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Particulate composite based on coconut fiber and castor oil polyurethane adhesive: An eco-efficient product

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ABSTRACT

This paper presents a study on the potential use of coconut fiber as material to produce particleboards, with two different densities (0.8 g/cm^3 and 1.0 g/cm^3), using castor oil-based polyurethane adhesive and urea-formaldehyde. The quality of the product that can be produced by industry was evaluated according to the normative NBR 14.810:2006, where density, thickness swell (TS), absorption, modulus of elasticity (MOE), modulus of rupture (MOR) in static bending and internal bond (IB) were determined. From the results, there was a decrease in TS and increase in MOR of coconut fiber panels with polyurethane resin panels compared with coconut fiber and resin urea-formaldehyde. Scanning microscopy electronic images (SEM) indicated that castor oil-based polyurethane adhesive occupies the gaps between the particles, a factor that contributes to improved physical and mechanical properties of the panels. The assessment of durability through accelerated aging tests shows that panels protected with waterproofing material can be used in environments that have contact with moisture.

1. Introduction

The agricultural sector depends directly or indirectly on the environment as a source of raw materials for its development, as well as on areas as “dumping sites” for byproducts and waste generated in the 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 to use it to produce particulate composites. These panels are generally manufactured from wood particles bonded by synthetic adhesive or other binders, being pressed under heat long enough for the adhesive to cure (Iwakiri et al., 2004).

Basically, these panels can also be produced from any lignocellulosic material which gives them high strength and pre-determined specific weight, since the chemical composition of lignocellulosic materials is similar to that of wood, especially hardwoods which have smaller lignin content and higher pentosan hemicelluloses content (Okino et al., 1997; Brito et al., 2004; Khedari et al., 2004; Passos, 2005; Contreras et al., 2006; Chamma and Leão, 2008; Barros Filho et al., 2011).

Senhoras (2003) says that in Brazil, the currently estimated annual production of coconut is over 1.5 billion units, being among the top 10 producers in the world. The coconut shell (*Cocos nucifera*) is a green waste with high potential for agricultural use but unfortunately has little use in Brazil. According to Rosa et al. (2001), 80–85% of the gross weight of the coconut is considered waste. Organic coconut residue degradation is difficult and takes more than eight years to decompose completely (Carrijo et al., 2002).

In recent years efforts have intensified to study the best use of lignocellulosic residues for production of new materials, such as particle boards (Chamma and Leão, 2008). This is due to the fact that the use of lignocellulosic residues contributes to mitigate the environmental impacts, featuring the production of new materials to appeal to sustainability. An alternative to this niche work is the use of coconut husk fiber.

The agglomerate panel industry in Brazil uses mostly wood shavings from pines reforestation and some eucalyptus species, what results is a higher quality product due to better control in raw-material homogeneity. However, the agro-industrial lignocellulosic residue is a recent alternative to produce such panels and the Brazilian agricultural boom and increase in residues may favor their use to replace wood in panel production.

Several studies have suggested coconut fiber as a material to produce particulate panels.

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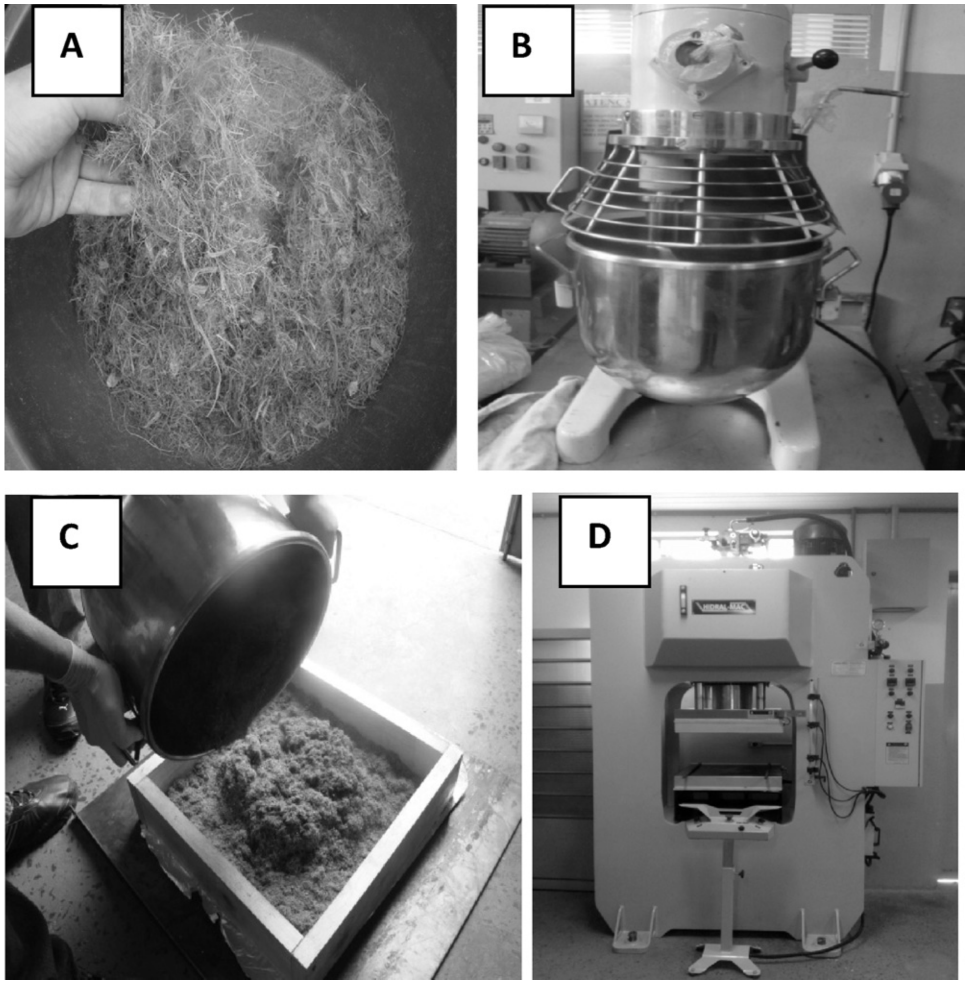

Fig. 1. Production of particle panel steps.

Urea-formaldehyde and phenol formaldehyde based adhesives have noticeable homogeneity (Mendes et al., 2010a,b). However, there is a global trend towards biodegradable, non-pollutant and renewable products. This trend led to further research, resulting in the castor oil-based polyurethane adhesive (Araújo, 1992). This paper aimed at demonstrating the feasibility of producing panels made of coconut fiber particles with fiber lengths of 7 mm and two different densities (0.8 g/cm^3 and 1.0 g/cm^3) and evaluating the efficiency of producing boards with castor oil polyurethane adhesive compared with panel made with adhesive urea-formaldehyde.

2. Materials and methods

2.1. Production of particulate panels

The coconut fiber panels were prepared using a heated automatic press, load capacity 100 MT, following detailed recommendations from (Maloney, 1996). The process began by collecting the coconut fiber from the coconut processing industry (Fig. 1a). The waste was dried to a moisture content of around 2 and 3%, had an average fiber length of 7 mm and panel density of 0.8 and 1.0 g/cm^3. To manufacture the particle boards, 10–15% castor oil-based bi-component polyurethane adhesive produced by Plural Brazil and urea-formaldehyde (Cascomite) produced by Momentive Brazil were used. More details are in Table 1.

The particles with 8 mm of length were mixed with adhesive in a planetary mixer (Fig. 1b). After mixing, the material was placed into a mold (Fig. 1c) and inserted into the hydraulic press (Fig. 1d), under 50 kg/cm^2 and temperature up to 100–140 °C for 10 min. Three particleboards with nominal dimensions of 40 cm × 40 cm and 10 mm thickness were made. From these panels 10 specimens were taken for each physical-mechanical test, according to recommendations of the standard NBR 14810:2006-Plywood Sheets. The choice of this normative document was due to the similarity between the panels produced (coconut fiber) and wood panels.

2.2. Physical-mechanical characterization

The performance of the panels was evaluated by physical-mechanical tests according to the normative document NBR 14810:2006-Plywood Sheets-Part 3. A completely random design (CRD) was used with four treatments (Table 1). The properties evaluated were the thickness swelling (TS), water absorption (WA), modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB). These were evaluated both before and after the accelerated aging test. The average was compared by a multiple comparison test (Tukey) when the ANOVA was significant at ($p \leq 0.05$).

2.3. Thickness swelling (TS)

The thickness swelling tests were conducted according to ABNT NBR 14810:2006. The thickness swelling is calculated from the difference in specimen thickness before and after soaking in water

Table 1
Experimental program.

Particle Board—coconut fiber				
Treatment	Density (g/cm^3)	Quantity of panels	Adhesive type	Accelerated aging test ASTMD 1037 standard
T1	0.8	3	Castor oil	–
T2	1.0	3	Castor oil	–
T3	1.0	3	Urea formaldehyde	–
T4	1.0	3	Castor oil	6 cycles

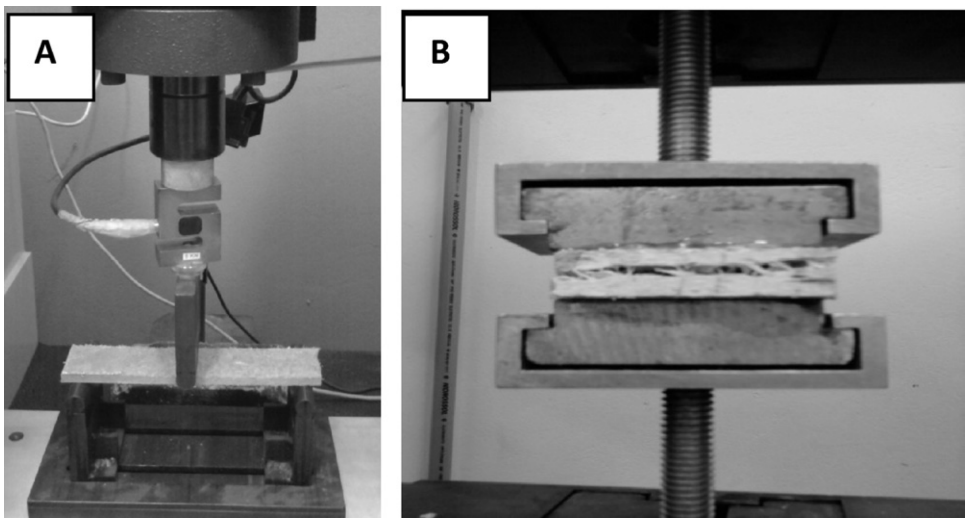

Fig. 2. Flexural is (a) and Ib is (b) in coconut fiber panel.

for 24 h. It was assessed using a digital caliper with a precision of 0.01 mm. The percentage of the thickness swelling was calculated using Eq. (1).

$$\text{TS}\quad(\%) = \left[\frac{T_f - T_i}{T_i}\right]100 \tag{1}$$

where T_f is the final thickness after soaking for a period of 24 h and T_i is the initial thickness.

2.3.1. *Water absorption (WA)*

The water absorption tests were conducted according to ABNT NBR 14810:2006. The samples before and after accelerated aging were soaked in water for 2 h and 24 h. The water absorption was calculated using Eq. (2).

$$\text{WA}\quad(\%) = \left[\frac{W_f - W_i}{W_i}\right]100 \tag{2}$$

where W_f is the final weight after soaking for a period of 2 h and 24 h and W_i is the initial weight.

2.3.2. *Mechanical testing*

The internal bond and flexural tests (Fig. 2) were conducted using a universal testing machine at room temperature, according to ABNT NBR 14810:2006. The loading rate for the bonding 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 the universal testing machine operating with a load cell capacity of 5 kN. A total of ten specimens were made and tested.

2.4. *Durability analyses*

The evaluation of the durability of panels made from coconut fiber and castor oil-based bi-component polyurethane adhesive was based on ASTM D 1037:1996-Standard test method for properties of wood-based fiber and particle panel materials. The accelerated aging test consists of the following six steps as shown in Fig. 3. Five test specimens were made with dimensions of 250 mm × 50 mm × 10 mm and protected with waterproofing (covering) material. After the accelerated aging test the specimens were conditioned at 65% relative humidity and 20 °C room temperature for 48 h before determining their physical and mechanical characteristics.

3. Results and discussion

This section presents the results of the physical-mechanical characterization of the coconut fiber panels (treatment T1, T2, T3 and T4). Average experimental values and their coefficients of

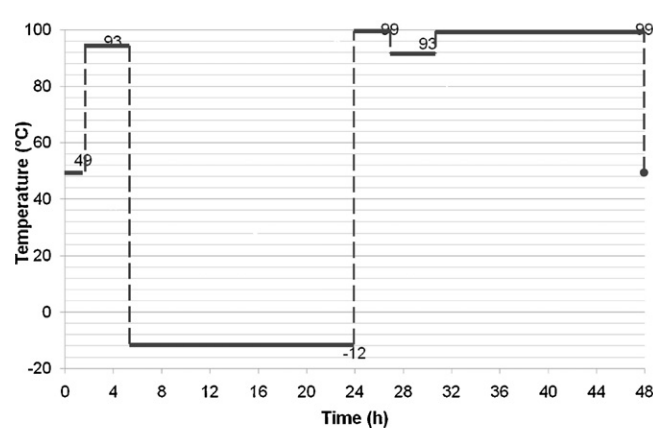

Fig. 3. Phases for ASTM D 1037 accelerated-aging test.

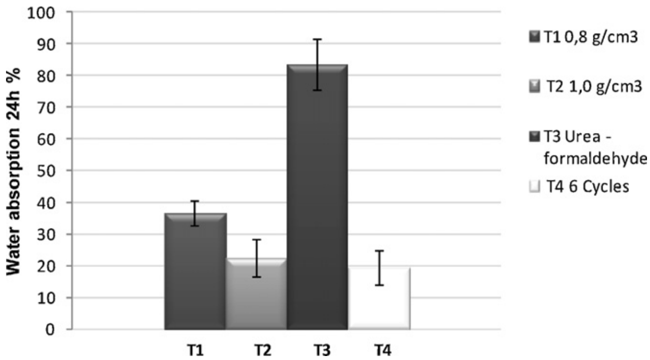

Fig. 4. Water absorption of the particle board coconut fiber.

variation for density, thickness swelling and mechanical properties are presented.

The obtained results were compared to those in the NBR 14810:2006 and ANSI A208.1:1993-Mat-formed wood particleboard: specification. This comparison is justified based on the similarity between the product developed in this study and wood particle panels.

3.1. Physical properties

Fig. 4 shows the variation in the percentage of water absorption for specimens of the four treatments. This percentage is typical of panels made from large flat flakes (such as wafer strand). The average water absorption values for the particle boards produced with urea formaldehyde (T3) were higher than those produced with other treatments. This fact can be explained by the microstructure formed between the particles and the castor oil-based bi-component polyurethane adhesive (Figs. 10 and 11). The particle board that was submitted to the accelerating aging test (T4) showed a similar rate of absorption after 24 h. The particle board with a density of 0.8 g/cm^3 (T1) had a higher rate of water absorption when compared to 1.0 g/cm^3 (T2). These two treatments (T1 and T2) both used the castor oil-based bi-component polyurethane adhesive.

The thickness swelling tests provided information on the bond conditions of the panels after they were immersed in water. These tests are systematically carried out by industries for quality control of their products.

Fig. 5 shows the differences in the thickness swelling after being submerged in water for 24 h. Specimens submitted to accelerated aging presented lower values of thickness swelling. This is most likely because the accelerated aging test already exposes the specimens to varying levels of water content under extreme temperature conditions. The panels produced with urea formaldehyde showed higher values of swelling in thickness after 24 h when compared to

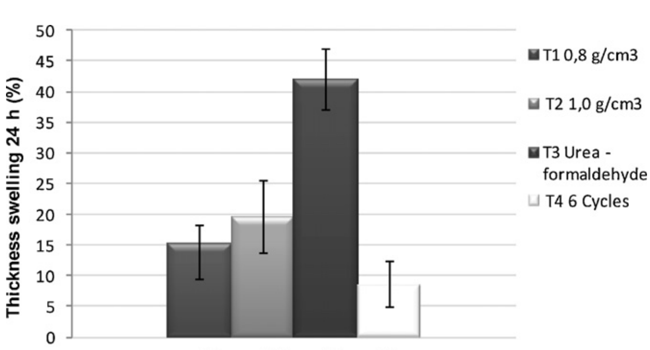

Fig. 5. Thickness swelling 24 h of the particle board coconut fiber.

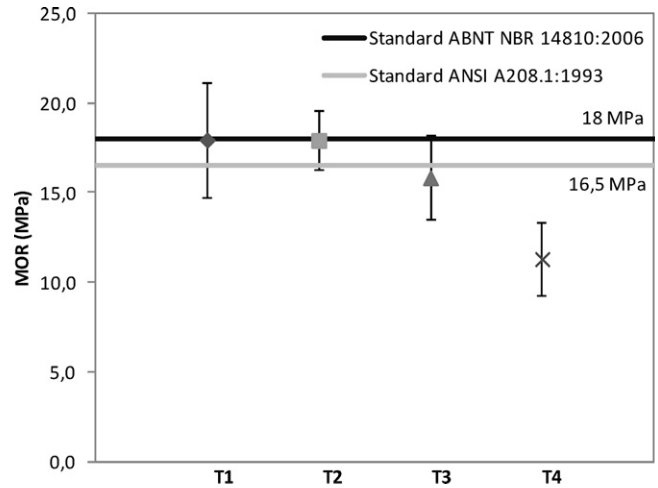

Fig. 6. Average values of modulus of rupture.

those manufactures with castor oil (Figs. 10 and 11), this result has a correlation with dispersion and expansion of the adhesive in cure process. The prolonged soaking in water may result in leaching of the water-soluble substances and hence reduce decay strength.

Table 2 shows the relation between physical–mechanical properties manufacturing with different density (T1 and T2 treatment).

We observe in Table 2 that we do not have a significant statistical difference ($p < 0.05$) for the properties TS, MOR, MOE, and IB, for the panels with densities of 0.8 and 1.0 g/cm^3 produced with polyurethane resin based on castor oil.

The panels studied can be classified as a high-density material according to ANSI A208.1:1993. This classification is important since the minimum MOE, MOR, IB and TS values are closely related to the density. Similar results were obtained by Marcilio et al. (2008), who examined physical properties of panels with a density up to 1.0 g/cm^3 made of sugarcane bagasse, bamboo (*Dendrocalamus giganteus*) stem leaves (*bamboo straw*) fiber and urea formaldehyde adhesive.

Based on these results we may recommend these panels for industrial and commercial use, according to the standard A208.1:1993.

3.2. Mechanical properties

Fig. 6 presents a correlation between the MOR of different treatments (T1, T2, T3 and T4). The panels with castor oil-based bi-component adhesive (T1 and T2) have higher values of MOR than panels produced with urea formaldehyde. These values are very similar to the recommendations in ABNT NBR 14810:2006 and ANSI A 208.1:1993. The specimens subjected to accelerating aging (T4) had a reduced MOR value to those without accelerated aging (T2).

The MOR values of T1 and T2 were superior to those obtained by Khedari et al. and Passos, demonstrating that the production process used in this study was consistent and that the castor oil-based bi-component resin is a viable adhesive material for manufacturing panels made of coconut fiber particles (Khedari et al., 2004) and Passos (2005).

Fig. 7 presents a comparison of the MOE values between different treatments (T1, T2, T3 and T4). The panels with castor oil-based bi-component adhesive (T1 and T2) have lower values of MOE than panels produced with urea formaldehyde and lower values compared to the recommendations of ANSI A 208.1:1993 to panels with same density. The specimens subjected to accelerating aging (T4) had a reduced MOE value to those without accelerated aging (T2). You can see that the panels made from coconut fiber

Table 2
Physical–mechanical properties experimental values—different density.

Treatment	Density (g/cm^3)	Absorption (%)	TS (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
T1	0.8	36.59a	15.30a	17.94a	1.405a	1.80a
CV	7.11	11.09	19.08	19.04	53.01	19.11
T2	1.0	22.38b	19.67a	17.92a	1.396a	2.07a
CV	3.24	26.37	29.74	9.20	11.75	27.94

The averages which are followed by the same letter in the same row do not differ in the Tukey test at a 5% significance level.
CV—variation coefficient.

Table 3
Physical–mechanical properties experimental values—density 1.0 g/cm^3.

Treatment	Absorption (%)	TS (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
T2	22.38a	19.67a	17.92a	1.396a	2.07a
CV	26.37	29.74	9.20	11.75	27.94
T3	43.43b	32.08b	15.83b	2.041b	1.04b
CV	9.59	11.82	14.75	18.91	62.56

The averages which are followed by the same letter in the same row do not differ in the Tukey test at a 5% significance level.
CV—variation coefficient.

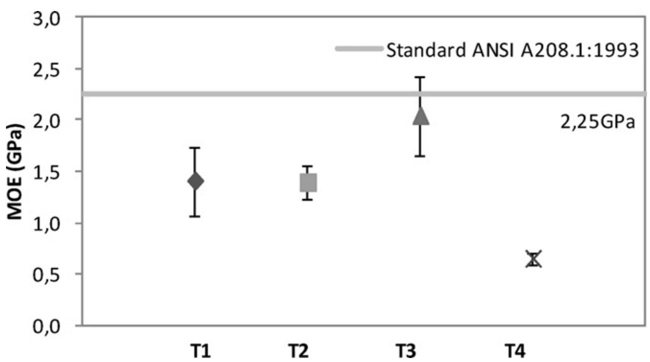

Fig. 7. Average values modulus of elasticity.

and adhesive castor oil and urea-formaldehyde, does not meet the minimum requirements established by the MOE in document ANSI 208.1:1993. This characteristic identified for panels with coconut fiber may have relation with the dimension and format of particles (Maloney et al., 1976) and compaction ratio panel (Maloney, 1993), once the normative document establishes parameters for wood particle boards.

In Fig. 8 it is observed that the panels presented higher IB values than those recommended by the normative document ABNT NBR 14810:2006 and ANSI A.208.1:1993. These values were also higher than the 0.4 MPa found by Battistelle et al. (2009) and the 0.6 MPa obtained by (Okino et al., 1997). These results show that the level of adhesive employed were appropriate in regards to IB.

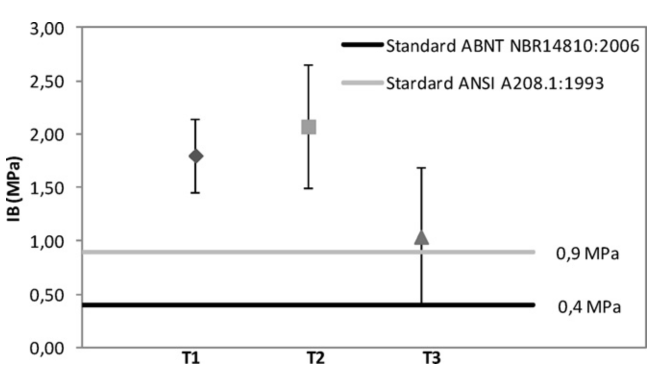

Fig. 8. Average values internal bond.

Table 4
Physical–mechanical properties experimental values—density 1.0 g/cm^3 – durability analyses.

Treatment	Absorption (%)	TS (%)	MOR (MPa)	MOE (MPa)
T2	22.38a	19.67a	17.92a	1,396a
CV	26.37	29.74	9.20	11.75
T4	21.75a	8.71b	11.34b	649b
CV	31.28	21.86	18.06	9.06

The averages which are followed by the same letter in the same row do not differ in the Tukey test at a 5% significance level.
CV—variation coefficient.

With respect to T4 panel IB analyses could not be conducted due to the occurrence of degradation after accelerated aging.

3.3. Efficiency of the adhesives (T2 and T3)

Table 3 represents the results of the physical-mechanical properties of the coconut fiber particle boards with castor oil polyurethane (T2) and urea-formaldehyde (T3) adhesives. The statistical analysis indicates a significant difference ($p < 0.05$) for all variables studied. The castor oil polyurethane adhesive was a more efficient binder of particles when compared with the urea-formaldehyde adhesive.

3.4. Durability analyses (T3 and T4)

The evaluation of the durability of the particle boards verified the behavior of the material when submitted to accelerated

Fig. 9. Modification of physical behavior of composites after aging test.

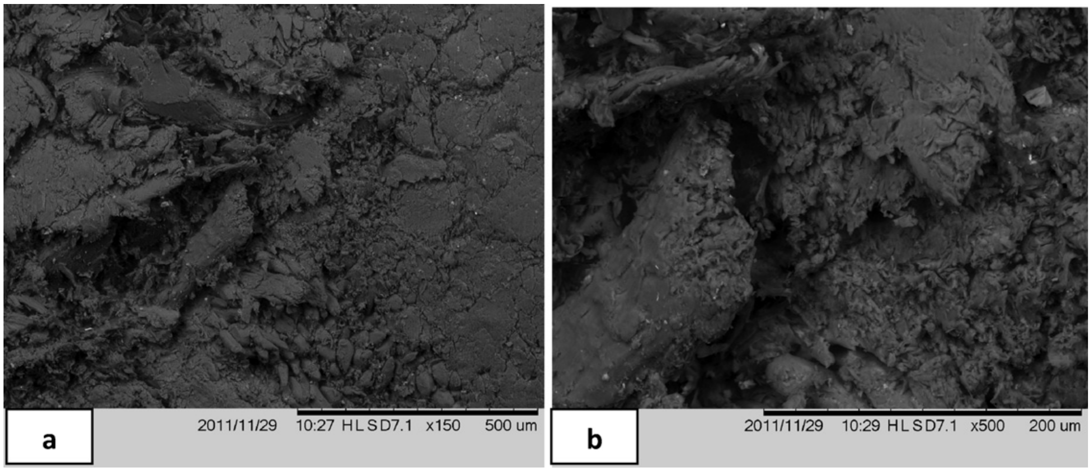

Fig. 10. SEM image—panel with coconut fiber and castor oil resin (T2). (a) Enlargement (150×) and (b) enlargement (500×).

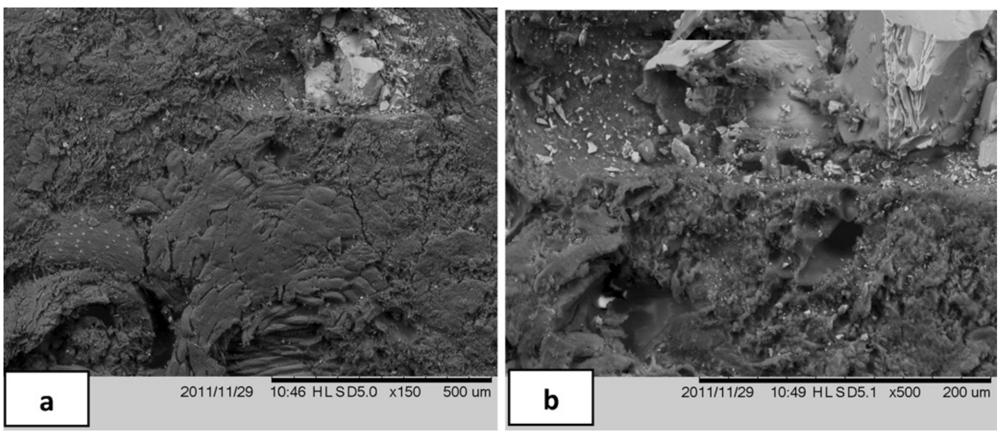

Fig. 11. SEM image—panel with coconut fiber and urea-formaldeído resin (T3). (a) Enlargement (150×) and (b) enlargement (500×).

aging. According to Lepage (1986) the principle factors that promote degradation of wood when submitted to weathering are: moisture, sunlight and heat. The accelerated aging test evaluated two of these factors (moisture and heat). Table 4 presents the results of the physical–mechanical properties for specimens with and without aging. The statistical analysis indicates statistically different ($p < 0.05$) values for both physical (TS) and mechanical (MOR and MOE) properties. The accelerated aging degraded the material and consequently reduced the physical–mechanical properties. A large difference in TS was observed because specimens subjected to accelerated aging were waterproofed in surface with castor oil polyurethane before testing.

Fig. 9 presents coconut fiber particle boards after aging test. It can be observed that coconut fiber panels present little superficial degradation. In addition the delamination on composites after stresses of six cycles of soaking, freezing, steaming and dry air. Such delamination in the composite caused an increasing in the thickness. The aged composite presented the highest percentage of water absorption as compared with those that were not submitted to accelerated aging.

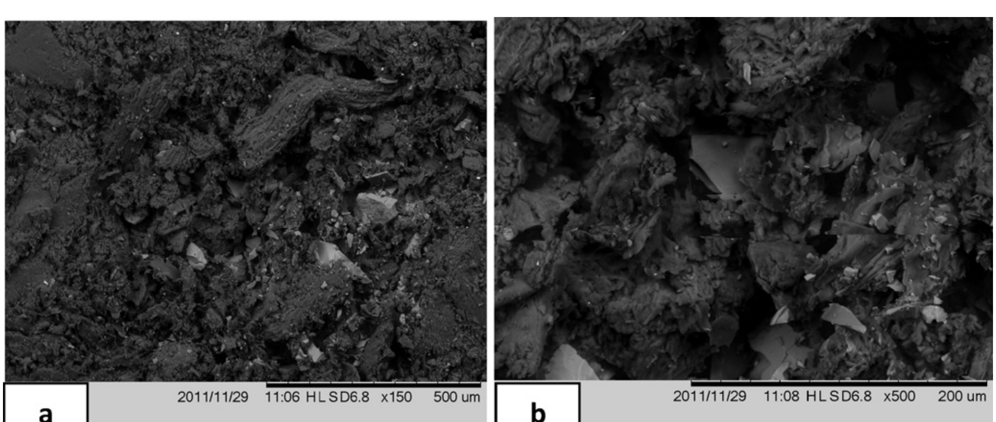

Fig. 12. SEM image—panel with coconut fiber and castor oil after aging test (T4). (a) Enlargement (150×) and (b) enlargement (500×).

3.5. Electronic microscopy analyses

Figs. 10–12 present, respectively a microstructure analysis SEM of the specimens of the treatments T2, T3 and T4. In Fig. 10 using different increases, there is a homogeneous dispersion of the resin between the particles, which is essential for there is a distribution of loads between the fibers for composite materials (Callister, 2002). Comparing these micrographs with those presented in Fig. 11(a) and (b) with different magnifications, it is observed that the homogeneous distribution of the resin between the particles did not occur, impairing the adhesion between particles.

Fig. 12 (T4), there is degradation and disruption of the fibers after accelerated aging test. This condition directly influenced in the performance of the panels, because the fibers are responsible for supporting the mechanical load imposed on the composite material (Callister, 2002).

4. Conclusions

Coconut fiber, a residue produced in large amounts in Brazil, is a promising material for manufacturing particleboard. This study presents a new alternative to produce boards from coconut fiber particles using castor oil polyurethane adhesive.

In the laboratory it was possible to produce panels made of coconut fiber particles using castor oil polyurethane adhesive.

Based on the conducted tests, the panels made of coconut fiber and castor oil-based polyurethane adhesive with density 1.0 g/cm^3 presented sufficient mechanical properties for use in civil and agricultural constructions, besides its use in homes, farm buildings and structural applications.

The accelerated aging test allowed verification that the panels in this study, whether or not coated with waterproofing product, should be used in environments with lower exposure to moisture.

The castor oil-based bi-component polyurethane resin presented superior results when compared to the urea-formaldehyde resin, proving that this resin can be utilized for production of coconut fiber and wood residue particle boards.

Scanning microscopy electronic images (SEM) indicated that castor oil-based polyurethane adhesive occupies the gaps between the particles, a factor that contributes to improved physical and mechanical properties of the panels.

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