.; CURTOLO, D.D.; BARRERO, N.G.; SAVASTANO JR., H,; PALLONE, E.M.J.A.; JOHNSON, R. Particulate composite based on coconut fiber and castor oil polyurethane adhesive: an eco-efficient product. **Industrial Crops and Products**, v. 40, p. 69-75, 2012. doi: 10.1016/j.indcrop.2012.02.033.

FIORELLI, J.; SARTORI, D. L.; CRAVO, J. C. M; SAVASTANO JR., H.; ROSSIGNOLO, J. A.; NASCIMENTO, M.F.; LAHR, F.A.R. Sugarcane Bagasse and Castor Oil Polyurethane Adhesive-based Particulate Composite. **Materials Research**, v. 16, n. 2, p. 439-446, 2013. doi: 10.1590/S1516-14392013005000004.

IWAKIRI, S. **Painéis de madeira reconstituída.** Curitiba: FUPEF, 2005. 247 p.

IWAKIRI, S.; SHIMIZU, J.; SILVA, J. C.; MENESS, C. H. S. D; PUEHRINGHER, A.; VEN-

SON, I.; LARROCA, C. Production of plywood panels of Grevillea robusta A. Cunn. ex R. Br. **Revista Árvore**, v. 28, n. 6, p. 883-887, 2004. doi: 10.1590/S0100-67622004000600013.

KHEDARI, J.; CHAROENVAI, S.; HIRUNLABH, J. New insulating particleboards from durian peel and coconut coir. **Building and Environment**, v. 38, n. 3, p. 435-441, 2003. doi: 10.1016/S0360-1323(02)00030-6.

MALONEY, T. M. The family of wood composite materials. **Forest Products Journal**, v. 46, n. 2, p. 19-26, 1996.

MENDES, R. F.; MENDES, L. M.; GUIMARÃES JÚNIOR, J. B., SANTOS, R. C.; BUFALINO, L. The adhesive effect on the properties of particleboards made from sugarcane bagasse generated in the distiller. **Revista de Ciências Agrárias**, v. 32, n. 2, p. 209-218, 2010.

OKINO, E.; ANDAHUR, J. P. V.; SANTANA, M. A. E; SOUZA, M. R. Physico-mechanical properties of chemically modified sugarcane bragas partidepanels. **Scientia Forestalis**, v. 52, p. 35-42, 1997.

OLIVEIRA, V. R.; FREIRE, M. F.; VENTURIN, R.; CARRIJO, A. O.; MACARENHAS, M. H. T. Caracterização física de substratos para a produção de hortaliças. In: CONGRESSO BRASILEIRO DE HORTICULTURA, 2003.

VITAL, B.R. **Effects of species and panel densities on properties of hardwood particleboard**. 1993. 111 p. (M.S.) – University of Wisconsin, Madison, 1993.

XU, X.; YAO, F.; WU, Q.; ZHOU, D. The influence of wax-sizing on dimensional stability and mechanical properties of bagasse particleboard. **Industrial Crops and Products**, v. 29, n. 1, p. 80-85, 2009. doi: 10.1016/j.indcrop.2008.04.008.

BABASSU HUSK FIBER PARTICLEBOARD

Nítalo André Farias Machado and **Celso Yoji Kawabata**
Federal University of Maranhão, Center for Agricultural and Environmental Sciences, Chapadinha, MA.
E-mail: nitalo-farias@hotmail.com and celso.kawabata@ufma.br

Juliano Fiorelli and **Holmer Savastano Júnior**
University of São Paulo, Faculty of Animal Science and Food Engineering, Pirassununga, SP.
E-mail: julianofiorelli@usp.br and holmersj@usp.br

Abstract: The development of new technologies is historically an important tool for social progress. In Brazil, the extraction of babassu (*Orbignya sp*) is one of the productive chains of great economic, social and cultural importance, more specifically in the north and northeast regions. In this context, the present study aimed to evaluate the feasibility of using babassu husk fibers in the particleboards manufacturing. High-density particleboards (900 $kg.m^{-3}$) were produced using two-component polyurethane resin based on castor oil. The results of physical and mechanical properties met the recommendations of national and international normative documents, making that product suitable for structural use.

Keywords: Unconventional materials. Agroindustrial waste.

1. INTRODUCTION

The territory of Maranhão, Brazil, consists of a variety of biomes with a large population of native species composing its fauna and flora. However, this ecological wealth is currently used only as subsidy income through ecotourism, since there is a lack in development of scientific studies that exploit this potential and provide technologies applicable to these conditions.

The development of technology is an important tool for social progress, and the extraction of babassu (*Orbignya sp*) is one of the supply chains of major economic, social and cultural importance of the Maranhão state. With several particularities, the babassu exploration is marked by family associations that extract palm kernel from the babassu fruit, especially women accompanied by their children, known as "coconut breakers" (Meirelles Filho, 2004).

Thus, the exploitation of babassu coconut is characterized as a traditionally family-based culture, with associations located at several municipalities in the state, especially in eastern of Maranhão (ALBIERO et al., 2007). The babassu palm is known as a robust isolated plant with a trunk up to 20 feet tall and 25-44 centimeters in diameter. The number of leaves goes from 7 to 22, measuring 4-8 meters in length. The cultivation is distributed especially in the transition zone between the Amazon basin and semiarid areas of the northeast of Brazil (MEIRELLES FILHO, 2004; BALICK AND PINHEIRO, 2000).

The growing pressure for increased production around agriculture fields, the competitiveness of domestic and foreign products and the orientation for conservation of environmental resources have led to the greater rationalization of production processes (Kawabata, 2003). At this scene, the use of waste is a practical conservationist method. With that, particulate panels are structural components with sustainable profile which applies agro-industrial wastes in form of particles in interaction with binders (resins), making the final product.

In addition, the population growth has led to an exponential demand for agricultural products, and these consumers require intense discussions on sustainability applied in production systems. Thus, there was a significant increase in production on a global scale and consequently a disorderly accumulation of residual organic matter from agricultural, commercial and industrial activities, causing ecosystem impacts.

These lignocellulosic residues from Brazilian agribusiness have great potential for using in the manufacturing of new materials (FIORELLI et al., 2012). Therefore, recycling of agro-industrial wastes from babassu coconut breakers and extraction of vegetable oil industry associations is a sustainable alternative that avoids deforestation of babaçuais (typical regional landscape of forests composed predominantly of babassu) and leads to a sustainable management of waste that is usually discarded.

Moreover, that technology, which is based on application of this material as a social tool, indicates an alternative source of income for these families that depend on artisanal mining of this palm. Thus, the babassu wastes discarded or used as energy source (charcoal) can be sold to local or more distant industries to meet the growing demand for wood in rural and urban buildings.

Currently, Brazil is a major global benchmark in food production, with large arable areas and suitable technology. Consequently, the agricultural sector is generating a vast amount of waste. Maranhão is a Brazilian state with a considerable diversity of ecosystems (examples are: Amazon Rainforest, Pre-Amazonian Forests, Cocais Forest, Cerrado, Caatinga, Plateaus, Hills, Mangroves, Flooded Fields, Deltas, Semi Deserts), with typical wildlife and flora for each landscape. In that state, that biomes existing in most of the country are contained in a relatively small territory, 331,935.507 km² (IBGE, 2010).

This work used the babassu husk fiber as a study center. Due to its socio-economic importance to the state of Maranhão, the present study aimed to produce particleboards using babassu fibers.

2. LITERATURE REVIEW

2.1 THE BABASSU PALM (*ORBIGNYA SP*)

The babassu (*Orbignya sp*) belongs to the family *Arecaceae*, and stands out as one of the most abundant palm trees of Amazon region. These plants are distributed widely in southern region, the Atlantic Ocean Bolivia (BALICK AND PINHEIRO, 2000), and especially in transition areas between the Amazon basin and the semi-arid northeast of Brazil (MEIRELLES FILHO, 2004).

The grace and beauty of the palm structure put the babassu as an important plant among another native plants from the Brazilian territory. The leaves of babassu are erect and firm, making them more suitable for capturing sunlight (increasing the photosynthetic rate) and avoiding senescence (death of leaves). According to Meirelles Filho (2004), its trunk is up to 20 feet tall and 25-44 centimeters in diameter, with 7 to 22 leaves measuring 4-8 feet long.

(a) (b)

Figure 1 – The babassu palm (a) and the babaçuais view (b). Source: CONAB (2010).

The exploration area of babaçuais extends to Piauí, Pará, Bahia, Ceará, Maranhão and Tocantins, according to IBGE (2007). This natural growth in this region is due to climate, light, topography and rainfall characteristics, that meet the needs of the plant. However, the extraction of babassu in this region is currently focused on the extraction of almond for the manufacture of soap, refined vegetable oil, olive oil and biofuel.

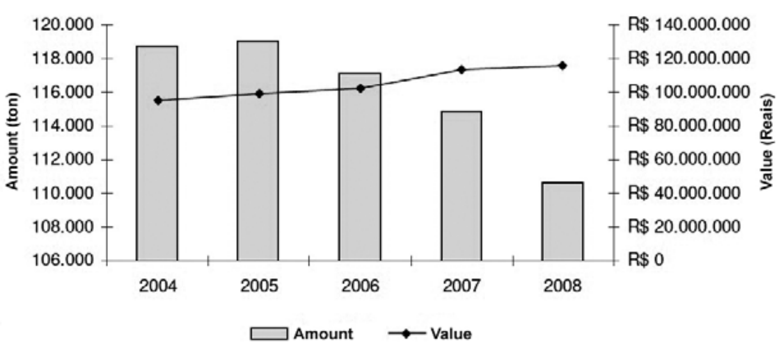


Figure 2 – National productivity of babassu extraction industry. Source: IBGE (2008).

The state of Maranhão concentrated 94.4% of the total national babassu production in 2008, and has the largest municipal producer, Vargem

Grande, located at the Baixo Parnaíba region, witch also has the worst human development index of the country (IBGE, 2008). The municipality of Vargem Grande has an area of 3247.383 km^2 and an estimated population of 76217 inhabitants (IBGE, 2010). This city produced about 5805 tons of babassu almond in 2008, equivalent to 5.2% of the national production (IBGE, 2008).

2.2 THE BABASSU COCONUT

The babassu spreads over an area of approximately 14.5 million hectares with a potencial production estimated at 15 million t/year. However, only 30% of the estimated potential is actually achieved (IBGE, 2008; CONAB, 2010).

The babassu extraction is one of the Amazon's ecological systems with greater economic, social and environmental potential. However, the production model that is currently used is focused on the kernel extraction from the fruit of the babassu palm (babassu coconut), which is the world's largest source of rape oil for domestic use, and also has industrial uses. Therefore, it is one of the major extractive products from Brazil, significantly contributing in some states economy.

(a) (b)

Figure 3 – (a) Agroindustrial babassu residue; (b) Division of the fruit.

As already said, the production model aims, at general aspects, the extraction of almond. Consequently, the layers involving that almond (epicarp, mesocarp and endocarp) become agro-industrial residues with huge potential for various scientific and industrial areas. Currently, the epicarp and endocarp are used as charcoal and crafts, while the mesocarp is already marketed as flour for human consumption and animal feed.

Vegetable fibers are increasingly used in the construction field, particularly in regards to engineering advances and new materials technologies. In his work, Franco (2010) describes the chemical composition of the babassu epicarp (region of the fiber concentrations) and got values of 17.8% of lignin; 62.2% of cellulose and 13.0% of hemicellulose. Therefore, bassassu residues (especially the epicarp), present a potential material for producing new materials, which will be reflected as a technology for social development of the main producing areas in Brazil.

2.3 CONTEXTUALIZATIONS ON PARTICLEBOARDS

Agro fibers are materials that have an approximately uniform geometry, tiny diameter over its length, and quite different nature, varying according to their physicochemical properties (FRANCO, 2010).

In addition, vegetable fibers are widely available in most of the developing countries, obtained from logging or annual trees. Cellulosic fibers have several interesting features, such as low density, renewable nature, biodegradable, availability at low cost and wide variety of morphologies and aspect ratios (TONOLI, 2009).

There are several definitions relating to particleboards. These panels may consist of a homogeneous or multiple layers, depending on the surface finishing and bonding strength of the inner layer, improving the degree of compaction plate. Typically, the particleboards are made from wood particles randomly distributed through the incorporation of an adhesive and further application of pressure and temperature to obtain the final product (IWAKIRI, 2005).

Wood panel can be defined as product of wood elements obtained from the reduction of solid wood and reconstituted by adhesive bonding

(IWAKIRI, 2005). These structures were produced in Germany in the early 40s, influenced by the advent of World War II, which was used as an alternative method due to the difficulty of obtaining good quality wood (MENDES et al., 2010).

Those particleboards can be produced in a wide variety of types and quality, depending on the wood species and type of resin and could be employed in several areas, such as the construction industry, furniture, shipbuilding, agricultural buildings and building industries.

The particleboards are also proposed as a sustainable destination of lignocellulosic materials, such as agro-industrial by-products. According to Fiorelli et al. (2012), Brazilian agribusiness has numerous lignocellulosic residues with great potential for use in the manufacture of particleboards.

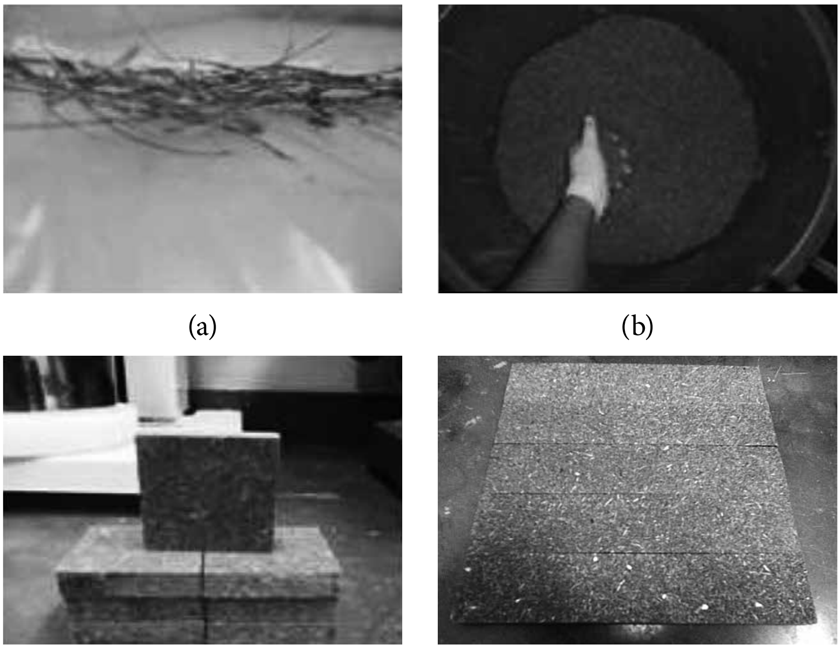
2.4 LIGAND-BASED POLYURETHANE RESIN OF CASTOR OIL

Abundant in Brazil, the castor oil is extracted from the seed of the plant (*Ricinus communis*), found in tropical and subtropical regions of the country. It is a viscous liquid obtained by squeezing the seeds or by solvent extraction. The adhesive is obtained by mixing the prepolymer with polyol at weight ratio of 1:2 (DIAS, 2005). The polyurethane based on castor oil resin is a more sustainable proposal to replace the resins based on formaldehyde, generally used by the panel industry.

As an alternative to replace the toxic adhesives used commercially and based on the results of work undertaken by Nascimento (2010) and Bertolini (2010), this study evaluated the effectiveness of castor oil polyurethane resin application in the production of particleboards made of babassu husk fibers.

3. MATERIALS AND METHODS

The agroindustrial by-product of babassu used in the production of particleboards was obtained in Vargem Grande, Maranhão, in an almond extraction industry and Chapadinha, in a pool of coconut breaks of babassu.



(a) (b) (c) (d)

Figure 4 – (a) Babassu fibers. (b) fibers after milling. (c) specimens of babassu particleboard panels. (d) babassu panel.

3.1 PHYSICAL-CHEMICAL CHARACTERIZATION OF BABASSU FIBER

Initially, it was proposed a physic-chemical characterization of babassu husk fibers by determining the bulk density (MOURA et al., 2002), hydrogen potential (pH) (VITAL, 1973) and chemical components (VAN SOEST, 1991).

3.2 PRODUCTION OF PARTICLEBOARDS

To obtain the particles, the waste was taken to the milling knives (Figure 5a) with 8 mm mesh to the core (inner layer) and 4mm mesh (outer layers). After grinding, the particles were sieved (Figure 5b) to separate them according to their particle size. Therefore, it was used the particles between 4 and 8 mm for the inner layer and particles up to 4 mm for the outer layers.

(a) (b)

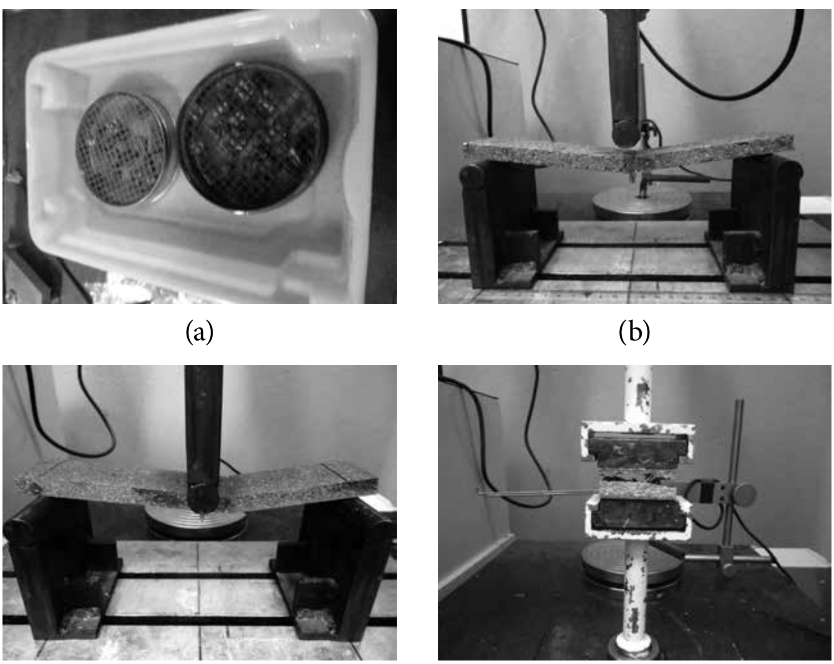
Figure 5 – Grinding of the material (a) and granulometric division (b).

The procedure adopted for the particleboards manufacturing began with the particles were brought to the mixer for 10 minutes. The proportion of resin used was 15% of the dry weight of raw material for the sides and 12% for the core. After mixing, the material was placed in a forming mold and inserted into the thermo-hydraulic press at a temperature of 100 °C for 10 minutes, with an average pressure of 5 MPa and a nominal density of 900 kg/m³. This density was required by the characteristics of the fiber, since the material used is too dense to form an adequate volume of particles in the mold. Therefore, there was the need to develop panels with high density.

After removing the panels from the thermo-hydraulic press, they were stacked for 72 hours, which ensured the continuation of the healing process of the resins for subsequent squaring and cutting of specimens, following the recommendations of the Brazilian standard NBR: 14810-1:2006 - Standard for Plywood Sheets.

3.3 PARTICLEBOARD CHARACTERIZATION

Tests were performed to analyze the physical (density, thickness swelling (TS) and absorption of water (Ab) in 2 and 24 hours (Figure 6a)) and mechanical properties (modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB) (Figure 6 b, c, d)) following the recommendations of the Brazilian standard NBR: 14810-1:2006. Such tests are usually performed by the industries to verify the quality of their products.



(a) (b) (c) (d)

Figure 6 – Test of water absorption and swelling (a). Bending tests (b,c). Internal bond (d).

4. RESULTS AND DISCUSSION

4.1 PHYSICO-CHEMICAL CHARACTERIZATION OF BABASSU FIBER

The results of mean value fiber density, pH and extractive material in the region of babassu epicarp are presented in Table 1.

Table 1 – Mean values of bulk density and pH babassu husk fiber

Parameter	Bulk Density (kg/m^3)	pH
Mean value	1,373 ± 0009	5.51 ± 0.035

Regarding the bulk density and pH it is possible to observe the similarity between the values found for the babassu husk fiber and wood (1,250 and 4.48) (FIORELLI et al., 2014). The very acidic pH inhibits the chemical reactions of the resin curing process, damaging the bonding (IWAKIRI, 2005).

As the results obtained in the chemical analysis of the fiber (Table 2) showed, it is evident the potential of lignocellulosic agroindustrial waste of babassu due to the concentration of lignin and hemicellulose in that material.

Table 2 – Mean values of the chemical composition of the babassu husk fiber.

Component	Lignin (%)	Cellulose (%)	Hemicellulose (%)
Mean value	35.75	32.32	20.88

The content of cellulose in fibers is closely related to the mechanical properties of particleboards. Lignin contributes to the adhesion mechanisms. Similar amounts of cellulose and lignin were identified for residual fibers and wood (FIORELLI et al., 2014).

4.2 PHYSICO-MECHANICAL PARTICLEBOARDS

Table 3 shows the results of the physical properties of the tested boards. The average value of density was 912 kg/m^3, so that panels are classified as high density product.

The wood particleboards, when exposed to moisture, also go through changes. In some cases the magnitude of this property is a limiting factor in the use of this product. Therefore, the results obtained with the test of water absorption and thickness swelling are very significant. The babassu specimens showed high values of TS in 2 hours, 13.1 ± 5.4 over 8% recommended by the ABNT 14810:2006 and it is lower than the 35% recommended by the normative standard CS 236-66:1968 for particleboards with 800 kg/m^3.

Table 3 – Average values of physical properties.

<table>
<tr><th colspan="2">Physical properties</th><th>Experimental</th></tr>
<tr><td colspan="2">Density (kg/m^3)</td><td>912 ± 48.7</td></tr>
<tr><td rowspan="2">TS (%)</td><td>2 hours</td><td>13.1 ± 5.4</td></tr>
<tr><td>24 hours</td><td>57.6 ± 17.5</td></tr>
<tr><td rowspan="2">Ab (%)</td><td>2 hours</td><td>31.9 ± 16.2</td></tr>
<tr><td>24 hours</td><td>76.15 ± 17.5</td></tr>
</table>

The mechanical properties of the panels under study showed high values considering the strength of the material (Table 4). The MOR average value of 33.81 MPa fits the protocol recommended for high density panels by ABNT 14810:2006 which requires a minimum value of 18 MPa and also by CS 236-66:1968 standard, that prescribes a minimum value of 16.8 MPa.

The IB presented an average value of 1.47 MPa, above recommended for high density panels by ABNT 14810:2006 which requires a minimum value of 0.4 MPa.

Table 4 – Average values of mechanical properties.

MOR (MPa)	MOE (MPa)	IB (MPa)	Energy (J/m2)
33.81 ± 6.4	2,034 ± 304	1.47 ± 0,2249	3999 ± 773

Knowing the mechanical properties of wood has a great importance due to their influence on the structural performance and strength. It was observed satisfactory values of these properties.

The results obtained in the mechanical and physical properties were in accordance with the American Standard ANSI A208.1:1993 that specifies the performance properties required for particleboards, where the panels under study can be categorized as high-density H2. In the laboratory it was possible to produce panels of babassu hisk fibers with average values of physical and mechanical properties, and variability, equivalent to those made of wood shavings on an industrial scale.

5. CONCLUSIONS

Supported by the NBR 14810:2006 and CS 236-66:1968 standards, the babassu husk waste has high potential in the production of particleboards, since the average values of physical and mechanics properties are above the minimum recommended by them. The polyurethane resin bi-component based on castor oil was efficient in the adhesion of the particles of babassu.

ACKNOWLEDGEMENT

The authors thank the Foundation for Research and Technological Development of Maranhão (Fapema), the Center for Agricultural and Environmental Sciences, Federal University of Maranhão, the Faculty of Animal Science and Food Engineering, University of São Paulo.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

ALBIERO, D.; MACIEL, A. J. S.; GAMERO, C. A. Desenvolvimento e projeto de colhedora de babaçu (*Orbignya phalerata* Mart.) para agricultura familiar nas regiões de matas de transição da Amazônia. **Acta Amazonica**, v. 41, n. 1, p. 57-38, 2011. doi:10.1590/S0044-59672011000100007.

AMERICAN NATIONAL STANDARDS INSTITUTE. **Mat-formed wood particleboard:** Specification ANSI A208.1. National Particleboard Association, Gaithersburg. 1993. 9p.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS**. NBR 14810**. Chapas de madeira aglomerada. Rio de Janeiro, 2006. 51p.

BALICK, M. J.; PINHEIRO, C. Babaçu (*Orbignya phalerata*). In: CLA,. J.; SAMPAIO, P. & CLEMENT, C. (EDS.). **Biodiversidade Amazônica: Exemplos e Estratégias de Utilização. Óleos Industriais.** Manaus, Instituto Nacional de Pesquisa da Amazônia, SEBRAE, 2000.

BERTOLINI, M.S. **Emprego de resíduos de *Pinus sp* tratado com preservante CCB na produção de chapas de partículas homogêneas utilizando resina poliuretana a base de mamona.** 2011. 126 p. Dissertação (Mestrado em Ciência e Engenharia de Materiais), Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2011.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Conjuntura mensal da amêndoa do babaçu**. 2010. Available at: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/14_07_17_09_27_35_babacuagosto2014.pdf>. Accessed on: September 03.

DIAS, F.M. **Aplicação de resina poliuretana à base de mamona na fabricação de painéis de madeira compensada e aglomerada.** 2005, 15 p. Tese (Doutorado em Ciências e Engenharia de Materiais), Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2005.

FIORELLI, J. et al. Particulate composite based on coconut fiber and castor oil polyurethane adhesive: An eco-efficient product. **Industrial Crops and Products**, v. 40, p. 69-75, 2012. doi:10.1016/j.indcrop.2012.02.033.

FIORELLI, J.; GOMIDE, C. A.; LAHR, F. A. R.; NASCIMENTO, M. F.; SARTORI, D. L.; BALLESTEROS, J. E. M.; BUENO, S. B.; BELINI, U. L. Physico-chemical and anatomical characterization of residual lignocellulosic fibers. **Cellulose**, v. 21, p. 3269-3277, 2014.

FRANCO, F. J. P. **Aproveitamento da fibra do epicarpo do coco babaçu em compósito com matriz de epóxi: estudo do efeito do tratamento da fibra.** 2010. 77 p. Dissertação (Mestrado em Ciências e Engenharia de Materiais) – Centro de Ciências Exatas e da Terra, Universidade Federal do Rio Grande do Norte, Natal, 2010.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). **Censo de extrati-**

vismo. Indicadores de volume. Rio de Janeiro, 2007.

______. **Censo de extrativismo.** Indicadores de volume. Rio de Janeiro, 2008.

______. **Censo de extrativismo.** Indicadores de volume. Rio de Janeiro, 2010.

IWAKIRI, S. **Painéis de madeira reconstituída.** Curitiba, Paraná: Fupef, 2005. 247p.

KAWABATA, C. **Desempenho térmico de diferentes tipos de telhado em bezerreiros individuais.** 2003. 94 p. Dissertação (Mestrado em Zootecnia) – Faculdade de Zootecnia e Engenharia de Alimentos, Universidade de São Paulo, Pirassununga, 2003.

MEIRELLES FILHO, J. C. **O Livro de Ouro da Amazônia:** Mitos e verdades sobre a região mais cobiçada do planeta. 4 ed. São Paulo: Ediouro, 2004. 397p.

MENDES, R.F. et al. Painéis aglomerados produzidos com bagaço de cana em associação com madeira de eucalipto. **Scientia Forestalis**, v. 38, n. 86, p. 285-295, 2010.

MOURA, M. J.; FIGUEIREDO, M. M. **Aplicação das técnicas de picnometria de gás e de porosimetria de mercúrio à caracterização da madeira de *E. globulus*.** Coimbra: Labgran, 2002.

NASCIMENTO, A. R. T. Riqueza e etnobotânica de palmeiras no território indígena Kraho, Tocantins, Brasil. **Floresta**, v. 40, n. 1, p. 209-220, 2010. doi: 10.5380/rf.v40i1.17112.

SILVA, D. J.; QUEIROZ, A. C. **Análise de alimentos**. 3. ed. Viçosa, Minas Gerais: Editora da Universidade Federal de Viçosa, 2006. 235p.

TONOLI, G. H. D. **Fibras curtas de Eucalipto para novas tecnologias em fibrocimento**. 2009. 148 p. Tese (Doutorado em Ciências e Engenharia de Materiais) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2009.

U.S. DEPARTMENT OF COMMERCE **Mat-formed Wood Particleboard**. Commercial Standard CS 236-66, 1968.

VAN SOEST, P. J. **Nutritional ecology of the ruminant**. New York: Cornell University Press, 1994.

VITAL, B. R. **Effects of species and panel densities on properties of hardwood particleboard**. Dissertation – University of Wisconsin, 1973.

PARTICLEBOARDS PRODUCED WITH AGROINDUSTRIAL WASTES OAT HULLS (*AVENA SATIVA*) AND REFORESTATION WOOD

Luciano Donizeti Varanda, Amós Magalhães de Souza and **Sabrina Fernanda Sartório Poleto**
University of São Paulo, Department of Materials Engineering, São Carlos, SP.
E-mail: lu.varanda@sc.usp.br; amosmag@gmail.com and sabrina.poleto@gmail.com

Diogo Aparecido Lopes Silva
University of São Paulo, Department of Production Engineering, São Carlos, SP.
E-mail: diogo.apls@gmail.com

Túlio Hallak Panzera
Federal University of São João del Rei, Department of Mechanical Engineering, São João del Rei, MG.
E-mail: tuliopanzera@hotmail.com

André Luis Christoforo
Federal University of São Carlos, Department of Civil Engineering, São Carlos, SP.
E-mail: alchristoforo@yahoo.com.br

Francisco Antonio Rocco Lahr
University of São Paulo, Department of Structural Engineering, São Carlos, SP.
E-mail: diogo.apls@gmail.com

ABSTRACT: The large volume of waste generated by agroindustrial enterprises enables the development of alternative materials and sustainable, highlighting the particleboards. This paper presents a study of production and evaluation of panels of *Eucalyptus grandis* and oat hulls (*Avena sativa*), bonded under pressure with polyurethane resin based on castor oil. Physical-mechanical performance of these panels was evaluated based on standards ABNT NBR 14810:2006, BS EN 312:2003 and CS 236-66:1968. Accelerated aging performance was preceded according to the standard APA PRP 108:1994. Variance analysis (ANOVA) was employed to investigate the influence of the proportion of particles (compositions between particles of both materials), adhesive and interaction between these factors in physical and mechanical properties of the panels produced. Experimental factor proportion of particles was significant at all the physic-mechanical properties before and after panels aging. For panels without accelerated aging, all evaluated properties showed results that met national and international standards requirements. After particleboards accelerated aging, only a few experimental conditions met the cited requirements.

Keywords: Waste recovery. Physical-mechanical properties. Lignocellulosic particles. Analysis of variance.

1. INTRODUCTION

After industrial revolution, in eighteenth century, gradual increasing in production of goods and services has implied positively both in improving life quality and in caring people needs.

In contrast to large scale production of goods and services serious environmental aggravating had emerged. Irreversible disturbances were generated by human activity and exacerbated by intensification of industrial activities from the 1950s. Consequently, great global problems were observed such as increased levels of pollution in great centers urban-industrial, global warming, deforestation, besides a lot of damage to ecosystems.

It is relevant to note that humanity has experienced a series of transformations, not only environmental, but also social, political, cultural, economic and technological (BAPTISTA, 2010). But back to emphasize the environmental character, the main focus of this work, is the fact that not only corrective measures, but mainly preventive continue to be discussed and implemented to achieve satisfactory results in relation to sustainable development.

Environmental sustainability is a much discussed topic currently, as part of actions and strategies of most companies required to solve questions related to reusing waste resulting from human activities.

In Brazil, agro-industrial wastes are available in large volumes and have significant potential for employment. According Tamanini and Hauly (2004), wastes production in these segments is about 250 million tons per year.

Among agroindustrial wastes, oat hulls (result of oat cereal beneficiation process) have great potential in relation to raw material availability. According to Webster (1996), oat hulls correspond to 30% by weight of oat cereal, whose production, in Brazil, reached 400 000 tonnes in 2011 (Brazilian Institute of Geography and Statistics - IBGE, 2013).

Thus, Brazilian production of oat hulls represented about 120 tonnes in 2011. The hulls, a byproduct of oat cereal, are discarded during its processing, becoming a environment pollutant. Therefore, it is necessary and essential to establish alternatives for reuse.

In turn, particleboards are notable in the scenario of wood products, precisely because they are the main product for a range of other wood industries sectors. Mendes et al. (2012) claim that the civil construction and furniture industries are the main responsible for the technological evolution of the particleboard manufacturing industries.

Particleboard is the most consumed wood-based product in the world. In Brazil, the production of particleboard is expanding besides continue growing prospects for the coming years (Brazilian Association of the Wood Panels Industry - ABIPA, 2014).

The particleboard may be produced from any lignocellulosic material which imparts high mechanical strength and pre-established specific weight, exactly by lignocellulose structure be similar to the timber (ROWELL; HAN; ROWELL, 2000).

In the production of wood-based panels, another factor worth mentioning is the resin used. Traditionally, such panels are produced with resins based on formaldehyde, that exhibit inconvenience as the emanation of formaldehyde during pressing, making it problematic in countries with strict environmental control. With the development of polyurethane resin based on castor oil, an alternative resin emerges from natural sources. This resin is considered not aggressive to the environment and to human beings, derived from Brazilian technology.

In this context, the aim of this work is to produce particleboards with *Eucalyptus grandis*, oat hulls (*Avena sativa*) and polyurethane resin based on castor oil and evaluate their physic-mechanical and accelerated aging performances. Another aim this study is the use of wastes, as reforestation wood *Eucalyptus grandis* (residue from sawmills) and oat hulls (agroindustrial waste) in particleboards production.

2. LITERATURE REVIEW

2.1. PARTICLEBOARDS

Particleboards emerged in Germany in the early 1940s as a way to enable the use of wood waste, considering the difficulty of obtaining good quality wood for plywood production, because the isolation of Germany during world War II (IWAKIRI, 2005).

In Brazil, records about the history of particleboard manufacturing are divergent. Barros Filho (2009) describes in detail the entire history of particleboard panels in the world, emphasizing the production in Brazil.

There are several definitions for particleboards. Iwakiri (2005) considers a panel made from wood particles by incorporating a synthetic adhesive and reconstituted in a random matrix, consolidated by applying heat and pressure in the press hot. Other lignocellulosic materials can also be used in the manufacture of particleboards.

According to Campos and Rocco Lahr (2004), the manufacture of wood products, especially wood-based panels, has become an interesting alternative in the context of available materials for applications in construction, and the furniture industries naval, among others. Thus, the production of wood-based panels is relevant to the forest sector and consequently for the Brazilian economy, because it is responsible for generating a significant number of direct and indirect jobs. However are necessary investments in technologies aimed at optimizing wood-based panels production, allowing further development this sector.

Stages of the production process of particleboards are described by several authors, as Maloney (1996), Iwakiri (2005) and Barros Filho (2009), among others.

2.2 ADDITION OF FILLERS IN WOOD PANELS

Raw material used in the particleboards production can be either reforestation woods as the use of various types of forest or agricultural wastes (DACOSTA, 2004).

Mendes (2008) says that waste generated by Brazilian agribusiness has potential use in various applications, such as composting (organic fertilizer), extraction of oils and resins, manufacture of particleboards, briquettes production, among others, besides to contribute to the reuse of wastes, also add value to them. Brazil presents a great potential for production of renewable resources such as agricultural and forestry products. The proper use of these wastes helps minimize environmental and energy problems, besides generate products with relevant applications in industry.

Aiming to improve some properties of particleboards, some chemicals are additioned during adhesive application such as catalyst or hardener, paraffin emulsion, fire retardant and repellent to wood decay organisms. According to Maloney (1977) and Iwakiri (2003) those are additives commonly used in the particleboards production.

Several researchers have succeeded in development, characterization and application of wood-based panels composed of agro-industrial wastes such as Arruda (2009), Melo et al. (2009), Pierre (2010), Bertolini (2011), Fiorelli et al. (2013), Ferro (2013), Macedo (2013), Castro Junior et al. (2014), among others.

2.3 RAW MATERIALS USED

Possible solutions involving alternative inputs, emission control and the many possibilities of waste reusing should be improved to develop a product that is less harmful to the planet along its life cycle.

2.3.1 Oat Hulls

Oats, cereal of *Avena* genus and *Gramineae* family, began to be cultivated recently, compared to crops such as wheat. Cultivation began in northern Europe due to the increased use of horses as working animals, about two thousand years B.C. (CERES, 2011).

According to Sá (1995), there are multiple possibilities of use of oats as grain production (human and animal food), forage (hay, silage or cut and delivered fresh in the trough), ground cover (protection and improvement of soil physical conditions), besides inhibiting infestations of invasive plants.

In Brazil, agro-industrial wastes are available in large volume, with significant potential for employment. Among these organic wastes, the oat hulls generated in the process of processing of oat cereal has great potential especially in relation to the availability of raw material. According to Webster (1996), oat hulls is about 30% by weight oat cereal. The Brazilian oat production reached 400 000 tonnes in 2011 (Brazilian Institute of Geography and Statistics - IBGE, 2013). Thus, the Brazilian production of oat hulls represented about 120 000 tonnes in 2011. Oat hulls which is byproduct of oat cereal, is discarded during the processing of cereal, becoming a pollutant to the environment. Therefore, it is necessary and essential to establish alternatives for reuse.

2.3.2 Eucalyptus *Wood*

Currently, *Eucalyptus* wood is grown in almost all the world, for being a genus that possess easily adaptable to various climatic conditions. Most species planted in Brazil presents rapid growth as a result of high quality genetic material used. The production of wood and its derivatives occurs on a large scale, due to the large demand for wood by Brazilian forestry market (MALINOVSKY, 2002).

According to Garcia and Mora (2000), the *Eucalyptus* wood is highly versatile, with opportunities to use in various segments such as essential oils (pharmaceuticals, hygiene products and cleaning), cellulose (various papers, viscose, acetate, medications coating), treated wood (poles and fences), charcoal and firewood, lumber (construction, furniture industry and toys), wood-based panels (veneer, plywood, waferboard, particulate and fiber), bee products (honey, propolis), among others.

2.3.3 Adhesive

Adhesive is a component of great importance in wood-based products development, with significant technical and economic implications, which may represent up to 50% of the total cost of the final product (CARNEIRO et al., 2004).

Main types of resin used for the panels of wood-based industries are urea formaldehyde (UF), phenol formaldehyde (FF), melamine formaldehyde (MF) and diphenyl methane diisocyanate (MDI). As the adhesive is component of the higher cost of the panel, it is necessary to define the type and amount of resin to be used, seeking to improve the cost-benefit ratio (MARRA, 1992). According to Saldanha (2004), some industries produce composite melamine-urea-formaldehyde (MUF), and phenol-melamine-urea-formaldehyde (PMUF) as an alternative for the panels production with improved dimensional stability and cost similar to when using only one type of resin.

Several factors may influence the performance of bonding, related to wood and the adhesive used. As factors related to wood, there are anatomical, chemical and physical characteristics of this material (LIMA et al., 2007).

In relation to the adhesive, the factors influencing the performance of gluing are the physical chemical properties (viscosity, gel team, solids content and pH) and the composition of this (KOLLMANN, KUENZI and STAMM, 1975). Factors belonging to the process particleboards producing also affects the bonding, mainly the pressing variables, as temperature, time and pressure cycle (VICK, 1999).

Researchers have developed a polyurethane resin base on castor oil, which has several advantages such as high resistance to the action of water and ultraviolet, manipulation at room temperature, high mechanical strength and natural and renewable source, abundant throughout the country (JESUS, 2000).

Internationally known as castor oil, castor bean (*Ricinus communis*) is a plant from the *Euphorbiaceae* family, from which castor oil, which is used in the manufacture of polyurethane resin based on castor. According to Peterson (1964), panels bonded with polyurethane resin give high moisture resistance and superior mechanical properties compared to the panels bonded with phenolic resins, and does not emit formaldehyde.

2.4 PARAMETERS THAT INFLUENCE PHYSICAL AND MECHANICAL PERFORMANCE OF PARTICLEBOARDS

Wood-based panels quality evaluated by their physical and mechanical properties such as static bending (modulus of elasticity and modulus of rupture), internal bond, density, pullout resistance of connectors, water absorption, thickness swelling and other (IWAKIRI, 2005).

Maloney (1977) says that factors such as moisture content and dimensional homogeneity of the particles directly influence the particleboard properties. Another factor that influences panel mechanical performance is their density. This should be as uniform as possible throughout panel thickness, to ensure uniformity in their physical-mechanical properties.

Particleboards are generally produced with a density in the range from 0.60 to 0.70 g/cm^3. According to Kelly (1977), is required a minimum degree of compression of the wood particles in order to consolidate the particleboard during the pressing cycle. The compression ratio is the relation between the density of the panel and the density of the wood used. Values between 1.3 and 1.6 are considered acceptable to occur proper contact between the wood particles and formation of the adhesive bond between them (MOSLEMI, 1974).

Adhesive is an important factor in particleboard production and the amount to be used is based on dry weight of the particles. Iwakiri (2005) says that normally the amount of adhesive for particleboard production should be in the range 6 to 12%. Attention in homogeneity of the distribution of adhesive on the surface of the particles, to ensure uniform properties over the entire length of the panel produced must be take in account.

Another important point is to achieve physical and mechanical properties which meet the regulatory requirements, producing panels acceptable by the market (MENDES, 2001).

2.5. ACCELERATED AGING

Tests simulating exposure to severe weather conditions have been relevant in seeking new applications for particleboard (BERTOLINI et al., 2013). The accelerated aging test also evaluates the durability of the panels.

Several studies with accelerated aging panels were developed, as McNatt and Link (1989), Kojima, Norita and Suzuki (2009), Kojima and Suzuki (2011), Garzón et al. (2011) and Bertolini et al. (2013).

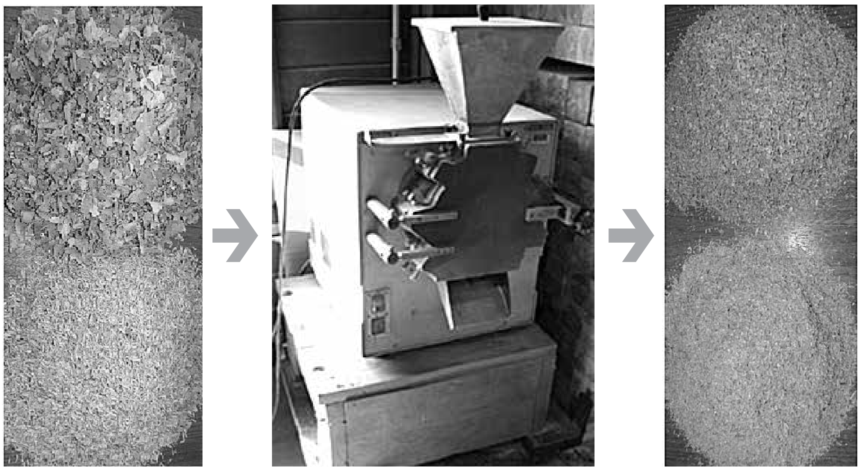
3. EXPERIMENTAL PROCEDURES

3.1 PARTICLES PRODUCTION

Species of *Eucalyptus grandis* (apparent density of 640 kg/m^3) and oat hulls waste (apparent density of 290 kg/m^3) were used as raw material sources to the particles production process. The production of particles was carried out by using knifes mill type Willye (Marconi brand, MA 680 model), with 2.8 mm of sieve opening.

The *Eucalyptus grandis* wood was obtained from companies in the city and region of São Carlos, São Paulo state, Brazil, while oat hulls waste (*Avena sativa*) were obtained from industry sector. For both cases, a particle size analysis was performed through a vibration process in order to determine the final dimensions of particles. SOLOTEST was the equipment used for that, with sieves of 7, 10, 16, 30, 40 and 50 meshes. Samples mass of 200 grams were defined for each raw material source by using a balance equipment (Marconi brand, model AS 5000C), with an average sensitivity of 0.1 grams. Then, all samples were mechanically separated and particles that passed through the 50 mesh sieve were considered "fine". Each vibration process lasted ten minutes, the final moisture content of particles was 9% on overage, and there were three replicates of samples for both wood and oat hulls material.

Regarding the size distribution, 70 to 75% of particles were between 0.595 to 1.190 mm (16 to 30 mesh), in accordance with prior studies on the topic (BERTOLINI, 2011; DIAS 2005). Fig. 1 shows the particles of both materials before and after the milling process, and the milling machine used.



(a) (b) (c)

Figure 1 – (a) Particles before the milling process, (b) mill used and (c) particles after the milling process.

3.2 PANELS MANUFACTURING

Particleboards with one layer (homogeneous panels) and with high density were produced. For the matrix phase of panels were used castor oil based on polyurethane resin (PU) with solids content of 100%. This resin is bi-component, since 1:1 proportion between the prepolymer and the poliol components were applied. The 1:1 resin proportion was adopted because of excellent performance achieved by prior researches of the LaMEM lab (Laboratory of Wood and Timber Structures), when using this proportion (BERTOLINI, 2011; DIAS, 2005). The polyol resin component is derived from vegetable oil with a density of 1.10 g/cm^3, and the other component (prepolymer) is the polyfunctional isocyanate with a density of 1.24 g/cm^3, both supplied by the industry sector. This resin was used due to the excellent performance achieved in previous studies, developed in the LaMEM with wood panels (BERTOLINI, 2011; FERRO, 2013; SOUZA, 2012).

For each panel composition it was used 640 g of particles and the PU resin in different proportions, 10, 12 and 14% relative to the dry mass of particles. The amount of 640 of particles per panel was defined to ensure a high density (above 800 kg/m³) of the final manufactured panels.

Regarding to the pressing process of panels the set of parameters used in press cycle was: pressure of 4 MPa, time of 10 minutes, and temperature of 100°C. Such parameters as well as the dimensions of the residues (residues with size distribution similar to this study) were already evaluated by Dias (2005), that is why they were also adopted in the present study. Fig. 2 shows the panels manufacturing.

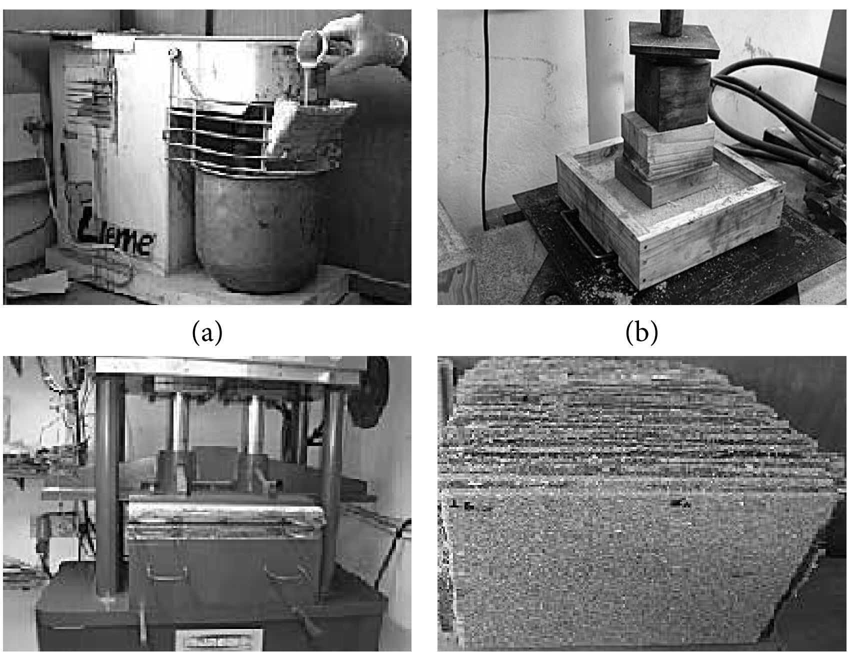


Figure 2 – (a) equipment that mixes the resin and particles, (b) pre-press machine (c) hydraulic press machine and (d) the final manufactured panels.

The particles of both materials were weighed and mixed with resin for five minutes approximately. The glue machine used was a Lieme brand, BP-12 SL model, as showed in Fig. 2a. Then, the particles with glue were subjected to small press (about 0.013 MPa). The pre-pressing of panels was performed by manual the pre-press machine in Fig. 2b. The last step was the pressing process in a semi-automatic press Marconi brand, MA 098/50 model, as showed in Fig. 2c.

For each experimental condition (EC), six panels with the same particles proportion were produced. In total, seventy-two panels were produced with nominal dimensions: 280x280x10 mm.

After that, 72 hours was necessary to fully cure the PU resin with particles and the panels reach equilibrium moistures. All manufactured panels were squared being removed 10 mm from each edge in view of achieving final dimensions of 260x260x10 mm.

As it can be seen in tab. 1, all particleboards were divided into groups according to the different amounts of *Eucalyptus grandis* and oat hulls particles.

Table 1 – Experimental factors and levels.

EC	Proportions constituents
1	100% *Eucalyptus grandis* - 10% resin
2	100% *Eucalyptus grandis*- 12% resin
3	100% *Eucalyptus grandis*- 14% resin
4	(85% *Eucalyptus grandis*- 15% Oat hulls) - 10% resin
5	(85% *Eucalyptus grandis* - 15% Oat hulls) - 12% resin
6	(85% *Eucalyptus grandis* - 15% Oat hulls) - 14% resin
7	(70% *Eucalyptus grandis* - 30% Oat hulls) - 10% resin
8	(70% *Eucalyptus grandis*- 30% Oat hulls) - 12% resin
9	(70% *Eucalyptus grandis* - 30% Oat hulls) - 14% resin
10	100%Oat hulls- 10% resin
11	100%Oat hulls- 12% resin
12	100%Oat hulls- 14% resin

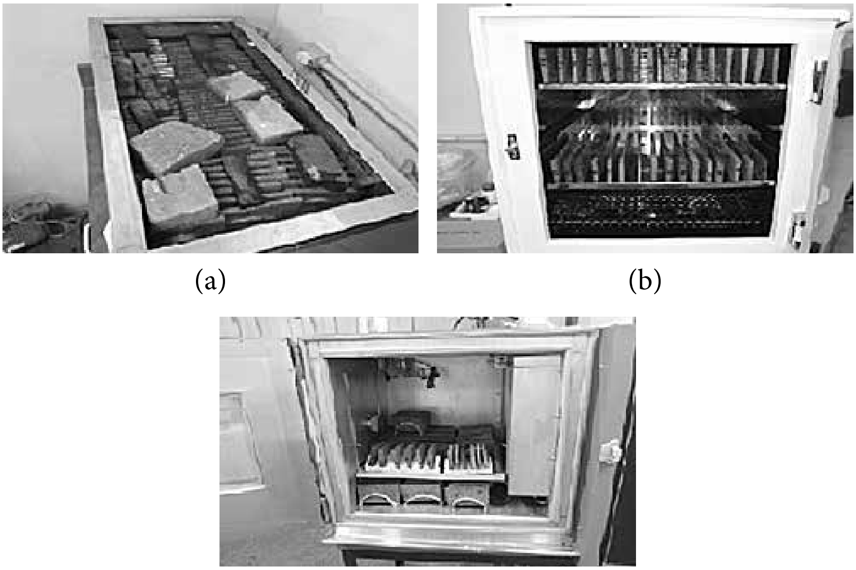
3.3 PHYSICAL-MECHANICAL TESTS, ACCELERATED AGING TESTS AND RESULTS ANALYSIS

In each panel, it was removed one specimens for each property evaluated. The mechanical properties evaluated were modulus of rupture (MOR) and internal bond (tension perpendicular to the panel surface). The physical property evaluated was thickness swelling after two hours of immersion in water. Physical and mechanical properties were evaluated for all EC before and after an accelerated aging process. Specimen dimensions as well as physical and mechanical tests were performed according to the ABNT NBR 14810:2006 standard.

In this study, the accelerated aging tests evaluated the exposure of the panels in the environment (critical conditions of heat and humidity) and its influence on physical and mechanical performance. These tests were conducted at the Laboratory of Construction and Ambience, Faculty of Animal Science and Food Engineering (FZEA - USP), in Pirassununga city, São Paulo state, Brazil.

The accelerated aging tests followed the APA PRP 108: 1994 standard, specifically APA D-1 Cycle method. The choice of selecting this method was due to recent findings of Kojima and Suzuki (2011), whose stated that among five conventional accelerated aging methods, APA D-1 Cycle was the least aggressive to the panels.

Fig. 3 shows the set of equipments used in accelerated aging tests.



(a) (b)

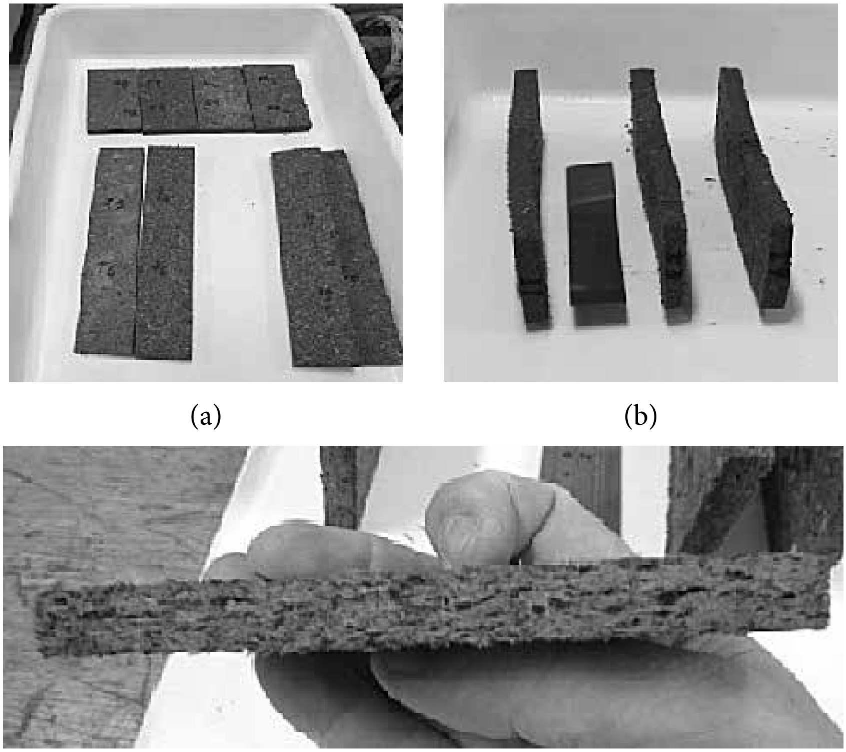
(c)

Figure 3 – (a) bath with circulation, (b) drying greenhouse and (c) climatic chamber.

The equipments used were: bath with water circulation of Marconi brand, MA 470 model (Fig. 3a), drying greenhouse of the New Ethics brand, 400-5 ND model (Fig. 3b) and the environmental chamber of the Thermotron brand, SM-S 3.5 model (Fig. 3c).

The set of process parameters used were: bath with circulation at 66 °C for eight hours, dried at 82 °C for 14.5 hours and climatizing with temperature of 20 ± 3 °C and humidity of 65 ± 2% during 1.5 hours.

The Fig. 4 shows some of the specimens after accelerated aging tests. As noted, the specimens were damaged with apparent defects of warping and delamination. Such damage occurred due to the severity of accelerated aging test adopted (APA D-1 Cycle).



(a) (b)

(c)

Figure 4 – Specimens with damage: (a) and (b) warping and (c) delamination.

The variance analysis (ANOVA) was used to investigate the influence of the proportion of particles (compositions between particles of both materials), adhesive and the interaction between these factors in the physical and mechanical properties of the panels. The significance level (α) was 5%, considering the null hypothesis (H0) the equivalence between the averages and the non-equivalence as the alternative hypothesis (H1). P-value greater than the significance level involves accepting H0, rejecting it otherwise. If points (data) are evenly distributed along a line, they are met the conditions of normality required for ANOVA model validation. Otherwise, the Box-Cox normalization was used. This normalization is a statistical fit that transform data in evenly distributed to finally validate the ANOVA model (MONTGOMERY, 2005).

4. RESULTS AND DISCUSSION

Table 2 shows average results of moisture content (MC) with variation coefficients (VC) and density (D) and compaction ratio (CR) ranges of the panels manufactured (before and after the aging process).

Table 2 – Average values of moisture content (MC) and ranges of the density (D) and compaction ratio (CR) before and after the aging process.

	Before aging	After aging
MC (%)	9.1 (6.8)	7.5 (6.4)
D (kg/m^3)	913 to 1016	758 to 927
CR	1.45 to 3.50	1.25 to 3.20

Note: in parenthesis are variation coefficients expressed in percentage (%).

Particleboards produced by Trianoski (2010) presented MC values from 9.4 to 10.2%, i.e., similar results to that obtained for this study when considering the before aging's panels result (9.1%). On the other hand, Trianoski (2010) MC result was a little above when compared to the after aging's MC result (7.5%) found in this study.

The reduction in MC after accelerated aging is mainly associated with the severity of the accelerated aging test, in which, at one stage, the panels were dried at 82 °C for a period of 14.5 hours, as described in the methodology.

The panels before accelerated aging had high density (above 800 kg/m^3) and after the accelerated aging test the panels showed medium and high density values (758 to 927 kg/m^3).

4.1 PHYSICAL PROPERTY

4.1.1 Thickness Swelling (2h)

Tab. 3 presents the average values of physical property thickness swelling after two hours of immersion in water, for the twelve experimental conditions (EC).

All results for the thickness swelling (2h) without the accelerated aging test were below the 8% stipulated by the ABNT NBR 14810: 2006 and CS 236-66: 1968 standards. The standard BS EN 312: 2003 does not set property values for the swelling in thickness (2h).

The thickness swelling (2h) after the accelerated aging process did not meet the requirements of the ABNT NBR 14810: 2006 and CS 236-66:1968 standards, except for the experimental conditions 1 and 2.

The results of thickness swelling (2h) before the accelerated aging process were consistent with those found by Bertolini (2011) and Weber (2011). The coefficients of variation obtained between 3.1 and 40.5%, were similar to those found by Bertolini (2011). The panels after accelerated aging showed results that resemble those obtained by Trianoski (2010).

Table 3 – Average values of thickness swelling - 2h (TS 2h) of the panels.

EC	Before aging		After aging	
	TS 2h (%)	VC (%)	TS 2h (%)	VC (%)
1	4.3	20.4	7.4	24.6
2	3.8	25.2	7.1	34.0
3	3.3	26.6	8.4	19.1
4	4.2	11.4	8.5	12.3
5	4.2	16.2	8.2	16.2
6	2.6	23.0	10.3	18.7
7	5.5	21.4	11.4	12.8
8	5.0	25.0	12.6	11.8
9	3.9	17.9	12.0	3.1
10	4.2	28.2	16.0	26.3
11	4.6	13.4	15.1	7.7
12	2.8	40.5	15.5	9.0

Tab. 4 shows the results of ANOVA for the average values of thickness swelling (2h).

Table 4 – P-values of the factors and interactions investigated in relation to thickness swelling - 2h (TS – 2h).

Experimental factors	Before aging	After aging
Proportion of particles	<u>0.002</u>	<u>0.000</u>
Resin	<u>0.000</u>	0.296
Proportion of particles - resin	0.598	0.263

The data of the thickness swelling (2h), before and after accelerated aging were distributed uniformly along the straight, in compliance with the conditions of normality required to validate the model of ANOVA.

Thickness swelling (2h) of the panels ranged between 1.5 and 7.1%. Analysis of variance shows that the experimental factors *proportion of particles* and *resin* were significant in the results of thickness swelling (2h), as shown in tab. 4.

The *proportion of particles - resin* interaction (before and after accelerated aging) were not significant, exhibiting p-values greater than 0.05, as shown in tab. 4.

The panels after accelerated aging showed thickness swelling (2h) values ranged from 4.7 to 24.0%. The analysis of variance showed that only the *proportion of particles* was a significant factor, as shown in tab. 4.

4.2 MECHANICAL PROPERTIES

4.2.1 Modulus Of Rupture (MOR)

Tab. 5 shows the average values of the modulus of rupture (MOR) for the twelve experimental conditions evaluated.

The reduction in MOR after accelerated aging is associated with the severity of the method (Cycle APA D-1).

The coefficients of variation remained in range of 8 to 32.3%, being similar to those obtained by Weber (2011).

For the MOR results without the aging process, all of them met the requirements of ABNT NBR 14810:2006, BS EN 312:2003 and CS 236-66:1968 standards, which set minimum values of 18; 16 and 11 MPa, respectively.

For the MOR values after the aging process, only the experimental conditions 3 and 6 (tab. 5) met the requirements of ABNT NBR 14810:2006. The BS EN 312:2003 standard had met their requirements in three experimental conditions (EC 3, 6 and 12). The CS 236-66:1968 standard had met their requirements in five experimental conditions (EC 2, 3, 6, 9 and 12), as shown in tab. 5.

Table 5 – Average values of modulus of rupture (MOR) of the panels.

EC	Before aging		After aging	
	MOR (MPa)	VC (%)	MOR (MPa)	VC (%)
1	18	19.5	10	24.9
2	19	14.2	11	18.2
3	24	14.0	22	11.4
4	18	18.6	9	17.2
5	18	8.0	10	10.9
6	24	16.5	19	17.9
7	20	14.6	6	24.3
8	20	21.5	8	24.4
9	21	20.2	13	18.7
10	24	17.1	6	25.5
11	25	16.1	9	32.3
12	27	11.0	16	28.9

Tab. 6 shows the results of ANOVA for the average values of MOR.

Table 6 – P-values of the factors and interactions investigated in relation to the MOR.

Experimental factors	Before aging	After aging
Proportion of particles	0.000	0.000
Resin	0.003	0.000
Proportion of particles - resin	0.555	0.061

Results of MOR before and after the accelerated aging process were uniformly distributed along the straight, in compliance with the conditions of normality required to validate the model of ANOVA.

MOR results of the panels ranged between 12 and 31 MPa. Analysis of variance showed that the experimental factors *proportion of particles* and *resin* were significant for both before and after the aging process, with p-values 0.000 and 0.003, respectively, as shows the tab. 6.

The *proportion of particles - resin* interaction (before and after accelerated aging) were not significant, exhibiting p-values greater than 0.05, as shown in tab. 6.

The manufactured panels after the accelerated aging process presented MOR values between 4 and 25 MPa. The experimental factors *proportion of particles* and *resin* were significant in the results of MOR, with p-values smaller than 0.05, as shows tab. 6.

4.2.2 Internal Bond

Tab. 7 shows the average values of the internal bond of the panels.

The variation coefficients obtained between 12.6 and 68.3%, were slightly higher than those found by Trianoski (2010).

Table 7 – Average values of internal bond (IB) of the panels.

EC	Before aging		After aging	
	IB (MPa)	VC (%)	IB (MPa)	VC (%)
1	1.84	32.7	0.73	28.3
2	2.56	24.5	0.79	34.5
3	2.50	13.8	2.53	35.5
4	1.65	34.3	0.39	21.3
5	1.55	40.4	0.53	51.2
6	1.83	32.9	1.07	31.3
7	1.74	24.8	0.21	47.5
8	2.37	18.3	0.33	38.4
9	2.06	45.3	0.73	32.7
10	1.60	13.7	0.12	56.3
11	1.99	12.6	0.25	68.3
12	1.52	39.6	0.68	49.3

For the internal bond results before the aging process, all of them met the requirements of ABNT NBR 14810:2006, BS EN 312:2003 and CS 236-66:1968 standards, which establish minimum values of 0.40, 0.40 and 0.48 MPa, respectively. The results were excellent, as they were above of the expected standard requirements.

Other studies also reported satisfactory results to the internal bond property (Mendes, R.; Mendes, L. and Almeida, 2010; Weber, 2011).

For the panels after the accelerated aging process, the requirements of ABNT NBR 14810:2006 and BS EN 312:2003, i.e. 0.40 MPa, did not meet in five experimental conditions: EC 4, 7, 8, 10 and 11 (tab. 7).

Tab. 8 shows the results of ANOVA for the average values of internal bond.

Table 8 – P-values of the factors and interactions investigated in relation to internal bond (IB).

Experimental factors	Before aging	After aging
Proportion of particles	0.011	0.000
Resin	0.609	0.000
Proportion of particles - resin	0.468	0.000

The data of the IB property before and after the accelerated aging process were uniformly distributed along the straight, in compliance with the conditions of normality required to validate the model of ANOVA.

IB results ranged between 0.72 and 3.24 MPa. Analysis of variance showed that only the experimental factors *proportion of particles* was significant to the IB results before the aging process, presenting p-value of 0.011, as showed in tab. 8.

The panels after the accelerated aging process show IB values between 0.04 and 3.40 MPa. The analysis of variance showed that all experimental factors were significant, with p-values smaller than 0.05, as shows tab. 8.

5. CONCLUSIONS

For the panels before the accelerated aging process, all the evaluated physical and mechanical properties have met the requirements of national and international standards;

After the accelerated aging process, only a few group of experimental conditions showed results in accordance with the standards' requirements;

The severity of the accelerated aging method caused a significant reduction of the physical and mechanical properties of panels;

The experimental factor *proportion of particles* was the most significant factor for all the physic-mechanical properties for both, before and after the accelerated aging process;

The experimental factor *resin* was significant in the thickness swelling properties, MOR (before the aging process), and was also relevant in MOR and IB properties after the aging process;

The *proportion of particles - resin* interaction was significant only in the values of IB after the accelerated aging process;

Even the panels produced with 10% resin obtained satisfactory results for all properties evaluated before the aging process.

ACKNOWLEDGEMENTS

The authors would like to thank FAPESP - São Paulo Research Foundation (process number 2010/14407-7) and CAPES - Agency for the Improvement of Higher Education Personnel for the scholarships granted and support research.

PERMISSION FOR PUBLICATION

It is the responsibility of the authors the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

APA – THE ENGINEERED WOOD ASSOCIATION. **APA PRP 108** - Performance Standards and Policies for Structural-Use Panels. Washington, 1994.

ARRUDA, L. M. **Propriedades de painéis aglomerados com resinas sintéticas a partir da mistura do bambu Guadua magna Londoño e Filg. e da madeira de Pinus taeda L**. 2009. 89 f. Monografia (Graduação) – Universidade de Brasília, Brasília, 2009.

ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DE PAINÉIS DE MADEIRA – ABIPA. **Números do setor em 2012**. Available at: <http://www.abipa.org.br/numeros.php>. Accessed on: August 05, 2014.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR14810** - Chapas de madeira aglomerada. Rio de Janeiro, 2006

BAPTISTA, V. F. A relação entre o consumo e a escassez dos recursos naturais: uma abordagem histórica. **Saúde e Ambiente**, Duque de Caxias, v. 5, n. 1, p. 08-14, 2010.

BARROS FILHO, R.M. **Painéis aglomerados a base de bagaço de cana-de-açucar e resinas ureia formaldeído e melamina formaldeído.** 2009. 99 f. Dissertação (Mestrado) – Rede Temática em Engenharia de Materiais – (UFOP – CETEC – UEMG), Ouro Preto, 2009.

BERTOLINI, M.S. **Emprego de resíduos de Pinus sp tratado com preservante CCB na produção de chapas de partículas homogêneas utilizando resina poliuretana à base de mamona.** 2011. 128 p. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Instituto de Física de São Carlos, Instituto de Química de São Carlos, Universidade de São Paulo, São Carlos, 2011.

BERTOLINI, M. S.; ROCCO LAHR, F. A.; NASCIMENTO, M. F.; AGNELLI, J. A. M. Accelerated artificial aging of particleboards from residues of CCB treated *Pinus* sp. and castor oil resin. **Materials Research**, São Carlos. v. 16, n. 2, p. 293-303, 2013. doi:10.1590/S1516-14392013005000003.

BRITISH STANDARD. **BS EN 312** - Particleboards – specifications. London, 2003.

CAMPOS, C. I.; ROCCO LAHR, F. A. Estudo comparativo dos resultados de ensaio de tração perpendicular para MDF produzido em laboratório com fibras de pinus e de eucalipto utilizando ureia-formaldeído. **Matéria**, Rio de Janeiro. v. 9, n. 1, p. 32-34, 2004.

CARNEIRO, A. C. O.; VITAL, B. R.; PIMENTA, A. S.; DELLA LUCIA, R. M. Propriedades de chapas de flocos fabricadas com adesivo de ureiaformaldeído e de taninos de casca de *Eucalyptus grandis* W. Hill ex Maiden ou de *Eucalyptus pellita* F. Muell. **Revista Árvore**, v. 28, n. 5, p. 715-724, 2004. doi: 10.1590/S0100-67622004000500011.

CASTRO JUNIOR, S. L.; GARZON, N.; WILLIAMS, D.; GUESSO, F. L.; SAVASTANO JUNIOR, H.; ROSSIGNOLO, J. A.; FIORELLI, J. Particleboards with Agricultural Wastes: Sugar Cane Bagasse and Reforestation Wood. **Key Engineering Materials** (Online), v. 600, p. 667-676, 2014. doi: 10.4028/www.scientific.net/KEM.600.667.

CERES - LABORATÓRIO DE CIÊNCIA E TECNOLOGIA DE CEREAIS. **Cultura de Aveia.** Departamento de Ciência e Tecnologia de Alimentos, Centro de Ciências Agrárias, Universidade Federal de Santa Catarina, Florianópolis. Available at: <http://www.cca.ufsc.br/dcal/labs/ceres/aveia.html#carac>. Accessed on: February 16, 2011.

COMMERCIAL STANDARD. **CS 236-66** - Mat formed Wood particleboard. s. l., 1968.

DACOSTA, L. P. E. **Utilização de resíduos do processamento mecânico da madeira para fabricação de chapas de partículas aglomeradas.** 2004. 118 p. Dissertação (Mestrado) - Universidade Federal de Santa Maria, Santa Maria, 2004.

DIAS, F. M. **Aplicação de resina poliuretana à base de mamona na fabricação de painéis de madeira compensada e aglomerada**. 2005. 150 f. Tese (Doutorado) - Escola de Engenharia de São Carlos, Instituto de Física de São Carlos, Instituto de Química de São Carlos, Universidade de São Paulo, São Carlos, 2005.

FERRO, F. S. **Painéis OSB com madeira Schizolobium amazonicum e resina poliuretana à base de óleo de mamona**: viabilidade técnica de produção. 2013. 101 p. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Instituto de Física de São Carlos, Instituto de Química de São Carlos, Universidade de São Paulo, São Carlos, 2013.

FIORELLI, J.; CURTOLO, D. D.; BARRERO, N. G.; SAVASTANO JUNIOR, H.; PALLONE, E. M. J. A.; JOHNSON, R. Particulate composite based on coconut fiber and castor oil polyurethane adhesive: An eco-efficient product. **Industrial Crops and Products**, v.40, p. 69-75, 2012. doi:10.1016/j.indcrop.2012.02.033.

GARCIA, C. H.; MORA, A. L. **A cultura de eucalipto no Brasil.** São Paulo: SBS, 2000.

GARZÓN, N.; SARTORI, D.; ZUANETTI, I.; BARBIRATO, G.; RAMOS, R.; FIORELLI, J.; SANTOS, S. F; SAVASTANO JUNIOR, H. Durability evaluation of agro-industrial waste -based particle boards using accelerated aging cycling tests. In: INTERNATIONAL CONFERENCE ON NON-CONVENTIONAL MATERIALS AND TECHNOLOGIES. **Anals...** Single volume, 13, Changsha, Hunan, China, 2011.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE. **Levantamento Sistemático da Produção Agrícola.** Available at:<http://www.sidra.ibge.gov.br>. Accessed on: August 26, 2013.

IWAKIRI, S. Painéis de madeira: características tecnológicas e aplicações. **Revista da Madeira**, Edição especial, Maio, Curitiba, 2003.

____________. **Painéis de madeira reconstituída.** Curitiba, Paraná: FUPEF, 2005. 247p.

JESUS, J.M.H. **Estudo do adesivo poliuretano à base de mamona em madeira laminada colada (MLC)**. 2000. 106 f. Tese (Doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2000.

KELLY, M.W. **A critical literature review of relationship between processing parameters and physical properties of particleboard**. USDA. Forest Service. Forest Products Laboratory General Technical Report, Madison, n.10, p. 1-66, 1977.

KOJIMA, Y.; NORITA, H.; SUZUKI, S. Evaluating the durability of wood-based panels using thickness swelling results from accelerated aging treatments. **Forest Products Journal**. Chapter 59, p. 35-41, 2009.

KOJIMA, Y.; SUZUKI, S. Evaluating the durability of wood-based panels using internal bond strength results from accelerated aging treatments. **Journal Wood Science**, Japan, v.

57, p. 7-13, 2011. doi:10.1007/s10086-010-1131-4.

KOLLMANN, F. P.; KUENZI, E. W.; STAMM, A. J. **Principles of Wood science and technology:** wood based materials. New York: Springer-Verlag, 1975. 703p.

LIMA, C. K. P.; MORI, F. A.; MENDES, L. M.; CARNEIRO, A. C. O. Características anatômicas e química da madeira de clones de Eucalyptus e sua influência na colagem. **Cerne**, Lavras, v. 13, n. 2, p. 123-129, 2007.

MACEDO, L.B. **Painéis OSB de madeira Pinus sp. e adição de partículas de polipropileno biorientado (BOPP).** 2014. 84 p. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Departamento de Engenharia de Estruturas, Universidade de São Paulo, São Carlos, 2014.

MALINOVSKI, R.A. **Reflorestamento em áreas limítrofes de propriedades rurais em São José dos Pinhais (PR*):*** análise de percepção e de viabilidade econômica. 2002. 161 f. Dissertação (Mestrado) – Universidade Federal do Paraná, Curitiba, 2002.

MARRA, A.A. **Technology of wood bonding: principles and practice.** New York: Van Nostrand Reinhold, 1992. 454p.

MALONEY, T.M. **Modern particleboard and dry-process fiberboard manufacturing.** San Francisco: Miller Freeman Publication, 1977. 672p.

______. The family of wood composite materials. **Forest Products Journal**, v. 46, n. 2, p. 19-26, 1996.

MCNATT, J. D.; LINK, C. L. Analysis of ASTM D 1037 accelerated-aging test. **Forest Products Journal,** v. 39, n. 10, 1989.

MENDES, L. M. ***Pinus* spp. na produção de painéis de partículas orientadas.** 2001. 156 f. Tese (Doutorado em Engenharia Florestal) – Universidade Federal do Paraná, Curitiba, 2001.

MELO, R. R.; SANTINI, E. J.; HASELEIN, C. R.; STANGERLIN, D. M. Propriedades físico-mecânicas de painéis aglomerados produzidos com diferentes proporções de madeira e casca de arroz. **Ciência Florestal**, Santa Maria. v.19, n. 4, p. 449-460, 2009.

MENDES, R. F.; MENDES, L. M.; CARVALHO, A. G.; GUIMARÃES JÚNIOR, J. B.; MENDES, R. F. **Utilização do bagaço de cana de alambique na produção de painéis aglomerados**. 2008. 104 f. Monografia (Graduação) – Universidade Federal de Lavras, Lavras, 2008.

MENDES, R. F.; MENDES, L. M.; ALMEIDA, N. F. Associação de eucalipto e pinus na produção de painéis aglomerados de bagaço de cana. In: ENCONTRO BRASILEIRO EM MADEIRAS E EM ESTRUTURAS DE MADEIRA, 12. **Anais...** CD-ROM. Lavras, 2010.

MESQUITA, R. G. A. Determinação do módulo de elasticidade de painéis aglomerados por Stress Wave Timer. **Floresta e Ambiente**. Rio de janeiro. v. 19, n. 2, p. 117-122, 2012. doi: 10.4322/floram.2012.013.

MONTGOMERY, D. C. **Design and analysis of experiments**. 6. ed. Arizona: John Wiley & Sons Inc, 2005.

MOSLEMI, A. A. **Particleboard:** materials. London: Southern University Press, v.1, 1974. 244 p.

PETERSON, R.W. **Wood adhesives**. Ottawa: Forest Products Research Branch, 1964. (Boletim, 1055).

PIERRE, F. C. **Caracterização físico-mecânica de painéis aglomerado de *Eucalyptus grandis* com adição de resíduos industriais madeireiros**. 2010. 122 p. Tese (Doutorado) – Universidade Estadual Paulista, Botucatu, 2010.

ROWELL, R. M.; HAN, J. S.; ROWELL, J. S. Characterization and Factors Affecting Fiber Properties. In: FROLLINI, E.; LEÃO, A.L.; MATTOSO, L.H.C. (eds). **Natural Polymers and Agrofibers Based Composites**. Section II – Agrofibers Composites, p. 115-134, São Carlos: Embrapa Instrumentação Agropecuária Ed., 2000.

SÁ, J. P. G. **Utilização da aveia na alimentação animal**. Circular, n. 87, Londrina: Iapar (Instituto Agronômico do Paraná), 1995.

SALDANHA, L. K. **Alternativas tecnológicas para produção de chapas de partículas orientadas OSB**. 2004. 83 f. Curitiba. Dissertação (Mestrado) - Universidade Federal do Paraná, Curitiba, 2004.

SOUZA, A.M. **Produção e avaliação do desempenho de painéis de partículas orientadas (OSB) de Pinus sp com inclusão de telas metálicas**. 2012. 116 p. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Instituto de Física de São Carlos, Instituto de Química de São Carlos, Universidade de São Paulo, São Carlos, 2012.

TAMANINI, C.; HAULY, M. C. O. Resíduos agroindustriais para produção biotecnológica de xilitol. **Ciências Agrárias**, Londrina, v. 25, n. 4, p. 315-330, 2004. doi: 10.5433/1679-0359.2004v25n4p315.

TRIANOSKI, R. **Avaliação do potencial de espécies florestais alternativas, de rápido crescimento, para produção de painéis de madeira aglomerada**. 2010. 260 f. Dissertação (Mestrado) - Universidade Federal do Paraná, Curitiba, 2010.

VICK, C. B. **Adhesive bonding of wood materials.** Wood handbook – wood as an engineering material. Madison, WI: U.S. Department of Agriculture. Forest Servic, 1999. Chap. 9, p. 1-24.

WEBER, C. **Estudo sobre viabilidade de uso de resíduos de compensados, MDF e MDP para produção de painéis aglomerados.** 2011. 87 f. Dissertação (Mestrado) - Universidade Federal do Paraná, Curitiba, 2011.

WEBSTER, F. H. Oats. In: HENRY, R.J.; KETTLEWELL, P.S. (Ed.) **Cereal grain quality**. Atlanta, 1996. p. 179-203.

PARTICLEBOARDS WITH PEANUT HUSKS AND CASTOR OIL POLYURETHANE ADHESIVE

Mariana Pilar Gatani and Victoria Granero
Consejo Nacional de Investigaciones Cientificas y Tecnológicas (CONICET), Centro Experimental de Vivienda Economica (CEVE), Córdoba, Argentina.

Juliano Fiorelli and Holmer Savastano Junior
University of São Paulo, Faculty of Animal Science and Food Engineering, Biosysten Engineering Department, Pirassununga, Brazil.

ABSTRACT: Peanut husks are an abundant waste into the agricultural field, which can be used as raw material for new products. This article analyzes the physical and mechanical properties of low and medium density panels (0.6 g/cm^3 and 0.75 g/cm^3) made of peanut husks and two different types of resin: urea formaldehyde and castor oil polyurethane. Brazilian standard NBR 14810:2006 was used to determine and evaluate density, water absorption and swelling, modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB). A satisfactory behavior was observed in medium density panels prepared with castor oil adhesive, reaching density values of 0.71 g/cm^3, water absorption percentages of 50.66% at 2 h and 95.11% at 24 h, swelling percentages of 14.67% at 2 h and 21.79% at 24 h, MOR and MOE values of 7.61 MPa, and 1069.5 MPa respectively and IB values of 3.5 MPa. Moreover, analysis of the components by SEM (Scanning Electron Microscopy) showed that low density panels has low compaction, which is likely the cause of the least resistance of these panels.

Keywords: Peanut husks. Urea resin. Polyurethane Resin from castor oil. Physical Properties. Mechanical Properties.

1. INTRODUCTION

The indiscriminate use of raw materials and non-renewable energies, added with high waste generation, had led to demand for alternatives coming from several scientific and technological fields. The main purpose of this new looking is to ensure the availability of resources for future generations. These new solutions are based on the approach of sustainable development, defined by the World Commission on Environment and Development in 1987, which aims to meet the needs of the present without compromising the ability of future generations in meeting their own needs (WCED, 1987).

One of these renewable resources is wood, which is widely used in many applications, such as paper and energy production. It is also highly consumed in areas of construction and design. One of these approaches in wood use is the development of effective wood-based particleboards and plywood panels. Nutsch (2000) defines them as panels made from wood-based fibers or chips, usually pine and eucalyptus, bonded together using synthetic resins. With that, that products have gotten several advantages in its properties, including homogeneity, greater dimensional stability, larger dimensions, reduced weakening, less waste during process, and increased possibility to employ fast-growing tree species (Medina, 1999; Chan Martin, 2004). However, the high demand for these products also leads to an excessive use of raw materials and consequently to the need for monoculture forestation (MARKESSINI, ROFFAEL & RIGAL, 1997).

The use of local agricultural lignocellulosic wastes as raw materials in the particleboard industry comes as an alternative to the intensive use of wood, and scientists are getting good results with their use. Their main objective is giving an application to these wastes and reducing environmental impacts caused by them. Lignocellullosic compounds can be feasible alternatives, highlighted by a sustainable production process. Some of these raw materials are residues coming from crops like wheat, sugar cane bagasse, cereal, corn and rice husks, peanut husks, coconut fibers, among others (MEDINA, 1999; ANDERSON, YUNG, TANAKA, 2005; GATANI, 2010; HAYETS, 1998; FIORELLI et al., 2012).

Youngquist et al. (1993) discussed the different possibilities for crop residues (like sugarcane, cereals, corn and rice husk) to be used into the production of panels. In addition, kenaf, flax, hemp fibers, and crop residues of wheat have been studied as potential complements or even substitutes for wood boards (LLOYD & SEBER, 1996; MARKESSINI et al., 1997). Granero and Aravena (2008) developed particleboards composed with tree leaves and urea resin, used in interior furnishing design. Moreover, Gatani (2010) have developed technologies in the use of peanut husks-based materials.

However, wood-based particleboards and lignocellulosic panels still having some unsolved issues. One of the major challenges associated with wood-based particleboards is the use of formaldehyde resin: Nutsch (2000) explains that formaldehyde is expelled during the resin´s hardening process in the manufacture of urea, melamine or phenolic particleboards. As a gas of pungent odor, the exposure to high concentrations of formaldehyde can cause nasal and throat congestions, burning eyes, and increasing the risk of developing cancer. That formaldehyde´s effect is confirmed by the International Agency for Research on Cancer (International Agency for Research on Cancer, 2004), and it was discovered by a scientific study carried out in ten countries that this substance is carcinogenic to humans. Furthermore, this study states that the most common emission sources of formaldehyde are the productions of particleboards and similar materials used in construction.

In 1977, Kelly referred to the emission of formaldehyde as a common object of study. The author indicates that its emission can decrease depending on pressing, temperature and humidity during panels' production. Kelly also describes a number of studies focused on the reduction of formaldehyde emission. The methodology used in those works was based on the reduction of the amount of resin and the introduction of additives that act as formaldehyde scavengers. However, in some cases, additives can contribute to the lack of mechanical strength of the panels. Despite this disadvantage, formaldehyde-based resins are still widely used due to its low cost and the good properties achieved in the final material.

Regarding the search for alternative binders, a resin derived from castor oil was developed in the early 1980s by the Department of Chemistry and Molecular Physics, Institute of Chemistry, Sao Carlos, Brazil. As great advantages, this resin has no emissions, comes from a renewable resource and is very resistant to water and ultraviolet light (MOURA DIAS, 2008).

Castor oil resin has been used in wood paneling in Brazil (MOURA DIAS, 2008; CAMPOS et al., 2008; NASCIMENTO et al., 2008), and in the production of plywood (MOURA DIAS, 2008). Alternative lignocellulosic panels such as coconut fibers bonded in a polyurethane matrix of castor oil resin have been studied by (FIORELLI et al., 2012).

Therefore, reducing dangerous emissions and finding new binder resins are essential to the development of lignocellulosic materials panels, considering both the environment and technical performance of this material. In this context, this paper present a comparison between physical and mechanical properties of low and medium densities panels (0.6 g/cm^3 and 0.75 g/cm^3) made from peanut husks bonded with urea resin and castor oil resin. Urea resins are formaldehyde-based resins while castor oil resins are volatile organic compounds free (VOC's).

2. MATERIALS AND METHODS

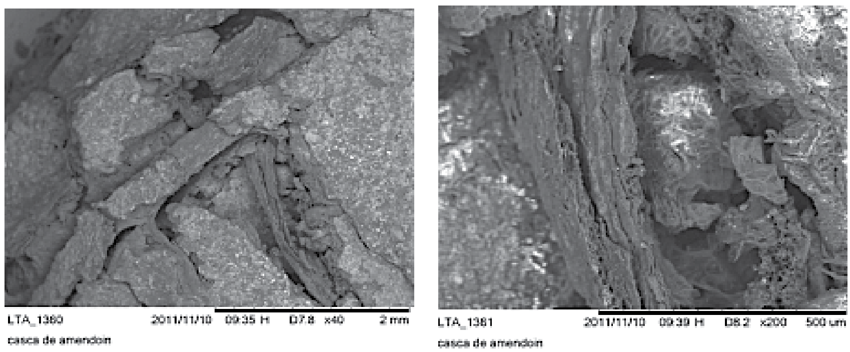
2.1 MATERIALS

The materials used in the preparation of the panels were:

Peanut husks without crushed treatment (fig. 1), obtained from Amendobras SA, Bauru, State of Sao Paulo, with bulk density of 0.81 g/cm^{3}..

Figure 1 – Peanut husks without crushed treatment

Figure 2 shows the microscopic morphology of peanut husks. It is possible to observe thin shells and fragmented sheets, and the presence of short and long fibers. Morphologically, these characteristics describe peanut husks as a heterogeneous material.



(a) (b)

Figure 2 – Imagen SEM – Peanut husks a. Increase x40. b. Increase x200

i) Monocomponent urea resin (cascomite) produced by Momentive Brazil, paraffin and ammonium sulfate.
ii) Bicomponent polyurethane castor oil resin produced by Plural Brazil.

2.2 METHODS

The manufacturing of panels using peanut husks bonded with urea resin and castor oil resin were prepared with formulation presented in Table 1.

Table 1 – Particleboards formulation

Amount of peanut husks (g)	% Resin*	Types of Resin	Amount of Resin (g)	Additives
1,440	15	Castor oil resin	216	-
1,920	15	Castor oil resin	288	-
1,920	15	Urea resin	288	-
1,920	15	Urea resin	288	1% paraffin** 1% $(NH_4)_2SO_4$*

References: * Regarding husks. ** Regarding resin.

2.2.1 Production Process

Figure 3 shows the panels manufacturing stages. Peanut husks were dried in an oven at 60°C for 24 h. Then, husks and resin were weighed and homogenized in a vertical shaft mixer for 2 minutes (Fig. 3a). That mixture was placed in a wooden mold using an aluminum foil for protection (Fig. 3b). Manual pressing was used to form a mattress of husks (Fig. 3c).

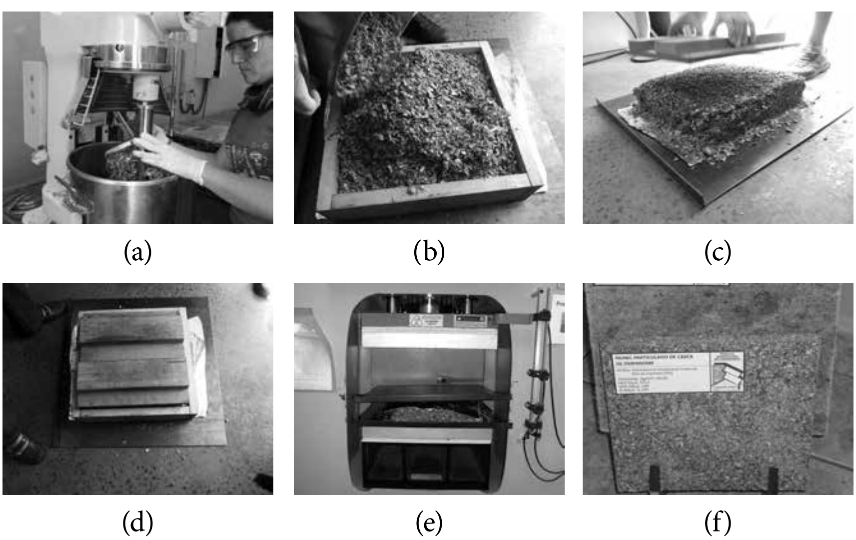


Figure 3 – Peanut husks particleboard production process. a: Vertical shaft mixer. b: Placing in wooden mold. c: Manual pressing. d: Husks mattress. e: Pressing. f. Finished particleboard.

Then, the mold was removed (Fig. 3d) and the husks mattress was put in a hydraulic press (Fig. 3e). Panels bonded using castor oil resin were pressed for 10 minutes at 100 °C, while panels bonded using mono-component urea resin were pressed for 10 minutes at 130 °C. The final measures were 50 cm x 50 cm x 1.8 cm (Fig. 4f). Specimens were extracted from these panels for physical and mechanical properties evaluation.

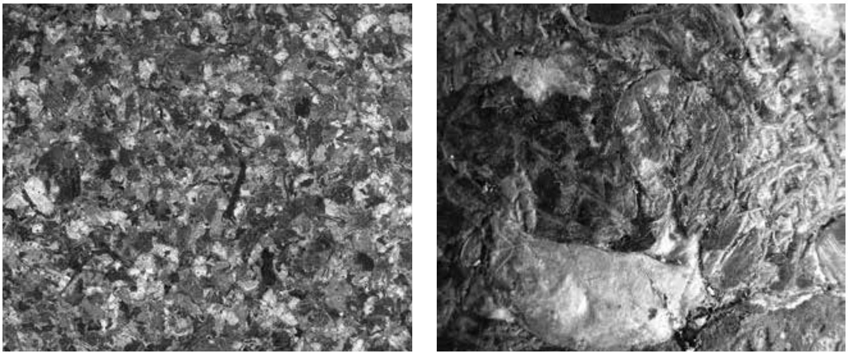
2.2.2 Properties Characterization

- Morphological characterization:
  It was performed by a scanning electron microscopy (SEM) using Hitachi Analytical Table Top Microscope, modelTM3000 - Laboratório de Tecnologia de Alimentos da FZEA/USP

- Physical and mechanical characterization:
  The physical (density, water absorption and swelling tests) and mechanical (Bending Test and Internal Bond) were performed according to the Brazilian Standard ABNT NBR 14810:2006. This standard was adopted based on the similarity between wood-based panels and peanut husk-based panels.

3. RESULTS

This section presents the results of the comparison, regarding physical and mechanical properties, between panels made with peanut husk and castor oil resin and urea resin, with and without additives.



(a) (b)

Figure 4 – Resulting particleboard. a. Surface aspect. b. Texture detail

3.1 PARTICLEBOARDS

Figure 4 exhibits the finishing of the panels (Fig. 4). It can be observed a consistent quality on the panel's surface. Colors are uniform: lignt brown, yellow ocher, dark brown. We can also observe the presence of particles in different sizes and other peanut plants parts, especially stalks. This condition gives a natural appearance to the panels.

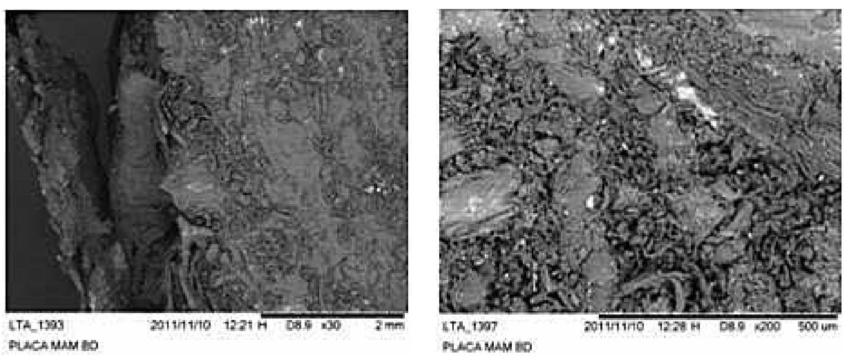
Four types of panels were obtained, differentiated according to the density and type of binder used:

i) MBD Particleboards: Peanut husks bonded with castor oil resin. Low density.
ii) MMD Particleboards: Peanut husks bonded with castor oil resin. Medium density.
iii) UMD Particleboards: Peanut husks bonded with urea resin. Medium density
iv) UMD+A Particleboards: Peanut husk panels bonded with urea resin with additives. Medium density

3.2 MICROSCOPY

3.2.1 MBD Particleboards: Peanut Husk Bonded With Castor Oil Resin. Low Density.

Figure 5 presents that panel morphology. A cross section shows slight detachment of husks (5a) due to an insufficient adhesion in the bonded surface. The specimen shown in figure 5b, taken in the center of the panel, exhibits internal bond differences and presence of voids. This figure also shows the presence of white particles, unknown contamination of the raw material.

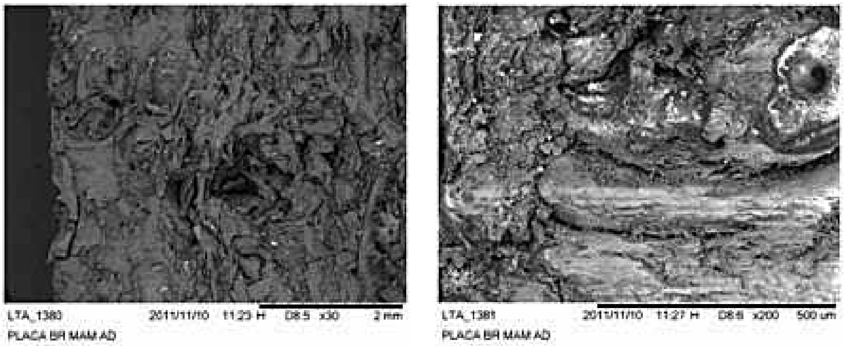


(a) (b)

Figure 5 – SEM image - Panel of low density, peanut husk and castor oil resin. a: Panel's edge view increased 30x. b: Panel's inside view, increased 200x

3.2.2 MMD Particleboards: Peanut Husk Bonded With Castor Oil Resin. Medium Density.

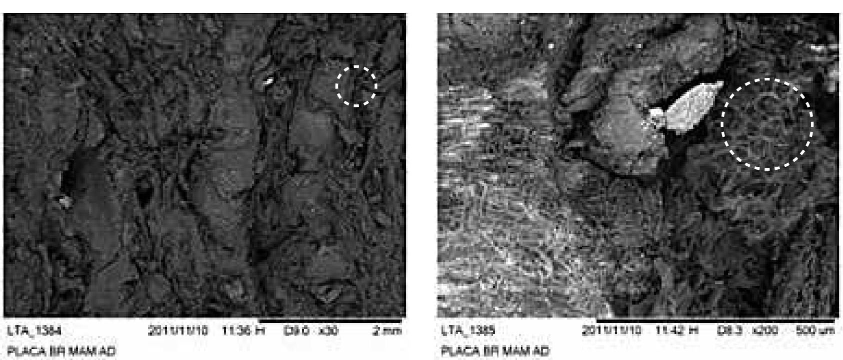
Figure 6a corresponds to a specimen taken in the edge of the panel where it is possible to observe sufficient internal bond in the peanut husks particles. The presence of flat sheets of peanut husks attached together and the presence of few voids in the panel edge composition suggests good molding and pressing conditions. Figure 6b corresponds to a specimen taken in the upper right corner and shows some resin residue.



(a) (b)

Figure 6 – SEM Image – Medium density particleboard. Peanut husks with castor oil resin a: Panel's edge view increased 30x. b: Panel's upper corner view increased 200x

The specimen presented in Figure 7a exhibits a heterogeneous compaction. This may suggest that the size and shape of peanut husks particles presents a resistance to compaction. The convex-concave shape of the husks avoids a proper homogenization with resin. Therefore, the inner layers are not completely bonded (GRANERO et al., 2012). The same test body, increased to 200x in figure 7b, shows unknown white particles: raw material contamination.

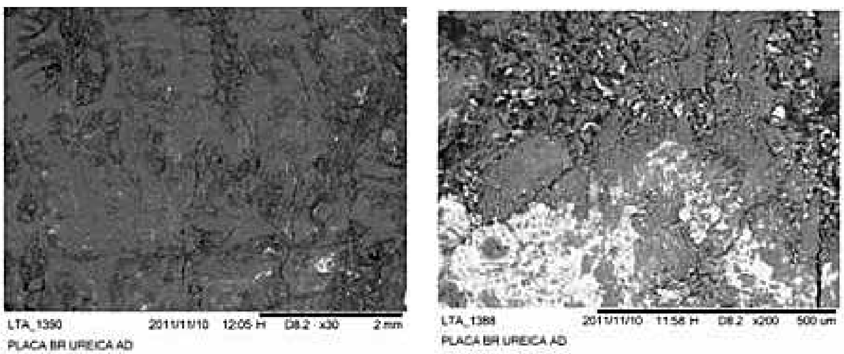


(a) (b)

Figure 7 – SEM Image – Medium density particleboard. Peanut husks with castor oil resin. a: Panel's inside view, increased 30x. b: Panel's inside view, increased 200x

3.2.3 UMD+A Particleboards: Peanut husks panels bonded with urea resin and additives.

Figure 8a shows that UMD presents greater homogeneity than MMD. However, a closer look (Figure 874b) exhibits an uneven distribution of urea resin. This situation may be caused by not only the shape and size of the particles, but also by the type of binder used.



(a) (b)

Figure 8 – SEM Image – Medium density particleboard. Peanut husks with urea resin. a: increased 30x, b: increased 200x

3.3 PHYSICAL PROPERTIES

3.3.1 Density

The density values obtained are summarized in Figure 9. A LSD average comparison test with a = 0.05 was used to compare density values of MBD, MMD, UMD and UMD+A. The test allowed inferring that MMD, UMD and UMD+A panels have similar density values while MBD panels have statistically significant lower density. That lower density is consistent with less amount of husk in the formulation.

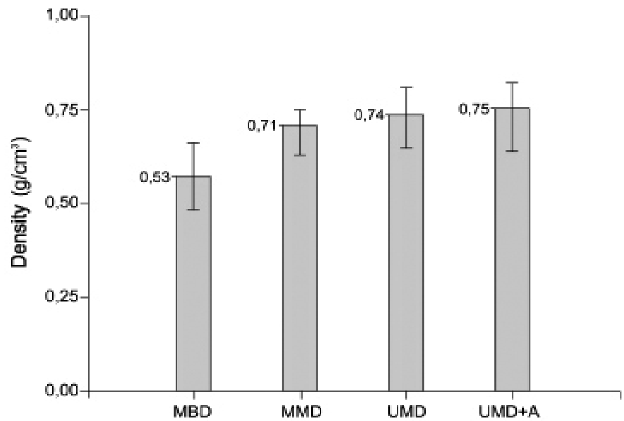


Figure 9 – Peanut husks panes average density according binder type

3.3.2 Water Absorption And Swelling

The specimens were fully immersed in water for 2 hours and 24 hours in order to determinate water absorption values of MBD, MMD, UMD and UMD+A. The resulting values are summarized in Figure 10. A LSD means comparison test with a = 0.05 was used to compare the results.

Regarding 2h test, water absorption values of MMD and MBD were lower than UMD and UMD + A. This indicates that the type of binder influences the absorption behavior. In the SEM analysis, we have already observed that castor oil resin takes up the interstitial spaces between the husks particles, blocking water access.

According to the LSD test related to the behavior at 24h, three statistically distinct groups can be distinguish: A first group of lower level of water absorption (MBD), a second group of medium level of water absorption (UMD), and a third group of high level of water absorption (MMD and UMD+ A).

It is clear that the presence of the polyurethane resin fills the interstitial voids delaying contact of water with husks particles. However, this behavior changes in longer immersion periods. At 24h test, the water absorption percentage increases significantly. Castor oil resin specimens show a significant difference between the amount of absorbed water in 2h and 24 h tests. Water absorption almost raised by 100 per cent in MMD.

The amount of absorbed water by urea resin specimens was less than their similar. The difference between 2h and 24h tests was 9% and 17% respectively. These results suggest that castor oil resin delays the contact of water with peanut husks particles. Despite this, when the water reaches the particles, husks get a high absorption capacity.

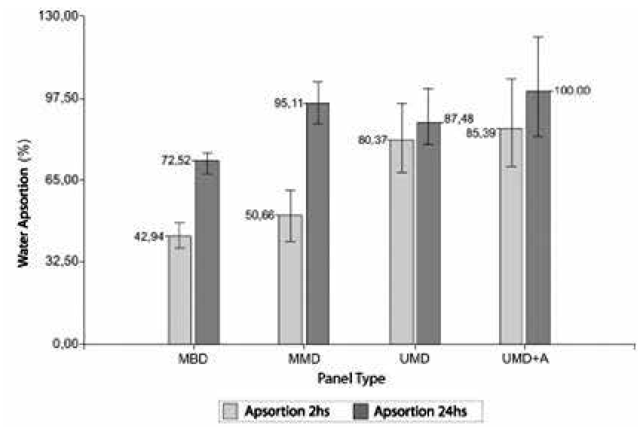


Figure 10 – Absorption values in 2 and 24 hs

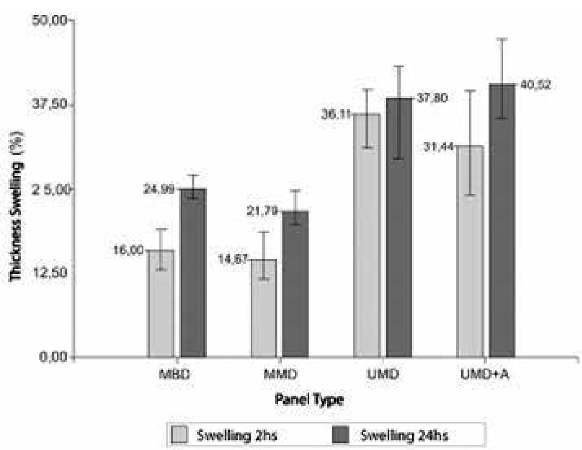


Figure 11 – Sweelling values in 2 and 24 hs

Figure 11 presents swelling values registered at 2h and 24 h tests. Castor oil resin specimens showed less swelling than urea formaldehyde resin ones. In a LSD means comparison test with a = 0.05 at 2h test, MMD and MBD obtained the lowest swelling values; UMD + A got a medium swelling value and UMD the highest. Results from LSD means test with a = 0.05 at 24h allow grouping castor oil resin specimens MBD and MMD in one group and urea formaldehyde resin specimens in another group, with less favorable performance. Wood-based particleboards with 0.67 g/cm^3 density sold on the domestic market (MASISA, Argentina) have a swelling value of 15% in 24h test in average, while castor oil resin particleboards exceeds 45% (MMD) and 66% (MBD). This difference related to commercial panels could be explained not only by the binder used, but also by differences in the production process.

Table 2 summarizes the results of water absorption and swelling and the relationship between these properties at 2 h and 24 h respectively.

Table 2 – Absorption and Swelling values in 2 and 24 hours

Particleboard	Absorption (%)		Swelling (%)		Absorption relationship 2/24 h (%)	Swelling relationship 2/24 h (%)
	2h	24 h	2h	24 h		
MBD	42.95_a	72.52_a	16.00_a	24.99_a	0.59_a	0.64
MMD	50.66_a	95.11_{bc}	14.67_a	21.79_a	0.53_b	$0.67_{e,f}$
UMD	80.37_b	87.48_b	36.11_b	37.80_b	0.92_c	0.95
UMD+A	85.39_b	100.00_c	31.44_c	40.52_b	0.85	0.77_f

Ref.: Same letter mean similar performance in LSD medias comparison test with a= 0.05

As shown in table 2, castor oil resin panels absorption and swelling was about 60% in 2 h and 24 h test. In the case of urea resin panels, absorption and swelling values reached 90%. Therefore, it can be concluded that castor oil resin panels do not absorb water as quickly as urea resin panels, have greater resistance and better performance against humidity.

3.3.3 Mechanical Properties

Figure 12 shows MOR (modulus of rupture) values obtained in medium density panels (MMD, UMD, UMD + A). Results are lower than those recommended by the reference standard (<11 MPa). MBD panel, classified as LD (low density), has a higher MOR value than the recommended by the standard (> 3 MPa). LSD means comparison test with a = 0.05 manages to group the specimens into categories with different behavior. MBD specimen had the lowest value of bending strength. UMD and UMD+A specimens had a similar mechanical performance. In another group, MMD and UMD panels share properties. These results demonstrate the relationship between mechanical strength and density.

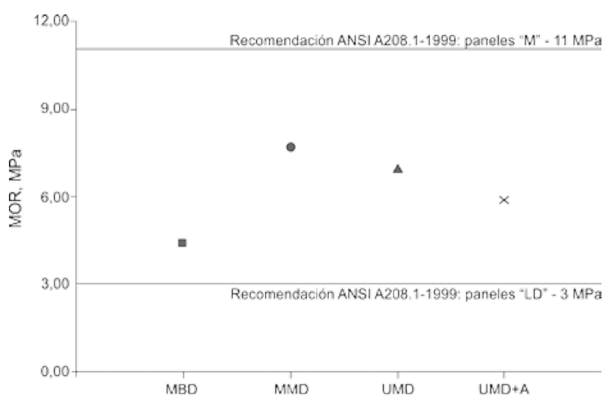


Figure 12 – MOR average values

Regarding MOE (modulus of elasticity), medium density panels (MMD, UMD and UMD+A) classified as M (medium density) had lower values than those recommended by the standard (<1725 MPa). The MBD panel, classified as LD, has a higher MOE value than recommended (> 550 MPa). Results are shown in Figure 13. The MMD panel is placed in the high-density group.

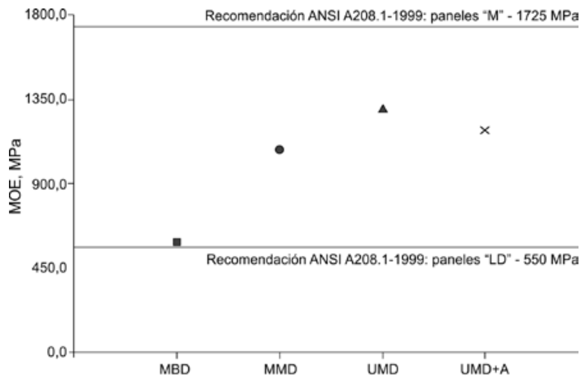


Figure 13 – MOE average values

As regards AI (internal bond), panels exceed the recommended standard for classification according to density values (Figure 14). Standard values for low density panels are 0,1 MPa, and for medium density panels are 0,4 MPa. Results showed the possibility to reduce the amount of resin, since MBD, MMD, UMD and UMD+A AI values were significantly higher than the ABNT NBR 14810:2006 recommended standard.

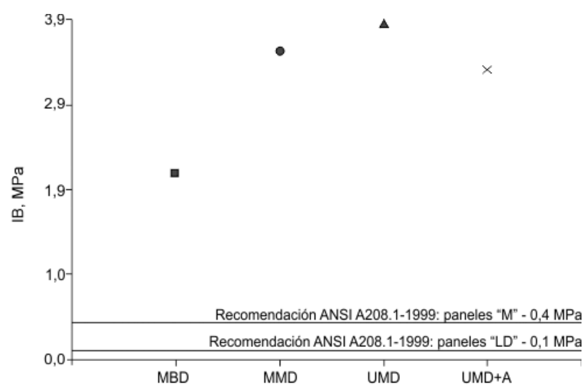


Figure 14 – IB average values

Table 3 summarizes the mechanical properties information (MOR, MOE and AI) and a classification according to density of the panels in relation with ANSI A208.1: 1999 standard.

Table 3 – Peanut husks panels mechanical properties

Type of panel	Density g/cm³	Clasification ANSI A208.1:1993	MOR MPa	MOE MPa	IB MPa
MBD	0.53	LD (Low density)	0.38_a	573_a	0.21_a
MMD	0.71	M (Medium density)	7.61_b	$1{,}069_b$	$0.35_{b,c}$
UMD	0.74	M (Medium density)	$6.9_{b,c}$	$1{,}274_c$	0.385_c
UMD+A	0.75	M (Medium density)	5.84_c	$1{,}175_{b,c}$	0.329_b

Ref.: Same letter mean similar performance in LSD medias comparison test with a= 0.05.

Results allow us to conclude that density of each treatment is directly related to the physical and mechanical material's performance. In panels with similar density values, castor oil resin shows higher mechanical capacity over urea resin. Furthermore, it was demonstrated that the use of urea resin additives did not improve panel's mechanical properties.

Similar properties were given by Fiorelli et al., (2012) when studying panels of coconut fibers bonded with castor oil resin. In the work of reference, better mechanical properties were obtained from coconut fibers panels with similar density to this study's peanut husks panels. This may have been achieved due to the coconut properties: The fibers are larger, have a flat morphology and present smaller cross-section area.

The physical-mechanical characteristics, including swelling, absorption, MOR and MOE properties of peanut husks panels can be improved changing the amount of resin and particle size, as well as the temperature and pressure during the production process.

4. CONCLUSIONS

The use of lignocellulosic waste as raw material in the manufacturing of particleboards, in association with the replacement of harmful emissions binders are a rising trend. This paper discusses the benefits of castor oil resin as an alternative binder in the manufacturing of panels made of peanut husks.

The surface appearance of the studied panels looks very attractive, which is important for architecture and design purposes.

In terms of physical properties, it was observed that the amount of water absorption and swelling at 2 and 24 hours of castor oil resin panels are lower than values of urea resin panels. These properties give castor oil resin panels a greater resistance to deterioration by moisture and water exposure. This behavior can be attributed to the hydrophobic character of the castor oil resin.

MOR, MOE and AI properties show satisfactory levels in castor oil resin panels with medium density (MMD). Castor oil resin panels with low density (MBD) presented an inferior mechanical behavior compare to the others.

Future interventions during the production process will allow the increasing of the physical and mechanical properties in those particleboards.

We conclude proposing an increase of the use of peanut husks particleboards bonded with castor oil resin with medium density (MMD) as an alternative to the traditional wood particleboard. This proposal is based on the distinctive low emission pollutants and good physical and mechanical properties of the panels, making it suitable for claddings, non-load-bearing structures, and another features in civil construction fields.

ACKNOWLEDGEMENTS

The authors would like to thank FAPESP, CNPq and FINEP for financial resources. The authors also acknowledge the financial support of Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), and Centro Experimental de la Vivienda Económica (CEVE) for providing institutional framework to carry out this partnership.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text

REFERENCES

ABNT. **NBR 14810-3**. Chapas de madeira aglomerada. Parte 3: Métodos de Ensaio. Associãçao Brasilera de Normas Técnicas, 2006.

ANDERSON, A.; YUNG, A.; TANAKA, T. **Eco-Friendly Alternatives to Wood-based Particleboard.** Available at: <http://www.stolaf.edu/people/jackson/08-124/gbreport/bioboard_j05.pdf>. Accessed on: January 25, 2005.

ANSI. **A208.1.** Particleboards. United States: American National Standard Institute, 1999.

CHAN MARTIN, M.; ARAUJO MOLINA, O.; AZUETA GARCIA, M.; SOLÍZ RODRIGUEZ, L. Tableros de madera de partículas. **Ingeniería***,* v. 8, n. 3, p. 39-46, 2004.

FIORELLI, J.; DONIZETTI CURTOLO, D.; GARZON BARRERO, N.; SALVASTANO, J.;AGNOLÓN PALLONE, E.; JOHNSON, R. Particulate composite based on coconut fiber and castor oil polyurethane adhesive: An eco-efficient product. **Industrials crops and products**, v. 40, p. 69-75, 2012. doi:10.1016/j.indcrop.2012.02.033.

GATANI, M. **Reciclado Post Industrial de Cáscara de Maní. Posibilidades de desarrollo de materiales no convencionales para la construcción de viviendas.** 2010. Tesis (doctorado) - Facultad de Urbanismo y Diseño, Universidad Nacional de Córdoba, Córdoba, Argentina, 2010.

GRANERO, A.; ARAVENA, D. **Material aglomerado de hojas secas.** 2008. Tesis (grado) - Carrera Diseño Industrial, Facultad de Arquitectura, Urbanismo y Diseño, Universidad Nacional de San Juan, San Juan, Argentina, 2008.

HAYES, M. **Agricultural residues: A promising alternative to virgin wood fiber.** Available at: <http://www.woodconsumption.org/alts/meghanhayes.html>. Accessed on: January 25, 1998.

IARC (INTERNATIONAL AGENCY FOR REASERCH ON CANCER). **Classifies formaldehyde as carcinogenic to humans.** Pressrelease n. 153**.** Available at: <http://www.iarc.fr/en/media-centre/pr/2004/pr153.html>. Accessed on: April 16, 2004.

KELLY, M. **Critical literature review of relationships between processing parameters and physical properties of particleboard. General Technical Report.** North Carolina State University, Department of Wood and Paper Science School of Forest Resources, Raleigh, United States, 1997.

LLOYD, E.; SEBER, D. **Bast fiber applications for composites.** International Particleboard--composite materials symposium. Washington: W.S.U. Pullman, 1996.

MARKESSINI, E.; ROFFAEL, E.; RIGAL, L. **Panels from annual plant fiber bonded with urea- formaldehyde resins.** International Particleboard-composite materials symposium Washington: W.S.U. Pullman, 1997. p. 147-160.

MEDINA, J.; AMBROGI, A. **Cáscara de maní en la elaboración de aglomerados.** Quebracho, 1994. p. 47-53.

MOURA DIAS, F. **Aplicação de resina poliuretana à base de mamona na fabricação de painéis de madeira compensada.** Productos derivados da madeira: síntese dos trabalhos desenvolvidos no Laboratório de Madeiras e de Estruturas de Madeira, SET-EESC-USP, São Carlos, Brasil, 2008. p. 49-72.

NUTSCH, W. **Tecnología de la Madera y del mueble.** Barcelona: Reverté, 2005.

WCED. **Our Common Future. World Comission on Environment and Development.** 1987.

YOUNGQUIST, J.; ENGLISH, B.; SPELTER, H.; CHOW, P. **Agricultural fibers in composition panels.** In: International Particleboard-composite materials symposium Washington: Maloney, Tomas M. Pullman, 1993. p. 133-152.

RESIDUES OF SUGARCANE BAGASSE AND POLYPROPYLENE WITHOUT ADDITIVES FOR PARTICLEBOARD PRODUCTION

Rosane Aparecida Gomes Battistelle
Department of Civil Engineering, UNESP - State University of São Paulo, Bauru, Brasil.
E-mail: rosane@feb.unesp.br

Barbara Stolte Bezerra
Departament of Civil Engineering, UNESP - State University of São Paulo, Bauru, Brasil.
E-mail: barbarabezerra@feb.unesp.br

Ivaldo De Domenico Valarelli
Departament of Mecanic Engineering, UNESP - State University of São Paulo, Bauru, Brasil.
E-mail: ivaldo@feb.unesp.br

Francisco Antonio Rocco Lahr
Department of Structural Engineering, Engineering School of São Carlos (EESC/USP), São Carlos, Brazil.
E-mail: frocco@sc.usp.br

ABSTRACT: In this research the aim was produce and evaluate a plastic composite using recycled polypropylene (PP) and fibers from sugarcane bagasse residues (SC), without the use of additives. This analysis was based on laboratorial tests for physical and mechanical characterization, according to the standards ASTM D256-00, ASTM D638-101and ASTM D570-98 were analyzed: water absorption, thickness swelling, impact resistance, tensile strength and deformation. For comparison it was elaborated three different traces: 100% PP; 80% PP+20%SC; 70%PP+30%SC. The results of the assays of water absorption had shown that bigger amount of fiber characterizes greater water absorption, and swell in thickness. In comparison with traces without PP in the composition, the plastic presented as an alternative for increase of surface waterproofing. Thus, indicating a positive correlation with the content of fiber and water absorption and thickness swelling. In the tension tests, the composites with fibers increase the value of resistance for physical efforts, bringing advantages as durability and integrity of the material, showing a viability of the composites.

Keywords: Particleboard. Sugarcane bagasse residues. Lignocelluloses composite. Recycled polypropylene. Physical and mechanical tests.

1 INTRODUCTION

The environmental issue has gained great prominence in the world, in recent decades, due to the urgency of preserving natural resources, with the threat of water scarcity, the need for fertile land for food production, and the reduction of pollution and waste generated by human activity. Given this scenario, nowadays there is a growing global concern about the environment, leading to the search for renewable materials that do not harm the environment. This new paradigm has become a differential tool in the survival of the industries in today's globalized and competitive market.

It is known that Brazil is a major generator of residues produced by agribusiness, which mostly end up being wasted and cause serious environmental problems both in the economic, social and environmental context. Within this Brazilian context, the sector of particleboard production presents itself as a viable alternative for these lignocelluloses residues, with the possibility to aggregate value for these residues through its use in construction materials Viola et al. (2013), Battistelle et al. (2014) and Pedreschi (2009).

According to Fiorelli et al. (2011), lignocelluloses materials from agro-industrial by-products have been used successfully in the manufacture of particleboard, highlighting the use of rice husks, corn, bamboo leaves, as well as sugarcane bagasse. Also according to Correa et al. (2003) the particle board can be manufactured from any lignocelluloses material that confers them high resistance mechanics and preset specific weight.

The sugarcane bagasse used in this study certainly is among the most widely used materials, mainly due to its low cost and abundance in the sugar and alcohol mills, as shown in Battistelle et al. (2014).

The disposal of residues occurs in all manufacturing processes, in this research we are focusing in residues stemming from two important industries: sugarcane extraction and polypropylene. Both products had become great icons in Brazilian exportation market.

The study of new composites using polypropylene with fibers materials had been developed by some authors such as Hillig et al. (2008), Najafi (2013) and Yamaji (2014), among others, which analyzed its mechanical and physical characteristics. The polymer composite can be thought of as a combination of two or more materials; reinforcement elements and/or charges incorporated into a polymeric matrix, differing in shape and / or composition. Also these studies are complemented by laboratorial and economical viability analysis and the availability of the raw materials Clemons (2012), especially in the construction, furniture and transportation industries; where the application of additives allows the material to adapt easily to the critical conditions of thermal stability, chemical and temperature resistance.

Our research has the novelty of production of composites with residues from sugarcane bagasse and polypropylene without resins or additives in laboratory scale, where the physical and mechanical characteristics for three different traces were analyzed.

2. MATERIAL AND METHODS

The raw material used in this research for the composite production are: residues of polypropylene (Homopolymer Polypropylene; PP-HO) donate by a plastic recycler industry located in Bauru, State of São Paulo, Brazil; and fiber material derived from sugarcane bagasse donated by the Plant of Bioenergia Paradise in Brotas, State of São Paulo, Brazil.

The raw materials had been extruded and injected in the Laboratory of Biocycle, of Federal University of São Carlos (UFSCar) for the production of test samples. For tension and impact tests were used the equipments CEAST and INSTROM 5569 also at the UFSCAR facilities. The tests of water absorption and thickness swelling had been made at the Laboratories of Wood and Residues Processing at State University of São Paulo (UNESP) Campus of Bauru.

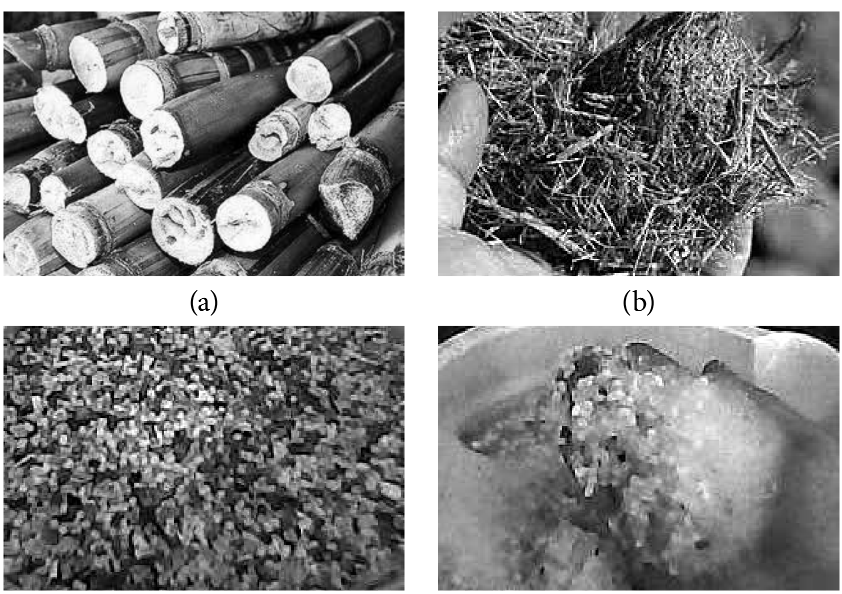
The polypropylene was in the shape of pellets, however without homogeneity and with some impurities. The material was then washed and dried in a kiln for 24 hours at 90°C. The sugarcane residue had large moisture content, and it was also dried in a kiln for 24 hours at 90°C (Figure 1).

After that the materials were extrude in order to mix the raw materials and to form homogeneity pellets, using a extruder model Extruale, scheduled for the heating zones, with water temperature at 25°C, as follows: Z1 at 110°C; the Z2 at 150°C; Z3 at 170°C; from Z4 to Z6 at 195°C; from Z8 to Z10 at 190°C; Z11 at 200°C; with extrude speed of de 50kg/h.

In order to make a comparison, the composite was produced in three traces: 100% PP (T1); 80% PP+20%SC (T2); 70%PP+30%SC (T3). After the extrusion, the pellets where dried in a kiln for a 24h at temperature of 60°C. Thus, with the dried pellets started the injection process using an Injector model Romi Pratica 130 for the confection of the test samples according to standard ASTM D256-00, ASTM D638-101 and ASTM D570-98.

The injection of composites in molds under pressure was carefully performed in order to avoid the appearance of cracks or gaps in the specimen. The mold used in the process of injection is shown in Figure 2.

The test samples were then cut following the dimensions and descriptions of the ASTM standards to respective test: impact (Figure 3a), traction (Figure 3b), and water absorption and thickness swelling (Figure 3c), these of circular form with 50.8 mm of radius dimension.



(a) (b) (c) (d)

Figure 1 – Samples of Pellets before and after cleaning, (a) sugarcane bagase before; (b)sugarcane bagase after; (c) recycled polypropylene before; (d) recycled polypropylene.

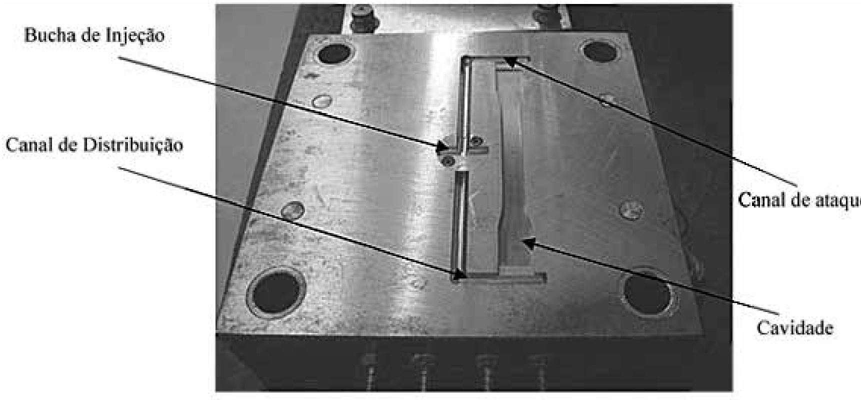


Figure 2 – Injection mold for specimens

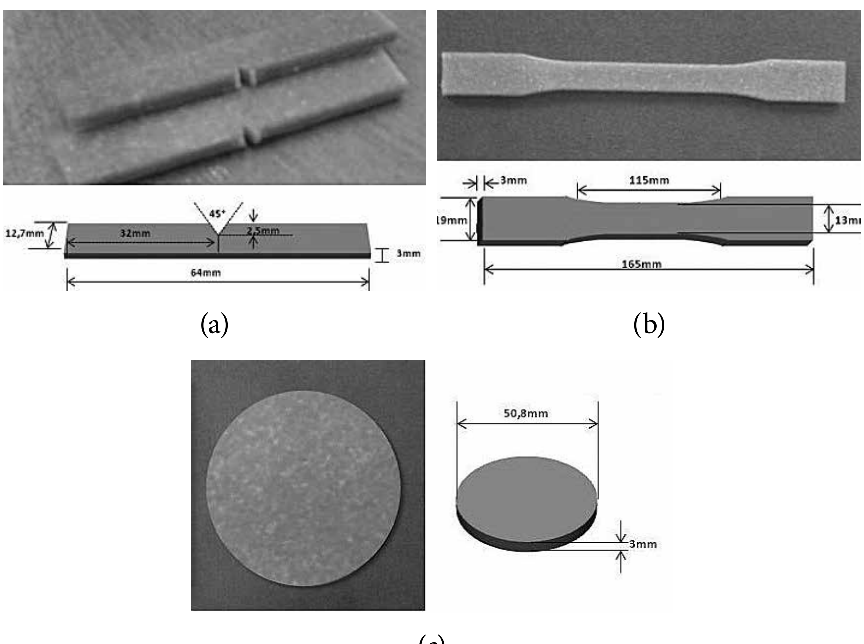
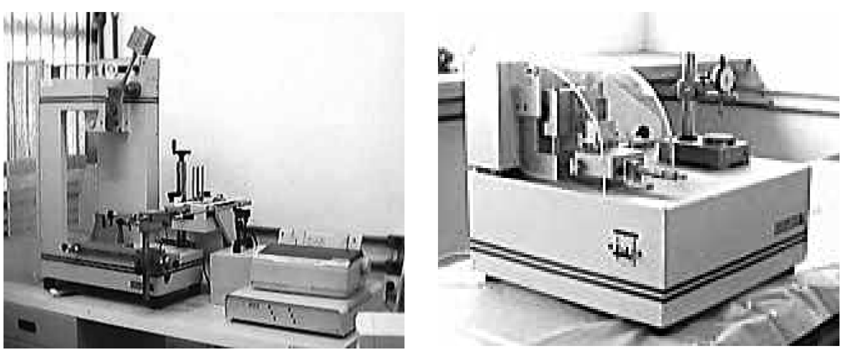


Figure 2 – Samples dimensions for mechanical and physical tests: (a) impact test (Charpy); (b) traction test; (c) water absorption and thickness swelling.

For the water absorption test it was used distilled water (provided by the Laboratory of Chemistry of the campus) in small basins separated by traces (100% PP, 20%SC, and 30% SC). The immersion test has two steps, following the standard ASTM D570-98. The first step is the method of Repeated Immersion, where the samples were fully immersed into the basin with distilled water for 2 hours at controlled temperature of 23°C±1°C. After the first hour, the specimens were removed from the basins, removing the excess of surface moisture and then were weighed and measured individually. After this first period, the samples were returned to containers and kept immersed for 24 hours and once again were weighed and measured individually.

The second step was the Long Term Immersion, where the specimens had greater length of time between one and another weighing. In this case, the specimens were weighted in the interval of one week, two weeks and finally one month.

In the impact resistance test with Izod slot, it was used the equipment CEAST (Figure 3a) using a 2J hammer and coefficient of friction of approximately 0.012 J. Furthermore, each sample received slot of 2.54mm at its medium point (Figure 1a).



(a) (b)

Figure 3 – (a) equipment CEAST, (b) carver, DEMa/UFSCar.

In this test, the samples were fixed on the bottom of the equipment, using a hammer of 2J capacity, which struck and broke the specimens in a kind of parabolic free fall.

In tensile tests were applied by INSTRON 5569, in the DEMa laboratory in São Carlos, in accordance with ASTM D638-101. The samples were subjected to tension by a 50kN load cell, the distance between the grips was 155 mm and the average speed of detachment between them was 5 mm / min (standardized by norm). The specimens used were approximately 3.25mm wide and 12,75mm long.

3. RESULTS AND DISCUSSION

The results for each trace are presented in the Table 1 with the requisites of standards ASTM D256-00 and ASTM D638-101 for the pure PP, therefore these standards do not have specification for the composites manufactured with recycled material of PP.

Table 1 – Summary of results obtained in the mechanical and physical tests

Test	Traces			Standard specification
	Control	Composite		
	T1	T2	T3	
σ_Y	23.69 ±0.63[#]	21.69±0.17[#]	21.70±0.25 [#]	(2) (PP pure 31.0-37.2 MPa)
ε_E	5.75±0.17[#]	3.23±0.15[#]	2.38±0.13[#]	(2) (PP pure 13%)
E	1.39±0.04***	1.86±0.02**	2.26±0.05**	(2) (PP virgem 1.14-1.55 GPa)
σ_T	20.11±0.55**	21.31±0.59**	21.61±0.33**	(2) (PP virgem: 3.63 MPa)
ε_U	267.82±17.03*	3.80±0.37[#]	2.49±0.31[#]	(2) (PP virgem: 8.79%)
I_s	75.55±6.42**	42.22±2.78**	38.89±2.12**	(1) (PP pure: 2.66J/m)

[1] This test is performed with 100g of the material and performed only once, so there is no standard deviation. * Close to the standard value; ** Above the normalized value; *** Within the standardized values; [#] Below the normalized values.

Where:
σ_Y: tensile flow stress in (MPa);
ε_E: flow deformation in (%);
E: Young's modulus (GPa);
σ_T: rupture tensile strength (MPa);
ε_U: deformation at rupture (%);
I_s: Impact strength (J/m)

The results for rupture tensile strength in the case of 100% PP had the higher deformation without reaching the rupture. The composites with 70% of polymer (P) and 30% of wooden flour (WF) evaluated in Correa et al. , (2003) using additives, presented the following results: σ_Y = 30.3 MPa; ε_E =5.8%; E= 2.6 GPa; σ_T= 24.6 MPa; ε_U =8%. In this way the presence of WF increased the resistance of the material regarding the plastic deformation and rupture compared with our composite using sugarcane bagasse. The modulus of elasticity remained in the same range, but the composites with WF had higher index of deformation after rupture.

In relation to the values of impact strength it was observed that the addition of sugarcane diminishes the resistance of the samples in relation to 100% PP, although is superior to WF. In similar research Correa et al. (2003) had an average result of 36.3J/m for composites with 70% P+30% WF, using additives. We obtained 42.22J/m for the composite with 80% PP + 20% SC and 38.89 J/m for the composite with 70% PP + 30% SC, both without any additive.

Regarding the results of Water Absorption (ASTM D570-98) samples showed remarkable differences in their initial weight according to each trace studied. In this case, the samples with 100% polypropylene were obtained with the smaller variation in mass, followed by 20%SC and 30% SC, respectively. The values are shown in Table 2.

Table 2 – Water absorption average

Trace	Initial mass (g)	Dry mass (g)	Mass after 1h immersion (g)	Mass after 24h immersion (g)	Mass after 1 week immersion (g)	Mass after 2 weeks immersion (g)	Total variation in mass (g)
100%PP	5.958	5.957	5.959	5.979	5.979	6.057	0.101
20%SC	6.262	6.252	6.268	6.340	6.364	6.391	0.112
30%SC	6.372	6.353	6.391	6.537	6.626	6.827	0.455

With the results presented in Table 2, it can be concluded that the trace with the highest percentage of plastic matrix (100% PP) produced greater waterproofing and resistance to water absorptions, as it was to be expected Battistelle et al. , (2014) and Eckert (2004). The high rate of water absorption was in the trace 30%SC, because the higher the percentage of organic matter (pulp) in a composite, the lower its resistance to water absorption.

It was also observed that higher percentage of PP make the samples more resistant to water absorption and thickness swallowing; and a positive correlation between the percentage of sugarcane bagasse and water absorption and thickness swallowing.

Regarding the values relating to the thickness swelling test, one can reach the same conclusion of the test water absorption, i.e., the higher the fibrous matrix, the greater the variation in thickness and weight of the samples. Values of this test are shown in Table 3.

Table 3 – Thickness swallowing averages

Trace	Initial thickness (mm)	Dry thickness (mm)	2h (mm)	24h (mm)	1 week (mm)	2 week (mm)	Total Variation (mm)
100%PP	3.112	3.191	3.176	3.180	3.167	3.162	0.050
20%SC	3.056	3.128	3.137	3.142	3.161	3.168	0.112
30%SC	3.081	3.108	3.148	3.178	3.188	3.201	0.120

The test for the fluidity index of the composites was developed in the Laboratory of Biocycle the Federal University of São Carlos - UFSCar, following the standard (ASTM 1238-10), for the polypropylene condition of

230°C and 2.16kg, usual values for this test. The compositions were dried in a kiln for 24 hours at 60°C. The results obtained are shown in Table 4.

Table 4 – Results for fluidity index

Fluidity index (g/10min)			
Traces	**1 ª measure**	**2 ª measure**	**Average (g/10 min)**
100%PP	30.0	30.0	30.0
20%SC	16.4	16.6	16.5
30%SC	10.4	9.5	10.0

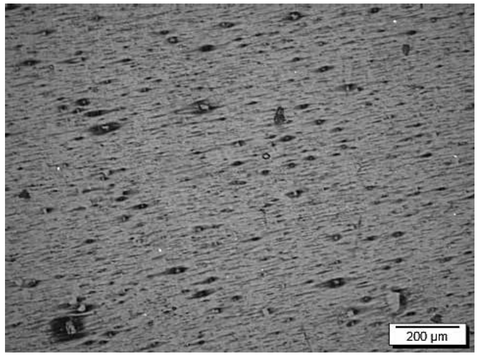
It can be observed in Table 4 that higher the percentage of pulp in the mixture, the lower the fluidity index, compared to pure PP. The composite with 20% SC showed best performance among the samples studied, with the result of 16.5g /10min, and also in relation to the work of Alfaro (2010) which obtained in their composite with rice husk, a fluidity index of 15.5g / 10min.

Because it is a new composite, with properties and characteristics different from particleboard produced with wood particles, Pedreschi (2009) and Rodolfo et al. (2013) for the recognition of the structure formed by the union of the two materials, fiber-plastic employed an optical microscope.

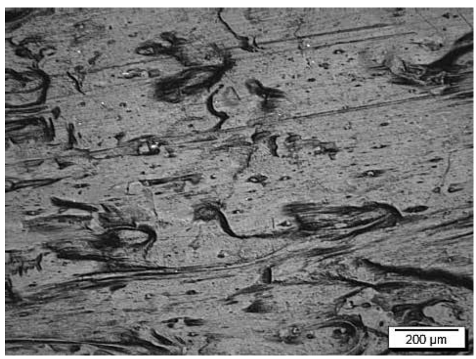
In Figure 5 are presented the micrographs of the composites amplified 100x by an optical microscope, model Olympus BX51M with image acquisition camera Olympus UC30, for the traces: 100% PP; 80% PP+20%SC; 70%PP+30%SC, respectively, were made in the Laboratory of Physics, UNESP, Bauru/Brazil.

The 100% PP presents in general a smooth and homogeneous surface. In the figure 5b and 5c, we can notice the presence of ridges in the surface of the material, detached for shades that appear as dark spots, besides small impurities. When comparing with the 100% PP (Figures 5a, 5b and 5c) it is noticed difference in the surface due to the addition of sugarcane bagasse which can have influence in the adherence and apparent fluidity of the composites.

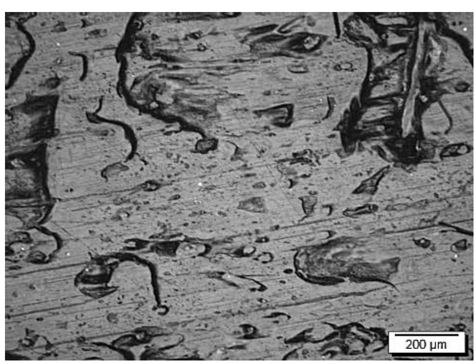
Also it was conducted the test of Artificial Aging by Ultraviolet Radiation (UV), which simulates the conditions of the material usage, including the effects of sunlight, moisture and heat. Some variations in results can be expected when operating conditions are varied.



(a)



(b)



(c)

Figure 5 – Surface of material amplified 100x: (a) 100% PP; (b) 80% PP+20%SC; (c) 70%PP+30%SC.

In Table 5 it is possible to verify the conditions that were submitted to the samples of composites.

Table 5 – Basic configuration of the artificial aging equipment.

Equipament	Atlas Weather-Ometer, model 65 XW-WR1
Radiation Source	Xénon lamp of 6500 W, with filters, internal and external borosilicate
Control of Irradiance	Irradiance of 0.55 W/m² to 340 nm (control with radiometer)
Accelerated aging cycle every 120 min	102 minutes of insolation and 18 minutes of insolation and rainfall simulation
Standard	(ASTM G-155-05)
Final time of accelerated aging	1,200hours

In visual appearance evaluation of the specimens after 1,200 hours inside the machine (Figure 6), in relation to the natural samples (not aged), no significant changes were observed, i.e., changes in color or brightness. Also did not appear cracks, bubbles, contact tackiness, brittleness or any other type of defect. It was also not detected the presence of micro-cracks or fissures.

Figure 6 – Partial view of the samples within the artificial aging equipment.

A research developed by Fabiyi et al. (2008) studied the effects of accelerated aging on composites of polyethylene (HDPE) and polypropylene (PP) reinforced with wood flour, occurred the bleaching of some composites, after the removal of the aging equipment, a fact not observed in this research.

4. FINAL CONSIDERATIONS

The research presented here aimed to find information that encourage the use of two residues (sugarcane bagasse and polypropylene) as an innovative product in the market, thereby reducing the disposal of these residues and adding value.

The addition of fibrous polypropylene matrix showed some difficulty of handling and injection, a great paradigm for its applicability. The variation in the size of the sugarcane bagasse particles can cause problems in production processes. So it was suggested a greater standardization of fiber with a smaller grain size.

The Moisture content is a crucial factor in the injection phase in both specimens, since the presence of water in the composites alters their patterns of pressure and density.

In relation to the 100% PP, the polypropylene material presented greater resistance to water absorption, and higher elasticity and less resistance to impact. The addition of fibers matrix to polypropylene presented difficult in handling and for injection, a great paradigm for its applicability. The varied dimensions of sugarcane bagasse particles can cause disturbances in productive processes.

The raw material humidity is as crucial factor during the injection processes, so the fiber matrix need to be dried in a kiln at least 24h. The presence of water in the composites modifies its pressure and density standards. The results of the mechanical and physical tests with a comparative analyses show the potential viability of the composites. For its implantation and performance in the market would demand a depth study of its chemical characteristics, and attempts of commercial application, since the use of residues could diminish the production cost.

For future works it is suggested a chemical analysis, in order to adjust the laboratorial working standards (injection and extrusion). It would be also interesting to study its applicability for products applied to the civil construction, as modular beams and pillars that already exist in the market. And for complementation of the laboratorial studies, test of aging, analysis of fluidity index (analysis of the viscosity of polymer), and scanning electron microscopy (it produces image with high resolution of the surface).

In continuity to this research is intended to evaluate other traces with both residues, using the dry material in order to avoid problems with moisture during the extrusion and injection phase. In addition, it is intended to use a polymer in powder, to obtain a more homogeneous mixture and improve the characteristics of the composite. And finally test the use of pigments in the production (extrusion and injection) and check for interference in its physical and mechanical properties.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

ALFARO, E. F. **Studies of the use of rice husk ash as filler in polypropylene matrix and the effect of ionizing radiation on this composite.** 2010. 78 p. Thesis (Master). Institute of Nuclear Energy Research, Universidade de São Paulo, 2010.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM D256-00:** Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics. 2000.

______. **D-638-10:** Standard Test Method for Tensile Properties of Plastics. 2010.

______. **ASTM D570-98:** Standard Test Method for Water Absorption of Plastics. 1998.

______. **ASTM 1238-10:** Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer. 2010.

______. **ASTM G155-05:** Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials. 2005.

BATTISTELLE, R. A. G.; VIOLA, N. M.; BEZERRA, B. S.; VALARELLI, I. DE D. Physical and mechanical characterization of a composite of recycled polypropylene and wood flour without additives (Portuguese). **Matéria**, v. 19, p. 7-15, 2014.

CLEMONS, C. M. Wood - Plastic Composites in the United States: The Interfacing of Two Industries. **Forest Products Journal**, v. 52, n. 6, p. 10-18, 2002.

CORREA, C. A.; FONSECA, C. N. P.; NEVES, S.; RAZZINO, C. A.; HAGE, E. JR. Thermoplastic composites with wood. **Polímeros: Ciência e Tecnologia**, v. 8, n. 3, 2003. 154p.

ECKERT, C. **Opportunities for natural fibers in plastic composites**, 2000, *apud* JEONG, G. Y. **Fracture behavior of wood plastic composite (WPC).** Thesis. Graduate School of the Louisiana State University and Agricultural and Mechanical College, Chonnam National University, 2004.

FABIYI, J.S.; MCDONALD, A.G.; WOLCOTT, M.P.; GRIFFITHS, P.R. Wood plastic composites weathering: Visual appearance and chemical changes. **Polymer Degradation and Stability,** v. 93, n. 8, p. 1405-1414, 2008. doi:10.1016/j.polymdegradstab.2008.05.024.

FIORELLI, J.; ROCCO LAHR, F. A.; NASCIMENTO, M. F.; SAVASTANO JR., H.; ROSSIGNOLO, J. A. Particleboard based on sugarcane bagasse and castor resin - production and properties. **Acta Scientiarum Technology**, Maringá, v. 33, n. 4, 2011. doi: 10.4025/actascitechnol.v33i4.9615.

HILLIG, E., IWAKIRI, S., ANDRADE, M. Z.; ZATTERA, A. J. Characterization of composites made with high density polyethylene and wood shavings from furniture industry. **Revista Árvore**, v. 32, n. 2, 2008. 299 p.

NAJAFI, S. K. Use of recycled plastics in wood plastic composites - a review. **Waste Management**, n. 33, p. 1898-1905, 2013. doi:10.1016/j.wasman.2013.05.017.

PEDRESCHI, R. **Utilization of sugarcane bagasse of sugar industry in the production of particleboards.** 2009. 49 p. Tese (Doutorado) - Universidade Federal de Lavras, Lavras, 2009.

RODOLFO JR., A.; JOHN, V. M. Development of PVC reinforced with *Pinus* waste to replace conventional wood in several applications. **Polímeros: Ciência e Tecnologia**, v. 16, n. 1, p. 1-11, 2006. doi: 10.1590/S0104-14282006000100000.

VIOLA, N. M.; BATTISTELLE, R. A. G; VALARELLI, I. DE D.; NASCIMENTO M. F.;

AZAMBUJA, M. DOS A. Applications of wood and plastic waste: Manufacture of wood--plastic composite and its applications. In: **Particleboards of wood and lignocellulosic materials**. São Carlos, EESC/USP, 2013. p. 313-331.

YAMAJI, F. M. **Production of wood-plastic composite from residues of timber industry.** 2004. 182 f. Tese (Doutorado em Engenharia Florestal) - Universidade Federal do Paraná, Curitiba, 2004.

USE OF AMAZON VEGETABLE FIBERS' WASTE AND WOODS FOR THE PRODUCTION OF POLYMERIC COMPOSITES

Raimundo Pereira de Vasconcelos
Universidade Federal do Amazonas, Faculdade de Tecnologia, Departamento de Engenharia Civil, Manaus, AM.
E-mail:vasconcelos@ufam.edu.br

João de Almeida Melo Filho
Universidade Federal do Amazonas, Faculdade de Tecnologia, Departamento de Engenharia Civil, Manaus, AM.
E-mail: jalmeida26179@gmail.com

Flávia Regina Silva dos Santos
Universidade Federal do Amazonas, Faculdade de Tecnologia, Manaus, AM.
E-mail: flavinharss@yahoo.com.br

Magnólia Grangero Quirino
Universidade Federal do Amazonas, Faculdade de Tecnologia, Manaus, AM.
E-mail: quirino.designer@gmail.com

Maria Gorett dos Santos Marques
Universidade Federal do Amazonas, Faculdade de Tecnologia, Manaus, AM.
E-mail: mgorettsmarques@bol.com.br

ABSTRACT: The Amazon region has a large biodiversity that enables the use of various types of plant species in the industrial production, especially the vegetable fibers, mainy jute and malva in the production of sacks for agribusiness, and curauá in the automotive sector. On the other hand, açaí, a fruit largely used by the food industry, produces seed's waste covered by fibers that are still untapped. In this context, this paper presents studies that point to the potential use of waste resulting from the processing of curauá, açaí and some species of wood used in construction, as raw material for production of polymer composites. Two surveys will be discussed: the first discusses the use of waste from the processing of curauá fiber and açaí seed as particulate reinforcement panels with polyurethane based on castor oil resin, and the second, examines the use of curauá fibers residual and two other species of wood commonly used in the construction industry, the louro inhamuí (*Ocotea Cymbarum H.BK.*) and amapá doce (*Brosimum Parinarioides Duke*). Hence, it was produced molded composites with a molding load of 100 kN, at a temperature of about 100°C. The composites were characterized from physical and mechanical tests of absorption, swelling, modulus of rupture, pull out of screw and internal bond. The test results showed that there is a great use potential of such waste for the production of composites for diverse applications.

Keywords: Vegetal fiber. Laminates. Cement. Particulate panels.

1. INTRODUCTION

The search for alternative materials that minimize environmental impacts, is a tendency in contemporary society. Eco-friendly materials or so-called “green materials”, which are intended for the construction industry and the furniture industry have been widely studied. According to Satyanarayana et al. (2009), the development of such materials has not only been a great motivating factor for researchers, but also provides an important source of opportunities to improve the standard of living of people around the world. This is true since many of the renewable materials are based on agricultural products as a source of raw materials, particularly for the plastics industry, and these generate a non-food source of economical development for agricultural and rural areas in developing countries.

For Spiegel and Meadows (2010), green materials destined for construction combine the natural cycle with the ecosystems’ relationships and both come from sources of recyclable materials and also allow themselves to be recycled. The “green materials” respect the limitations of non-renewable resources, namely coal and metal.

Within this context the use of various plant species in the form of fibers or particles, have gained increasing prominence. Several studies have been carried out in recent decades with composites using natural plant fibers (BRUCE et al., 2005; DWEIB et al., 2006; BOGOEVA-GACEVA et al., 2007; SATYANARAYANA et al., 2009; MISTRI et al., 2011; MONTAÑO-LEYVA et al. 2013).

The use of green materials, from natural sources, have become a strong ally for economical and ecological industries. Lots of researches are being carried out with these types, whose results are allowing the development of various products for various purposes in the main areas of engineering in Brazil and worldwide (DWEIB et al., 2006; SATYANARAYANA et al., 2009; SATYANARAYANA, 2010).

Moreover, the Amazon region has a wide diversity of plant species in the form of fibers or particles, whose physical and mechanical characteristics can be exploited in the production of composites. Several fibers are already commercially used in other types of products after they are processed. Among these, there are the fibers of jute, malva, and *curauá*.

Regarding *curauá* fiber, we observe that this is the same family as the pineapple, including very similar aspects, being a plant native to the Amazon region, the *Bromeliaceae* family, whose scientific name is *Ananás erectifolius*. The fiber obtained from this plant was used by Amazonian indians when making fishing lines and fishing nets with quality especially suitable for the production of thin ropes and strings.

With time, and the search for new alternatives, *curauá* fiber began to show great potential, because today is used in different market sectors, such as, automotive, geotextile, nonwoven, furniture making and construction. A fiber that is not favored by industry, but can be seized from the residue and the processing of a very common fruit in the Amazon region, is the fiber obtained from the seed of the açaí berry.

1.1 PLANT SPECIES USED IN CONSTRUCTION IN THE FORM OF WASTE

1.1.1 Curauá Plant

According to Santos (2013), generally several crops per year are held because, while the plant is not with fruit, it keeps producing new leaves. At each stage approximately five to ten mature leaves are torn out, always starting from the lowest leaf on the plant which, of course, is also the oldest. If the plant is already with fruit, usually almost all leaves are torn out at once, leaving only a few leaves to protect the fruit and ensuring a better seedling growth. When they reach a certain size, the fruit begins to dry.

At this point it is recommended to get the seedlings, put them on flower beds and then break the fruit stalk to the height of 15 cm to stimulate growth of the seedlings sprout, CEAPAC (2010).

The shredding is carried out with the use of a shredding machine of individual use, called *Tapuia* (Figure 1). The CEAPAC (2010) recommends that before the process, the leaves should be prepared by cutting off the dry ends and stacking them next to the machine.

Figure 1 – Shredding Machine called "Tapuia" used on the production of curauá fiber. Source: CEAPAC (2010).

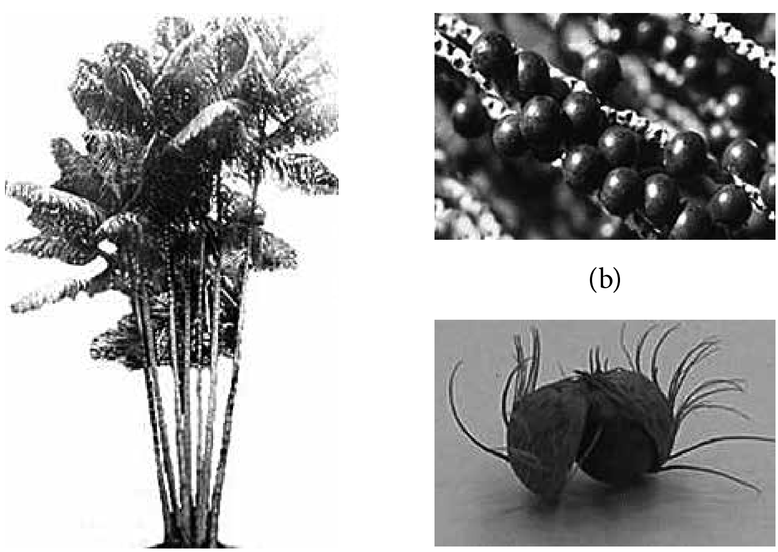
The processing requires: cut and stack the leaves next to the machine, join in an organized way the newly plucked fibers, lay the damp fibers on the clothes line, or take them to a place suitable for composting. The newly drawn fiber has a green color. For its drying on a line, it is laid for at least 24 hours. During the drying phase, the fiber loses its green color. Prepared this way, it is ready to be sold without needing to be washed, CEAPAC (2010).

A company called Pematec, located in the municipality of Santarém, in the state of Pará, Brazil, buys the production of about 400 families of small farmers, who grow the plant in the region of Grandes Lagos, Extractive Reserve Arapiuns – Tapajós, and in the Tapajós' National Forest, which sums the total of around 400 hectares of planted area, one hectare per family. This company makes the final processing of the fiber producing quilts and fabrics that will be utilized for the internal finishing of automotive vehicles.

Although a large amount of the benefit fibers are used, a portion of the production is not utilized during the process, being dropped or even used as a raw material for other products, such as the utilization as a reinforcement or as a booster charge for the production of composite materials. Such composites may be of cementitious or polymeric matrix.

1.1.2 Açaí Berry Plant

Açaí berry is a fruit originating from açaí palm tree (fig 2.), which is a typical palm tree of the tropical climate amazon, where there are two species: *Euterpe Oleracea* and *Euterpe Precatória*. Abundant in the states of Pará, Mato Grosso, Tocantins, Amazonas, Maranhão and Amapá in Brazil and countries in South America such as Venezuela, Colombia, Ecuador, Guyana and Suriname, and Central America such as Panama (QUIRINO, 2010).



(a) (c)

Figure 2 – (a) Açaí palm tree; (b) açaí berry fiber. Source: Quirino (2010).

Its fiber is extracted from the seed, where it is processed and dyed for the production of crafts and biojewelery. There is an emerging research on the raw material and its technical viability compared with other fiber such as sisal, abaca and bamboo, for example, in which has defined use, Quirino (2010).

A fiber obtained from the seed of the açaí berry, which is a waste product from the pulp, can be very well used in the production of polymer composites, as will be seen later.

1.1.3 Amazon forest species

Timber activities in the northern region of the country is one of its main economic activities. Despite such importance, the utilization rate of wood by the industry, of only 40% is still very low. It is noteworthy that species of lower economic value, and/or less noble use, could be used to produce an alternative product, MACÊDO et al. (2008).

Speaking about the environment and environmental issue in Brazil, mainly in the northern region of the country, brings back memories of the Amazon rainforest where this is a great laboratory for studies and research in order to reduce environmental impacts and possible solutions to an improvement between humans and the environment and this is the main focus.

Still in INPA, in 2012, the project "Technological Studies of alternative use of forest residues in central Amazon" was developed, which was led on by the researcher Basílio Vianez. As the main object of this Project, the reusing timber waste from the Amazon in order to build a house of rollers. Remains rollers, leftover after being processed for making sheets of wood to produce plywood were used. In this project with funds from the National Council for Scientific and Technological Development (CNPq), it was built a house in rollers in the Forest Science Institute, located at Avenida André Araújo, Petrópolis, south-central zone of Manaus.

It should be noted that the use of wood waste has always been seen as low quality or discomfort, its purpose being to improve the quality of life, be it ina a new source of income and employment, or in reducing waste in the environment, representing not only positive values already reported, but the concrete opportunity to maintain the forest alive and capable of being used sustainably.

In the timber industry waste, known as rollers, they are burned in boilers to produce steam in plywood factories, in the manufacturing of packaging and crates, and are considered as underutilized and low quality products, INPA (2012).

As technical visit to Mil Madeiras Preciosas Ltda. industry, located on Torquato Tapajós highway, KM 227- Itacoatiara-AM could state, there is a percentage of production wastes that are discarded, reaching somewhere around 60% where these wastes are reused in burning for production of electricity for the region. It was also observed that the burning of such waste, generates other waste, which are the ashes where its ultimate destination is the landfill and often even inappropriate places, thus causing environmental impacts such as soil infertility, decreased rainfall and increasing temperature in the region.

In order to reduce these environmental problems caused by the generation of wood waste discarded during its manufacturing process, the option can be reusing them for manufacturing of composite panels.

Among the various species of wood found in the Amazon region, we can mention two types largely used for making mold for concrete structures, Louro Inhamuí and Amapá Doce. Moreover, it is noteworthy that the use and exploration of Amazonian wood should be more sustainable than it is currently.

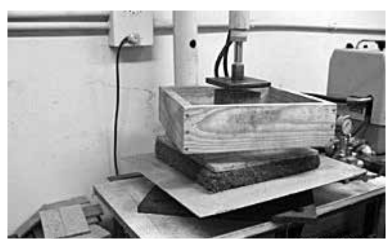
2. PRODUCTION OF POLYMERIC PANELS

An alternative to the use of residue from the *curauá* fibers, the açaí one and species used in construction is its use in the production of polymer composites in the form of panels. In this case, the fibers are used in a polymeric resin which after a polymerization process obtained by elevating the temperature for a predetermined time period, the mixture becomes a resistant composite. In this line of research, two works deserve mention. The composites made with fibers from the seed of the açaí (QUIRINO, 2010) and that obtained from *curauá* fibers with waste from amazon wood processed (SANTOS, 2013). Both papers have reported particulate panels with features that met the standards established by NBR 14810 (2006) and ANSI (1999).

For the production of panels as from seed of açaí and curauá fiber with wood waste fiber was adapted to the standard NBR 14810 (2006). The adoption of this regulatory procedure is due to the similarity of produced panels to those made of wood particles.

Quirino (2010) produced eight panels, with particles of fiber from the seed of the açaí berry and polyurethane resin based on castor oil. The açaí fiber was blended gradually to the adhesive (Figure 11(a)). After mixing, the particles were placed in the forming mold panel (Figure 11(b)) and introduced into a thermohydraulics press for a period of 10 min (Figure 11(c)). To the average pressure of 5 MPa. In the sequence, the panels were stored for 72 hours to a effective cure of the material (Figure 11(d)).

(a)



(b)

(c)

(d)

Figure 3 – (a) manual homogenization; (b) Pre-press: removal from the mold, mattress made; (c) hydraulic ress from Marconi. (d) Panel finalized ready for the curing period. Source: Quirino (2010).

Santos (2013) produced twenty-four panels, being only eight with particles of *curauá* fiber, eight with curauá particles and residues of amapá doce and eight with curauá particles and residues of louro inhamuí. The amapá doce and louro inhamuí are two common timber species in the Amazon region, the first being used in the manufacture of squeegee handle, broom and mop, household utensil handle (knife, pocket knife, cutlery, pot and tray hanble), handle for garden and garden utensil (knife, rake and hoe), racket (tennis, racquetball and ping-pong), coating in general (liner) and barrel. The second kind is used mainly in carpentry, general construction, paneling, beams, rafters, battens, baseboards, moldings, trims, cords, boards, planks, turnery, joinery, plywood, furniture manufacturing, production of decorative laminated sheets. (MAIA et al., 2001).

Santos (2013) employed the same process used by Quirino (2010) for the production of curauá fiber's particulate panels with wood waste, therefore, employed 50% of curauá fibers with 50% of residue wood, as much for the amapá doce residue and louro inhamuí one. However, in both cases it was used the same proportion of the polyurethane resin based on castor oil, 1:1.

Quirino (2010) obtained for the physical and mechanical tests of the polymeric panels with açaí seed fibers, according to NBR 14810 regulation (2006) the values are shown in tab. 1.

Table 1 – Values of physical and mechanical characteristics obtained by Quirino (2010) for polymer panels made of açaí seed fiber.

Panel's Characteristics	Average Values	Limit Values
Density (kg/m^3)	880 ± 40	551 Kg/m^3 a 750 Kg/m^3 Medium density panel
Absorption (%)	8.48 ± 2.43	≤ 8%
Swelling (%)	3.76 ± 1.12	≤ 8%
Modulus of rupture - MOR (MPa)	15.23 ± 2.37	≥ 16
Pull out of screw - PS (N)	1,080 ± 33	≥ 1,050
Perpendicular tensile strength (MPa)	0.66 ± 0.05	≥ 0.35

Source: Quirino (2010).

As the values were shown in tab. 2, Quirino (2010) made the following observations:

i) The tests' results showed a density of 880kg/m³ for the panel with the açaí fiber with CV of 4.54%. The NBR 14810-2 define as medium density panel those whose density is in the range of 551-750kg/m³, whereas the ANSI 208.1 for panels with a density above 800kg/m³ ranked as high density. Hence, the panel produced with açaí fibers can be classified as high density as the aforementioned standards;

ii) As for the swelling test as for the water absorption, NBR 14810-2 recommends a content of 8% or less for 2h in 14 mm panels. In the absorption test the average result was of 8.48%, with CV of 28.65%, exceeding the standard rate. As for the swelling test, the average was of 3.76%, with CV of 29.78%, lower than recommended by the standard value;

iii) The NBR 14810-2 recommendation for chipboard panels between 14 mm to 20mm of thickness is of a minimum value of 16 MPa for the Modulus of Rupture (MOR), while the ANSI A208.1 sets this parameter to the minimum value of 16.5 MPa for high density panels. In this test, the açaí fiber plates having a thickness of 10mm fiber showed an average value of 15.23 MPa (CV 15.56%), getting this a little below of what is set in both standards. However, it is expected that for thicknesses up to 14mm it is possible to obtain an average value for MOR above the minimum recommended value;

iv) The NBR 14810-2 standard for plywood sheets of 14mm to 20mm thick recommends a minimum value of 1.020 N for the poll out of screw test. In this test, the açaí fiber plates having a thickness of 10mm showed an average value of 1,080 N, meaning that this result is above the recommendation of NBR 14810-2, even for a thickness panel lower than the track displayed;

v) For plywood sheets, the NBR 14810-2 recommends, for perpendicular tensile testing, the minimum value of 0.35 MPa, while the ANSI A208. establishes the value of 0.90 MPa for panels of high density.

> As for this test the average value was 0.66 MPa, it is observed that the panel with the açaí fiber meets the NBR 14810-2 also for this requirement, however, below the established by ANSI A208.1.

Quirino (2010) also concluded that the process of production of polymeric panels with fiber from the seed of the açaí berry is simple and can be easily applied in the industrial sector, the panel can serve as raw material for the manufacture of furniture, or wall coverings and ceilings, in addition to finishing of buildings. The panel had developed physical and mechanical results very close and in some cases higher than those recommended by the norm NBR 14810-2, for particulate panels, although the parameters are still below the minimum values established by ANSI A208.1.

Santos (2013) conducted physical and mechanical tests on the polymeric panels with *curauá* fibers, according to NBR 14810, and presented the results shown in tab. 2, considering three types of different composite: with 100% of curauá fiber (FC); with 50% of curauá fiber and 50% of Amapá Doce residual (CA); 50% of curauá fiber and 50% of louro inhamuí residual (CL).

Table 2 – Values from the physical and mechanical characteristics obtained by Santos (2013) for polymeric panels with curauá fiber.

Panel's Characteristics	Average Values			Limit Values
	FC	CA	CL	
Density (kg/m³)	853.2 ± 55.3	910.9 ± 44.9	941.3 ± 28.2	551 Kg/m³ a 750 Kg/m³
Absorption (%)	25.1 ± 17.2	11.7 ± 7.6	8.7 ± 4.8	≤ 8%
Swelling (%)	17.6 ± 11.0	5.9 ± 3.7	6.2 ± 1.8	≤ 8%
Modulus of rupture - MOR (MPa)	33.37 ± 8.63	24.48 ± 3.81	26.62 ± 10.61	≥ 16
Pull out of screw – PS (N)	662.5 ± 204.6	1,125.0 ± 106.1	1,046.0 ± 482.3	≥ 1,050
Perpendicular tensile strength (MPa)	0.83 ± 0.49	0.94 ± 0.36	1.19 ± 0.59	≥ 0.35

Source: Santos (2013).

Santos (2013), based on the results obtained, showed the following main conclusions:

i) According to the density, the panels are classified as high density, as defined by the standards NBR14810-2 (2006) and ANSI (1999);
ii) It is also observed, in relation to physical tests of swelling and absorption, that the best results were obtained for the panel produced with curauá fiber and louro residuals, emphasizing that according to NBR 14810-2(2006) the swelling was below the established and the absorption near the maximum;
iii) All panels produced, showed MOR higher than in the NBR 14810-2 (18 MPa), and those produced with only curauá fibers presented the best results (33.37 MPa) compared to those produced with fibers and wood waste (amapá: 24.48 MPa; louro: 26.62 MPa);
iv) The pull out of screw tests and internal bond panels showed higher values to the minimum defined by NBR 14810-2 (1,020 N; 0.40 MPa), except the plate produced only with curauá fiber, which showed lower value for pull out of screw test (662,5 N). In addition to that, considering the specifications of ANSI (1999), in relation to the minimum values of MOE and MOR, the panels produced are classified as H3, being suitable for industrial and commercial use.

Comparing the values presented by Santos (2013) with those obtained by Quirino (2010) we can make the following observations:

i) The results obtained by Quirino (2010) for the polymeric panels with açaí seed fiber have a much smaller standard deviation than those obtained by Santos (2013)(34), which may indicate that Quirino (2010) produced panels more homogeneous than those made by Santos (2013);
ii) All panels produced were classified as high density, and only those produced from plant fibers showed lower density;
iii) The panels with açaí seed fibers showed absorption and swelling lower than those produced with *curauá* fibers;
iv) Regarding the mechanical properties, it is noted that the panels with *curauá* had far superior results to those obtained with açaí

fibers, with the exception regarding the pull out of screw test, in which the panels with amapá doce and louro inhamuí had their average values lower than the NBR 14810 recommends.

It should be highlighted that Quirino (2010) and Santos (2013) produced panels with a thickness of 10mm, being the reference values recommended by the NBR 14810 refer to particulate panels with 14mm in thickness. Hence, one would expect better results than those presented in tab. 1 and 2, mainly for the mechanical characteristics, for panels produced with fibers from the seed of the açaí berry and curauá fibers for thickness of 14 mm.

3. FUTURE PERSPECTIVES

Several studies have been developed in recent years with the use of plant fibers as reinforcement to cement or polymer matrix, but those in which make the application of waste vegetable fibers originating from the processing or production process are less frequent. In the Amazon region, various vegetable fibers have been employed in the industry, among them, it is highlighted jute, malva and curauá fibers, the first two already traditional in the production of sacks for the agro-industrial process, while the third has gained space in the automotive sector, mainly in the production of inner linings.

On the other hand, the açaí seed fiber isn't in use in the industrial sector, being only a residual of the production process of açaí pulp, much used as raw material for the food sector.

Of the results obtained for the açaí seed and curauá fiber waste applied in particulate panels (QUIRINO, 2010); (SANTOS, 2013), it is observed that these materials have potential for the production of composites that can be employed both in the construction sector and in the furniture industry sector. These panels can be applieds in the form of sealing elements and the raw material for the production of furniture.

Considering the production of furniture Quirino and Vasconcelos (2011) produced reduced models from polymeric panels with açaí seed fiber made in his research(fig. 4).

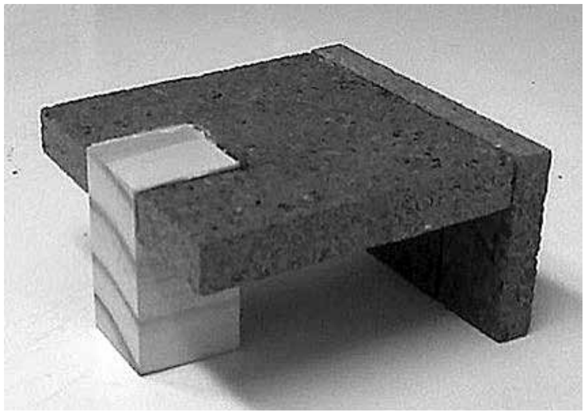


Figure 4 – Reduced model of a furniture produced from açaí seed fiber panels.

ACKNOWLEDGEMENTS

To the structural laboratories (Labest) from COPPE/UFRJ also wood and wooden structural laboratories (Lamem) from EESC/USP for the support when it comes to testing and composite's production aid. To CAPES, CNPq e FAPEAM for the financial support needed for the research development. Special acknowledgements to DGT/UFAM, DEC/UFAM, UFLA/MG, INPA, FZEA/USP, ESALQ/USP and PEMATEC.

PERMISSION FOR PUBLICATION

It is the responsibility of the author (s) the citation of organs and / or institutions as well as the content of their articles, and editors and visual designers reserved the right to modify the presentation of figures, tables and equations aiming to standardize the text.

REFERENCES

AMERICAN NATIONAL STANDARDS INSTITUTE. **ANSI A208.1:** mat-formed wood particleboard: Specification. Gaithersburg: National Particleboard Association, 1999.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 14810-1** – Plywood Sheets, Terminology. Rio de Janeiro, 2006.

______. **NBR 14810-2** – Plywood Sheets, Requirements. Rio de Janeiro, 2006.

______. **NBR 14810-3** – Plywood Sheets, Testing Methods. Rio de Janeiro, 2006.

BOGOEVA-GACEVA, G.; AVELLA, M.; MALINCONICO, M.; BUZAROVSKA, A.; GROZDANOV, A.; GENTILE, G.; ERRICO, M. E. Natural fiber composites. **Polymer Composite**, v. 28, n. 1, p. 98-107, 2007. doi: 10.1002/pc.20270.

BRUCE, D. M.; HOBSON, R.N.; FARRENT, J. W.; HEPWORTH, D.G. Highperformance composites from low-cost plant primary cell walls. **Composites Part A**, p. 1486-1493, 2005. doi:10.1016/j.compositesa.2005.03.008.

CEAPAC (Centro de Apoio a Projetos de Ação Comunitária). **Curauá Produção Agroecológica, Beneficiamento, Comercialização.** Santarém, Pará, 2010.

DWEIB, M. A.; HU, B.; O'DONNELL, A.; SHENTON, H.W.; WOOL, R. P. Biobased composite roof for structure: manufacturing and processing issues. **Composite Structures**, v. 74, n. 4, p. 379-388, 2006. doi: 10.1016/j.compstruct.2005.04.018

INPA (Instituto Nacional de Pesquisas da Amazônia). **Tecnologia em Resíduos de Madeira**. Available at: <http://http://www.inpa.gov.br/noticias/noticia_sgno2.php?codigo=2391>. Accessed on: April 14, 2012.

MACÊDO, A. N.; RAMOS, M. A.; FERNANDES, M. C. O.; BENTES, J. L. **Espécies de Madeira da Região Amazônica possibilidade de Aplicação na tecnologia da madeira laminada colada.** XI ENCONTRO BRASILEIRO EM MADEIRA E ESTRUTURAS DE MADEIRA, Londrina, Paraná, 2008.

MAIA, J. G. S.; ZOGHBI, M. G. B.; ANDRADE, E. H. A. **Plantas aromáticas na Amazônia e seus óleos essenciais.** Museu Paraense Emílio Goeldi, Belém, 2001.

MISTRI, E.; ROUTH, S.; RAY, D.; SAHOO, S.; MISRA, M. Green composites from maleated castor oil and jute fibres. **Industrial Crops and Products**, v. 34, p. 900-906, 2011. doi: 10.1016/j.indcrop.2011.02.008.

MONTANÕ-LEYVA, B.; SILVA, G.; GHIZZI D.; GASTALDI, E.; TORRES-CHÁVEZ, P.; GONTARD, N.; ANGELLIER-COUSSY, H. Biocomposites from wheat proteins and fibers: Structure/mechanical properties relationships. **Industrial Crops and Products**, 43, p. 545-555, 2013. doi:10.1016/j.indcrop.2012.07.065

QUIRINO, M. G. **Estudo de matriz polimérica produzida com resina e fibra de açaí (*Euterpe Precatória*)**. 2010. 155 p. Dissertação (Mestrado) – Mestrado em Engenharia Civil, Universidade Federal do Amazonas, 2010.

QUIRINO, M. G.; VASCONCELOS, R. P. Development of composite made with resin and fiber from the seed of açaí *(Euterpe Precatória)*. In: INTERNATIONAL SYSMPOSIUM ON SUSTAINABLE DESIGN, Recife, 2011. **Anais...** Recife, Pernambuco, v.1, p. 390-401, 2011.

SANTOS, F. R. S. **Desenvolvimento e aplicação de compósitos à base de matriz polimérica reforçado com fibras de curauá (*Ananás Erectifolius*) e resíduos de madeiras amazônicas.** Dissertação (Mestrado) – Mestrado em Engenharia Civil, Universidade Federal do Amazonas, 2013.

SATYANARAYANA, K. G.; ARIZAGA, G. G. C.; WYPYCH, F. Biodegradable composites based on lignocellulosic fibers — An overview. **Progress in Polymer Science**, 34, p. 982-1021, 2009. doi: 10.1016/j.progpolymsci.2008.12.002.

SATYANARAYANA, K. G. Biodegradable polymer composites based on brazilian lignocellulosic. **Revista Matéria**, v. 15, n. 2, p. 88-95, 2010. doi: 10.1590/S1517-70762010000200001.

SPIEGEL, R.; MEADOWS, D. **Green Building Materials:** A Guide to Product Selection and Specification. 3 ed., New Jersey: John Wiley & Sons, Inc., 2010. 400p.

About this book

Format	16 x 23 cm
Typefaces	Minion Pro (text) Helvetica Neue (titles)
Paper	Offset 75g/m² (pages) Supremo 250g/m² (cover)
Design	Canal 6 Editora www.canal6.com.br

In recent years, researches focusing on the development of non-conventional building materials, based on agro-industrial waste, have been gaining attention in the academic and scientific circles.

This book presents results of the research carried out with polymer based composites of some agro-industrial wastes: sugar cane bagasse, straw and husk left over from rice, açaí fiber, coffee husks, babassu husk fiber, residual materials of oat hulls, wastes of reforestation wood, peanut husks, residual materials generated in the production of Amazon vegetable fibers, bamboo particulate waste and life cycle of wood-based composites.

FINANCIAL SUPPORT

CAPES

PRÓ REITORIA Pós-Graduação USP

ORGANIZERS

USP BioSMat Materials for Biosystems

FZEA USP

PPG EnCiMat USP

EESC · USP

GRUPO Tiliform Comunicação Gráfica Integrada

ISBN 978-85-69233-00-8