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Incorporation of industrial laundry sludge in the manufacture of particleboards

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ABSTRACT. This study aimed to demonstrate a sustainable alternative to the use of residues by treating industrial laundry wastewater, thereby making them useful in producing wood particleboards as furniture. For this purpose, physical, chemical, and mechanical tests were carried out in order to characterize the product, which showed acceptable characteristics for commercial use as elements in the furniture industry.

Keywords: recycling, sustainability, waste, wood.

Incorporação de lodo de lavanderia industrial na fabricação de chapas de partículas

RESUMO. O presente estudo teve como intuito demonstrar uma alternativa sustentável para a utilização de resíduos provenientes do tratamento de efluente de lavanderia industrial, tornando-os úteis para a confecção de chapas de madeira aglomerada como elemento arquitetônico. Para tanto, foram realizados testes físicos, químicos e mecânicos para caracterizar esse produto, comprovando características aceitáveis para possível uso comercial como elemento da indústria moveleira.

Palavras-chave: reciclagem, sustentabilidade, resíduo, madeira.

Introduction

Solid waste is generated by human and natural activities, and part of this waste can be recycled, generating benefits to health and saving natural resources. Thus, there is a major concern in managing solid waste because of environmental impacts (SILVA et al., 2013).

Among the various types of waste suitable for recycling, those generated in industrial laundries are classified by NBR 10.004 (ABNT, 2004a) (Brazilian Association of Technical Standards) as Class II non-inert waste, i.e., according to (HEREK et al., 2012), this solid waste is suitable for recycling, otherwise the waste must be treated and properly disposed.

Adding organic matter such as wood to waste material (industrial sludge), besides being a sustainable manner to reuse waste from industrial processes, can produce benefits in regard to reducing the amount of solid residue by decreasing the use of natural resources and adding value to residue. Thus, it is utilized a co-product of the activity in industrial laundries, for the production of alternative materials, such as particleboards. The technical standard NBR 14.810-1 (ABNT, 2006a, p. 1), defines particleboards as: "Panel-shaped product, varying from 3 mm to 50 mm thick, consisting of wood particles bonded with natural or synthetic resins, thermoset under the action of pressure and heat".

Some studies on the use of different types of solid wastes and wood particles for particleboard manufacturing have been carried out. Among the wastes studied are the sludge from paper recycling (TARAMIAN et al., 2007), waste from municipal tree pruning (SILVA et al., 2013), sugarcane bagasse waste (FIORELLI et al., 2013), rice husk (AYRILMIS et al., 2012) bamboo waste (BISWAS et al., 2011), hazelnut husk (ÇOPUR et al., 2007), kiwi prunings (NEMLI et al., 2003), and walnut shell (PIRAYESH et al., 2012).

Considering the studies and facts mentioned above, the present study aimed to demonstrate a sustainable alternative to the use of waste from wastewater treatment of industrial laundries. It was intended to make useful the waste in a primary way by replacing the wooden parts with percentages of laundry waste, obtaining a quality product for commercial use in the furniture industry.

Material and methods

Collection and preparation of raw materials

For this purpose, 80 kg of wood particles was collected in a local carpentry in the city of Londrina-Brazil, and 28 kg of sludge from a wastewater treatment plant (WWTP), in dry form (dehydrated), was collected in an industrial laundry in the city of Umuarama-Brazil. Samples with particle mesh sizes of 4.0, 2.0, 1.40, 1.0, 0.85, and 0.50 mm were obtained from these materials, according to NBR 7.181 (ABNT, 1984). Figure 1 shows the wood and sludge particles, respectively. The materials were stored in plastic bags with a capacity of 50 kg. Urea-formaldehyde resin (UF; 5 kg) was also acquired.

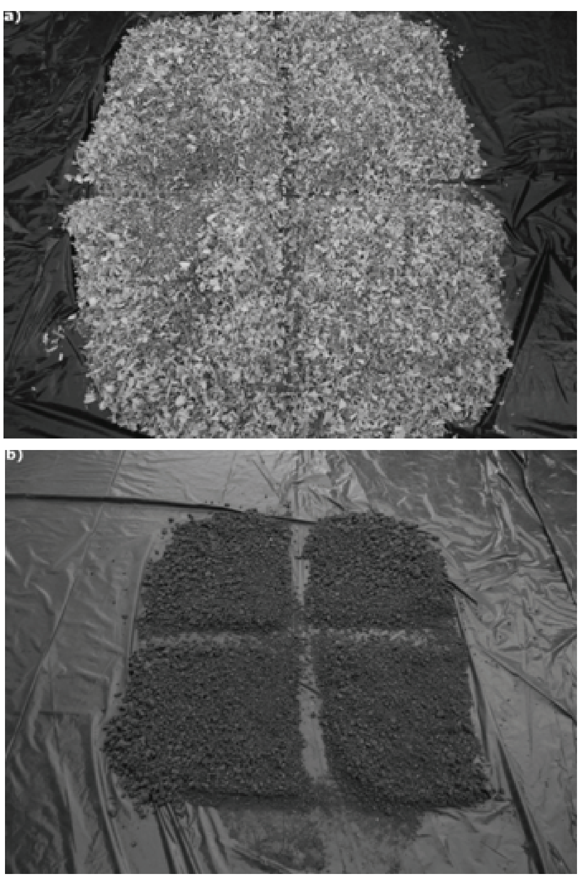

Figure 1. Particles of (a) wood and (b) sludge.

Manufacture of wood particleboards

The manufacture of boards was developed by the RG Esquadrias Company located in Londrina-Brazil. At this stage, we used a heated hydraulic press (SIRMA) to compact mass (wood, sludge, and resin) under a pressure of 1700 kg cm^{-2} at 105°C for 20 min. Different percentages of resin and waste incorporation were analyzed. Thus, three types of particleboards were prepared: B50 – control board without addition of WTTP waste with 50% resin; R30 – board with addition of 20 waste and 30% resin; and R50 – board with addition of 20 waste and 50% resin.

A total of 50 resin with 5 catalyst and 20% water was used. The materials were mixed and transferred to a form of wood, 1000 x 400 x 10 mm in size, compatible with the press platens. The particulate mass was shaped and compressed to form a bed of particles. This bed was wrapped with aluminum foil and fed into the heated hydraulic press. After pressing, the board was allowed to stand for 24 hours, as shown in Figure 2, and was then cut into smaller pieces according to NBR 14.810-3 (ABNT, 2006c), in order to perform physical, mechanical, and chemical tests.

Figure 2. Wood particleboards after pressing.

Analyses performed on raw materials

Wood and sludge were analyzed considering the following parameters: GMD (Geometric Mean Diameter), according to the methodology described in the literature (FILHO et al., 2007) on the aggregation of a red latosol; moisture content, bulk density, and tapped density, according to the methodology of the (IAL, 1985). In addition, the existing metals in the sludge were also examined.

It was used the Aqua Regia Digestion Method to opening the sample, and the solutions obtained were subjected to metal reading by plasma, ICP model - Optima - 5200/Plasma - Perkin Elmer. The leaching test was performed according to NBR 10.005 (ABNT, 2004b), and the solubility test according to NBR 10.006 (ABNT, 2004c).

Analyses performed on particleboards

Boards were analyzed regarding the physical tests for density, moisture content, water absorption, and swelling thickness, as well as the mechanical tests for Modulus of Rupture (MOR), Modulus of Elasticity

(MOE), and Parallel Tensile Strength, according to NBR 14.810-3 (ABNT, 2006c), and also a chemical test to determine metals, followed by a leaching test NBR 10.005 (ABNT, 2004b) and a solubility test NBR 10.006 (ABNT, 2004c). The morphology for the particleboards was analyzed using scanning electron microscopy (SEM; Superscan SS-550 Shimadzu, Japan).

The experiment for density detection consisted of weighing and measuring ten specimens with sizes of 50 x 50 mm, taken from different boards, in order to obtain the mean. For this purpose, the specimens were measured for thickness, width, and length, and weighed in a balance, accurate to 0.1 g, in order to obtain their respective masses according to NBR 14.810-3 (ABNT, 2006c).

As for the test of moisture content, the specimens for each board with the corresponding dimensions of 50 x 50 mm were weighed, thus obtaining the dry air mass, and then specimens were placed in an oven at 110°C until the complete removal of water, thereby obtaining the dry weight, and then the moisture percentage for the sample was determined according to NBR 14.810-3 (ABNT, 2006c).

Tests for water absorption and swelling, with sample sizes of 25 x 25 mm, were performed according to the methods described in NBR 14.810-3 (ABNT, 2006c).

The mechanical tests of MOR and MOE were performed using the universal testing machine EMIC DL 10000, and a 5-kN load with a constant cross-speed of 6 mm $min.^{-1}$. The parallel tensile strength was tested with equipment from CLOYD Instruments, using a constant speed of 1 mm $min.^{-1}$. For both analyses, ten samples with sizes of 50 x 250 mm were cut. Additionally, the mechanical tests were carried out according to NBR 14.810-3 (ABNT, 2006c).

In relation to the statistical analysis, ANOVA was used to check for significant differences between boards, and the Tukey's test (5%) was used to compare differences between the mean values.

Results and discussion

Analyses performed on raw materials

The physical analysis used in the study is shown in Table 1. The particles have to present moisture between 3 and 12% in order to allow greater penetration of glue, since very dry particles hampers the handling, requiring greater amounts of resin, as well as producing plates that easily disintegrate. On the other hand, very humid particles can influence the board quality during the pressing process by, for example, the formation of bubbles and the bursting of the boards. Thus, the moisture content found in the raw materials is within the optimal range to manufacture boards.

The bulk and tapped density of the wood particles was lower when compared to the WWTP waste.

Table 1. Physical analysis performed on the raw material.

ANALYSES	RESULT		
	Wood particles 1.40 mm	WWTP sludge	Normative standard
Moisture (%)	7.70	3.60	5.00 a 11.00
Bulk density (g mm^{-1})	1.74	3.96	-
Tapped density (g mm^{-1})	1.82	4.41	-
GMD (mm)	1.162	1.125	-

Figure 3 illustrates the particle size curve for the sludge from an industrial laundry (a) and the particle size curve for the wood waste (b).

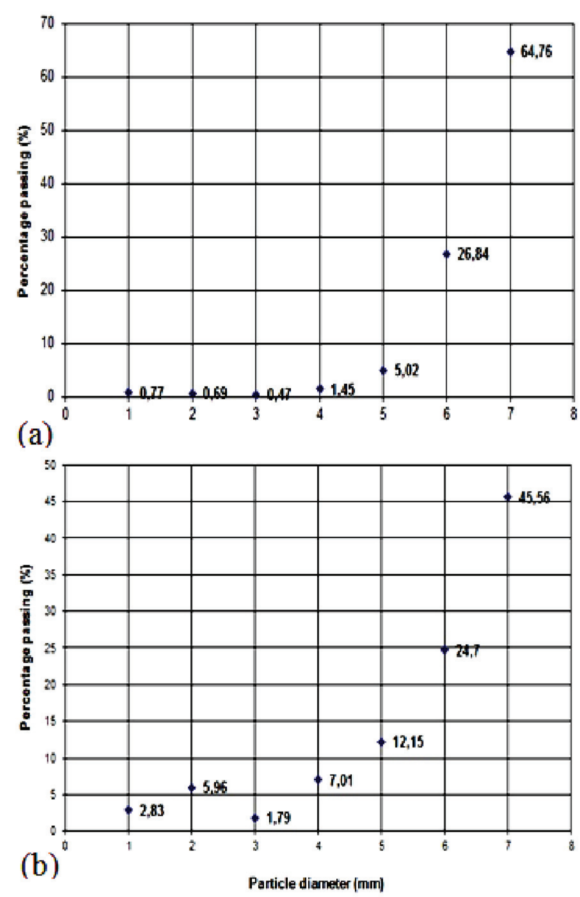

Figure 3. (a) Particle size curve for the sludge from industrial laundry. (b) Particle size curve for wood particles. Test performed according to NBR 7181 (ABNT, 1984).

The highest percentage of particles (64.8%) corresponds to the fraction retained in the mesh size ≤ 4.0 mm. The mesh size 1.40 ≤ x ≤ 2.0 mm retained 31.9% of the material, while the content retained by the mesh size 1.0 ≤ x ≤ 0.50 mm was around 2.61%. The sludge was ground to improve compaction with wood, because increasing the contact surface improves the resin absorption in the production of a resistant board. According to (KOLLMANN et al., 1975), the very small particles extend the surface area and, therefore, increase the demand for resin, producing a more resistant board. The largest particles can adversely affect the quality of the final product because of the internal flaws in the particles, i.e., a higher number of voids in the material. Due to the studies of the particle diameters mentioned above and the capacity to incorporate waste, the GMD values of the sludge samples were reduced to the maximum, being used in the form of particles, which according to (VIGNOTE; JIMÉCEZ, 1996), better distribute the stresses on the material and produce fewer slot cavities inside the boards, resulting in a more resistant product.

The particle size curve for the wood waste shows that the highest percentage of particles (45.56%) corresponds to the fraction retained in the mesh size ≤ 4.0 mm. The mesh size 1.40 ≤ x ≤ 2.0 mm retained 36.85% of the material, while the content retained by the mesh size 1.0 ≤ x ≤ 0.50 mm was around 14.76%. The wood fractions retained in the mesh size 1.40 mm were used to improve the mass homogenization and the resin absorption, in which the contact surface is increased. In consequence, GMD particles from the intermediate mesh were used to facilitate the mechanical characteristics. Table 2 lists the metals and the contents found in the textile sludge sample from the industrial laundry and the results for the leaching and solubility tests.

Table 2. Analysis of the levels of certain metals in the waste sample (industrial laundry sludge), by atomic absorption, leaching and solubilization.

METAL	RESULT				
	Metal (mg kg^{-1})	Leaching (mg L^{-1})	Limit leachate NBR 10.004	Solubility (mg L^{-1})	Limit Solubilized NBR 10.004
Aluminum	3.61×10^{4}	8.78×10^{-1}	-	1.96×10^{-1}	2.00×10^{-1}
Arsenic	n.d★	n.d★	1.0	n.d★	1.0×10^{-2}
Barium	6.44×10^{1}	1.15×10^{-1}	7.00×10^{1}	3.00×10^{-2}	7.00×10^{-1}
Cadmium	n.d★	n.d★	5.00×10^{-1}	n.d★	5.00×10^{-3}
Calcium	2.39×10^{2}	1.41×10^{1}	-	3.67×10^{1}	-
Lead	2.77×10^{1}	2.30×10^{-2}	1.00	3.7×10^{-2}	1.00×10^{-3}
Copper	2.00×10^{1}	6.40×10^{-2}	-	5.9×10^{-2}	2.00
Chrome	1.01×10^{2}	2.10×10^{-2}	5.00	2.5×10^{-2}	5.00×10^{-2}
Iron	4.81×10^{3}	1.50×10^{-1}	-	3.69×10^{1}	3.00×10^{-1}
Nickel	4.60×10^{1}	2.20×10^{-2}	-	8.1×10^{-2}	-
Manganese	3.06×10^{2}	5.1×10^{-2}	-	7.23×10^{-2}	1.0×10^{-1}
Mercury	1.13×10^{2}	2.34×10^{-2}	1.0×10^{-1}	5.83×10^{-2}	1.0×10^{-3}
Potassium	8.00×10^{1}	1.20×10^{1}	-	7.50×10^{1}	-
Silver	2.54×10^{3}	4.03×10^{-1}	5.0	3.76×10^{-1}	5.0×10^{-2}
Selenium	n.d★	5.14×10^{-1}	1.0	n.d★	1.0×10^{-2}
Sodium	2.10×10^{2}	5.00×10^{1}	-	1.50×10^{2}	2.00×10^{2}
Zinc	n.d★	4.20×10^{-1}	-	4.72	5.00

n.d★ = non-detected.

Calcium is found in the regional water supply and reduces the mechanical strength of the materials. Chromium, copper, and nickel contents are probably derived from the dyes used for staining, as well as the contents of barium, lead, and potassium. High contents of aluminum and iron in the sludge, as well as sodium and manganese, are due to the components used for water treatment, which are retained in the material, and the quantities of barium, chrome, copper, and nickel are due to the salts used in the dyeing process (HEREK et al., 2012).

The results for the analysis of the sludge leachate extract are in line with the technical standard NBR 10.004 (ABNT, 2004a), not exceeding the maximum limits, indicating that these sludge samples do not represent a hazardous waste sludge, thus being classified as Class II residue.

The analysis for the extract obtained by solubility tests indicates that the metals lead, iron, mercury, and silver are above the maximum limit established by NBR 10.004 (ABNT, 2004a), and other parameters quantified are within the limits set by the established standard. Thus, the textile sludge from the industrial laundries is classified as a residue Class IIA, non-hazardous – non-inert.

Analyses performed on particleboards

The density analysis on particleboards (Table 3) showed that the material composed of 20 waste and 50% resin had a density slightly higher than that mentioned in NBR 14.810-2 (ABNT, 2006b), which is between 551 and 750 kg m^{-3} for boards of medium density. This could be due to the waste high density and a failure in the mixing, since the process was performed manually, or even due to the concentration of UF resin used, as its homogeneous distribution is critical to provide uniformity throughout the product extension. In turn, the control board (0.0 waste and 50% resin) was in line with the established standard; however, the boards composed of 20 waste and 30% resin varied significantly to a density below the stipulated standards.

Table 3. Physical analysis performed on modular boards and experimental design for boards - ANOVA. (B - control board without adding WTTP waste, R - board with addition of 20% WTTP waste).

BOARD	RESULT			
(%) Resin replacing wood	Density (kg m^{-3})	Moisture (%)	Thickness swelling 24 hours (%)	Water absorption in 24 hours (%)
B 50	710.86^{b}	3.07^{b}	2.13^{a}	17.32^{b}
R 30	495.96^{c}	1.22^{c}	0.87^{b}	46.03^{a}
R 50	832.98^{a}	4.76^{a}	0.00^{c}	8.94^{c}

*Mean values followed by different letters in the same row are significantly different ($p > 0.05$).

Regarding the moisture content, the moisture must not be less than 5 or more than 11% NBR 14.810-2 (ABNT, 2006b). The moisture values obtained for the boards, as observed in Table 3, show that all the boards had values lower than the range established by the standard NBR 14.810-2 (ABNT, 2006b). These results can be explained because it was not possible to leave the boards for stabilization after manufacture in a chamber at controlled temperature and humidity.

The tests performed for water absorption, following NBR 14.810-3 (ABNT, 2006c), showed a decrease in this characteristic with increasing resin percentage, which can be observed in the swelling experiment, according to the same standard.

The (VIGNOTE; JIMÉCEZ, 1996) establishes a maximum thickness swelling of 8% after 2 hours for water absorption. When comparing the values set by the standard with the values obtained by the present study, all the treatments fall within the limit, even after 24 hours. It was clear that the resin proportion (binder material) in the board composition increased as the resistance to swelling and the water absorption also increased, confirming that a larger amount of resin, which in turn had 20% water, improved the physical characteristics of the product.

The experimental design used in the study is shown in Table 3, and was completely randomized. The ANOVA test was used to check for differences between boards, and the Tukey's test (5%) was used to compare the differences between mean values in cases where the samples showed significant differences in relation to the physical tests performed. The board with 30% resin showed lower moisture content, swelling, water absorption, and density, than the other treatments, while the control test showed intermediate values, and, therefore, the material with 50 of resin and 20% of waste replacement reached the highest values, which may be due to the increased application of adhesive. Thus, the board with 50 of resin and 20% of waste was the particleboard with higher compliance with the standards set by the regulation.

The MOR for the boards varied from 1.16 to 2.58 MPa, and the MOE varied from 29.33 to 77.75 MPa. As can be seen in Table 4, for both MOR and MOE analyses, the best result was presented by the treatment R50 (20 waste and 50% resin). The treatments B50 (0 waste and 50% resin) and R30 (20 waste and 30% resin) were not significantly different – in other words, the amount of waste added compensates for the decrease in resin. It can also be observed, for the treatments with incorporation of 20% waste, that raising the resin percentage from 30 to 50% also increased the MOR.

Table 4. Mechanical analysis performed on modular boards and experimental design for boards - ANOVA. (B - control board without adding WTTP waste, R - board with addition of 20% WTTP waste).

BOARD	RESULT		
(%) Resin replacing wood	MOR (Mpa)	MOE (Mpa)	Parallel Tensile Strength (Mpa)
B 50	1.28^b	29.33^b	0.14^b
R 30	1.16^b	29.65^b	0.29^a
R 50	2.58^a	77.75^a	0.28^a

*Mean values followed by different letters in the same row are significantly different ($p > 0.05$).

The standard NBR 14.810-2 (ABNT, 2006b) establishes that the minimum value for MOR, in a particleboard with 10 mm thickness, is 18 MPa. In the present study, the values found for the manufactured boards are below the value established by the standard NBR 14.810-2 (ABNT, 2006b). This may be because the waste from the textile industry was a porous material. Furthermore, it was not possible to obtain a uniform mixture, which led to the values found. In turn, this could be confirmed by photomicrography (Figure 4).

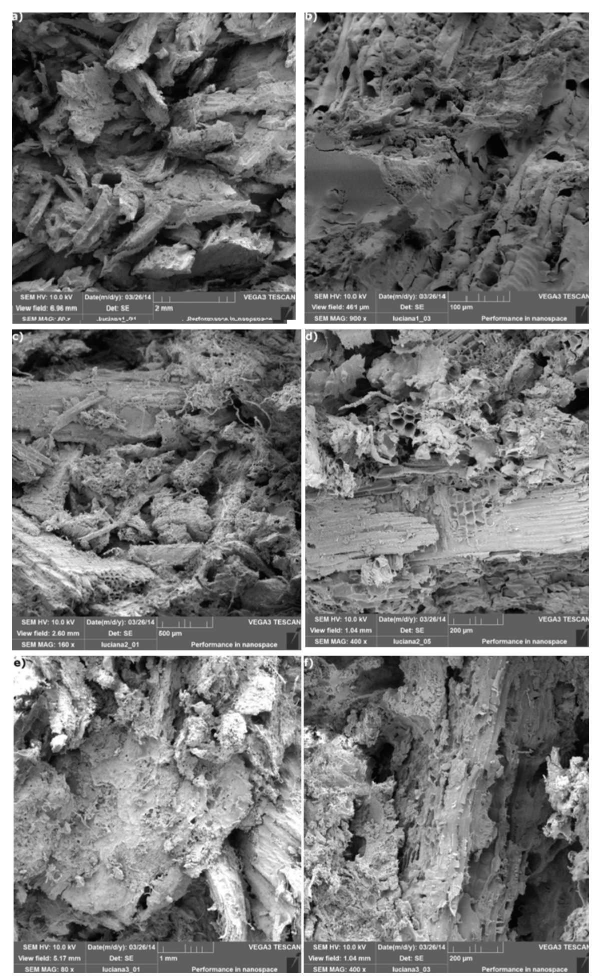

Figure 4. SEM of particleboards: a) B50, 60x; b) B50, 900x; c) R30, 160x; d) R30, 400x; e) R50, 80x; and f) R50, 400x.

Parallel Tensile Strength for the particleboards varied from 0.14 to 0.29 MPa. As shown in Table 4, the best results for the Parallel Tensile Strength were those from the particleboards with 20% WWTP sludge, but the treatments R30 and R50 were not significantly different. This can be justified by the waste addition, due to the inclusion of fibers, since the parallel direction increased the material strength. Table 5 lists the metals found in the particleboards and their contents.

Values for the particleboard sample indicate that this material has high concentrations of aluminum and iron, and the board with sludge has significant values for potassium and sodium (alkaline), calcium, and chromium (alkaline earth), and traces of copper, zinc, lead, nickel, and barium were also found, as shown in Table 6.

The results for the analysis of the leachate extract of particleboards (Table 6), were in line with the technical standard NBR 10.004 (ABNT, 2004a), not exceeding the maximum limits, indicating that these particleboard samples did not represent a hazardous material, and they were thus classified as Class II residue.

The analysis for the extract obtained by the solubility tests (Table 6) indicates that the metals aluminum, chrome, iron, and manganese were above the maximum limit established by NBR 10.004 (ABNT, 2004a), and other parameters quantified were within the limits set by the standard. Thus, the particleboards, with and without textile sludge, were classified as residues Class IIA, non-hazardous – non-inert.

Table 5. Analysis of the levels of metals in modular boards (wood plus 20% sludge from industrial laundry), by atomic absorption method.

METAL	RESULT (mg kg^{-1})		
	B50	R30	R50
Aluminum	2722.81	14173.58	13100.17
Barium	n.d*	121.70	149.41
Calcium	921.95	956.27	993.49
Lead	n.d*	4.92	3.18
Copper	116.09	41.08	43.89
Chrome	4.33	247.07	230.10
Iron	818.70	7809.08	8892.22
Nickel	2.64	90.05	87.93
Manganese	118.46	213.20	219.20
Mercury	n.d*	n.d*	n.d*
Potassium	646.06	4480.74	5092.45
Silver	n.d*	n.d*	n.d*
Sodium	35452.69	28779.99	28477.20
Zinc	76.41	35.32	35.99

n.d* = non-detected.

It is possible to observe, in Figures 4A and 4B, the presence of porosity in the wood particles. Figures 4E and 4F present the photomicrographs for the particleboard R50, where a significant interfacial interaction was observed between the sludge and the wood particles when compared to the treatment R30 (Figures 4C and 4D), which prevented the fiber pull out at the fracture.

In the treatments R30 and R50, besides the porosity of the woods, there is also the presence of fibers from the incorporated waste. The adhesion interface allows the transfer of stress from the matrix to the fiber and contributes to a superior tensile and flexural modulus in the particleboards. The presence of fibers, as seen in the tests of MOR, MOE, and the Parallel Tensile Strength, increase the material strength, probably due to the high fiber/polymer adhesion as presented in the treatments R30 and R50 (Figures 4C to 4F).

Table 6. Analysis of leaching and solubilization in particleboards by atomic absorption.

METAL	LEACHATE (mg L^{-1})			SOLUBILIZED (mg L^{-1})			
	B50	R50	Limit leachate NBR 10.004	B50	R30	R50	Limit Solubilized NBR 10.004
Aluminum	34.37	79.33	-	185.16	182.95	254.87	2.00×10^{-1}
Arsenic	n.d*	n.d*	1.0	n.d*	n.d*	n.d*	1.0×10^{-2}
Barium	n.d*	n.d*	7.00×10^{1}	n.d*	n.d*	n.d*	7.00×10^{-1}
Cadmium	n.d*	n.d*	5.00×10^{-1}	n.d*	n.d*	n.d*	5.00×10^{-3}
Calcium	8.20	7.92	-	30.39	25.72	20.87	-
Lead	n.d*	n.d*	1.00	n.d*	n.d*	n.d*	1.00×10^{-3}
Copper	0.03	0.03	-	0.13	0.04	0.06	2.00
Chrome	0.02	0.18	5.00	n.d*	0.08	0.24	5.00×10^{-2}
Iron	0.93	2.48	-	4.54	3.13	4.07	3.00×10^{-1}
Nickel	0.02	0.10	-	n.d*	0.12	0.18	-
Manganese	4.41	6.95	-	14.07	7.38	11.41	1.0×10^{-1}
Mercury	n.d*	n.d*	1.0×10^{-1}	n.d*	n.d*	n.d*	1.0×10^{-3}
Potassium	13.74	13.80	-	51.54	53.67	52.87	-
Silver	n.d*	n.d*	5.0	n.d*	n.d*	n.d*	5.0×10^{-2}
Selenium	n.d*	n.d*	1.0	n.d*	n.d*	n.d*	1.0×10^{-2}
Sodium	303.71	339.74	-	102.92	131.03	85.01	2.00×10^{2}
Zinc	0.23	0.55	-	0.48	0.72	0.75	5.00

n.d* = non-detected.

Conclusion

Manufacture of particleboards using WWTP residue proved to be an option that fits more benefits.

The physical tests showed that the addition of waste and resin to replace the wooden parts resulted in a product with acceptable characteristics regarding density, moisture, swelling thickness, and water absorption, in line with the standards regarding wood boards, and fits the studies on the topic. The mechanical tests showed that the incorporation of WWTP sludge gives resistance to the product.

As a consequence of the tests applied and the costs involved in modular board manufacturing, this product can be used in the furniture industry.

Acknowledgements

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