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Incorporation of water treatment plant sludge in wood-based particleboard manufacturing

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ABSTRACT

A typical water treatment plant (WTP) produces about 200,000 m^3 of sludge per day and this amount is expected to increase. The objective of this research was to evaluate the effect of the incorporation of WTP sludge in wood-based particleboard manufacturing, and the effect of temperature (110°C and 160°C) and time (7 and 12 min) of pressing on physical and mechanical properties of particleboard made from WTP sludge and wooden particles. Wood particles were replaced by WTP sludge at percentages of 0 and 20% and two ranges of particles sizes (0.08 mm < d < 2.0 mm and 0.08 mm < d < 9.5 mm). These WTP sludge-based particleboard types were bonded with resin (12%), and they were tested for density modulus of rupture, modulus of elasticity, thickness swelling and water absorption resin type. According to the results obtained, the agglomerated wood panel manufactured was classified as low density, this type of panel being able to be applied in insulation. Thus, incorporation of WTP sludge into particleboards is a promising alternative of final disposal for this residue, collaborating with the environment.

Keywords: WTP sludge; Wooden particles; Particleboards; Reutilization

1. Introduction

Improving drinking water quality has been a challenge worldwide. More extreme water degradation forces water treatment plant (WTP) to use high doses of coagulants and other chemicals to improve the drinking water quality. A typical WTP produces about 200,000 m^3 of sludge per day [1].

Sanitary landfills are typically used for sludge disposal, though some WTPs incinerate the sludge produced – an expensive method of sewage disposal. A substantial portion of WTP's sludge is still dumped into the environment, mainly into surface water bodies, which results in serious environmental pollution problems in some urban and suburban areas [2]. Inadequate disposal of WTP sludge contributes to environmental contamination because sludge can contain heavy metal from chemical coagulants, natural organic matter, and other contaminants (pharmaceuticals, pesticides, microorganisms) [3].

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Disposal of sludge is a persistent challenge for WTPs and adoption of alternative strategies must consider the environmental, economic and ecological aspects of disposal [4]. Research investigating alternative sludge disposal strategies and potential applications for the material in sludge has grown in popularity as the problem has compounded. Some alternatives applications for sludge include incorporation into building bricks [1,5] or ceramics [6] and application in soil as an amendment since the physical and chemical properties of sludge may improve soil structure and provide nutrients for plant growth [7,8].

Another industrial residual waste stream is wood. The recycling of wood waste can decrease environmental burdens through the reduction of materials, water, and energy used in production processes compared with use of virgin materials [9].

The global market for wood-based panels has increased annually despite of decreasing availability of wood resources, and this incongruence has produced substantial incentives to find alternatives. Particleboard is a wood-based panel product manufactured under pressure and temperature using particles of wood or other lignocellulosic material and a binder. Particleboard is widely in the manufacture of furniture, floor underlayment, cabinets, stair treads, and home construction among myriad other applications [10–12].

The characteristics of materials and the manufacturing technology needed to make particleboard with superior quality are important considerations. Particleboards with high density have found applications in floor, wall and ceiling panels, office dividers, bulletin boards, furniture, cabinets, counter tops, and desktops [13]. According to Wang and Sun [14], limited information for low-density straw-based particleboard is available, despite this material having potential application in insulation, packaging, or lightweight core materials. Lightweight particleboards have received special attention in an effort to facilitate handling and transportation. Further, there is a current trend in furniture design to use high-thickness components, which increases the demand for materials with reduced weight. Panels with a density below 600 kg/m^3 are defined as lightweight particleboard (CEN/TS 16368) [4,15–17].

This is the first time that the sludge from WTP of region of Arapongas, Paraná, Brazil, is characterized and used in a manufacturer process trying to find a ecofriendly solution to the problem that exist in various regions that produce tons of WTP sludge.

In this study, we used sludge from a WTP and wood shavings from of *Pinus pinaster* as a raw material to manufacture particleboards. The mechanical and physical properties of the newly designed panels were tested to determine if they have the required properties for general use. The authors also evaluated the effect of resin quantity, temperature, and pressing time on physical and mechanical properties of the resultant particleboards made from WTP sludge.

2. Materials and methods

2.1. Materials

The raw material utilized in this research consisted of sludge from a public WTP and *P. pinaster* wooden particles. The sludge was collected from a WTP located in the City of Arapongas, Paraná, Brazil. The samples were dried at room temperature and then ground with a roller mill to reduce and standardize particles size. The total sludge obtained was about 30 kg when dry.

The wood particles were collected from an industrial wood processor (Cia do Pinus located in Londrina, Paraná, Brazil) and ground to reduce particles size.

2.2. Characterization of WTP sludge and wood particles

The physical (moisture content and granulometry), chemical (pH, metal concentration, leachate, solubilized particles) and surface properties (SEM – scanning electron microscopy and EDX – energy dispersive X-ray spectroscopy) of the raw materials were analyzed.

The moisture content was assessed according to standard DNER 213/1994. Particle size evaluation was assessed in accordance with ABNT NBR 7.181/1984. The sludge pH was analyzed according to Chiang et al. [1] and the pH of wood particles was evaluated according to Atar et al. [18]. Heavy metal concentrations in the residues were assessed with total reflection X-ray fluorescence spectroscopy (S2 PICOFOX, Bruker Corp., Billerica, MA, USA). The leaching test was carried out according to Standard ABNT NBR 10.005/2004 [19], and the solubilization test was assessed in accordance with ABNT NBR 10.006/2004 [20].

Morphological and compositional characteristics were studied by means of SEM and the chemical composition of the matrix was analyzed with EDX (SS – 550 Superscan, Shimadzu Corp., Kyoto, Japan).

2.3. Production of particleboards

The particleboards were produced using *P. pinaster* wood particles and WTP sludge. The particleboard blending formulations are summarized in Table 1. Sixteen different particleboard formulations were created in triplicate yielding 48 particleboards in total (Table 1). The formulations consisted of varying four variables, particle size (0.08 mm < Particle A diameter < 2.0 mm, and 0.08 mm < Particle B diameter < 2.0 mm), WTP sludge content (0 and 20%), pressing time (7 and 12 min), and press temperature (110°C and 160°C). Other variables, including hardener content (1 wt%), press closing rate (5 mm s^{-1}), press pressure (35 kg cm^{-2}), board thickness (10 mm), and resin content (12%), were held constant and the target density was 0.60 g/cm^3. The resin content used was a little greater than normal (12%), because the wood particles were manually blended with the adhesive.

Mass of the WTP sludge and the wood particles was calculated based on the dry weight of the particles (0% moisture) and the particleboard size (55 × 55 × 1.5 cm). A 3% ammonium sulphate ($(NH_4)_2SO_4$) solution was used as catalyst (hardener) [21] and the percentage was based on the amount necessary to create the correct urea to formaldehyde (UF) resin ratio. A 1 wt% paraffin (32% water) ratio based on the solid content of the UF resin was used as a water repellent chemical in the manufacture of particleboards. The materials were manually mixed and the mats were then subjected to hot pressing.

Table 1
Particleboard formulations

Particleboard types	Granulometry	%WTP sludge	Time (min)	Temperature (°C)
1	Particle size A 0.08 mm < d < 2.0 mm	0	7	110
2		20	7	110
3		0	12	110
4		20	12	110
5		0	7	160
6		20	7	160
7		0	12	160
8		20	12	160
9	Particle size B 0.08 mm < d < 9.5 mm	0	7	110
10		20	7	110
11		0	12	110
12		20	12	110
13		0	7	160
14		20	7	160
15		0	12	160
16		20	12	160

d = particle diameter.

The boards were pressed under 50 kgf cm^{-2} pressure at different times and temperatures (Table 1). At the end of the press cycle, the board was removed from the press for cooling. The particleboards having dimensions of 5,500 mm × 5,500 mm × 15 mm were produced for each type of formulation. The samples were conditioned in a room temperature until the tests.

2.4. Characterization of the particleboard

The dimension of particleboard specimens used for evaluation was 100 × 100 mm^2. Prior to physical and mechanical analysis, board quality was assessed by measuring density, moisture content (MC), water absorption (WA) with 2 and 24 h, thickness swelling (TS), modulus of rupture (MOR) and modulus of elasticity (MOE), according to ABNT NBR 14810-3/2006 [22].

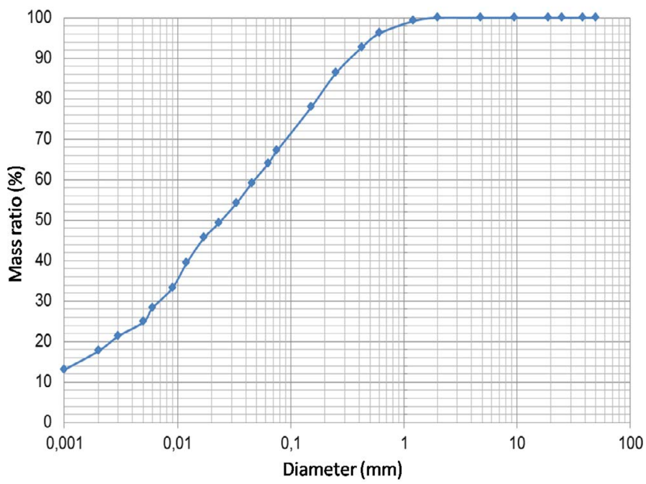

Fig. 1. WTP sludge particle granulometry curve.

3. Results and discussion

3.1. WTP sludge and wood particles characterization

The pH of WTP sludge (6.4) and wood particles (4.7), was important since pH can influence the quality of the particleboard produced. The pH of the wood particles decreased with the addition of the UF resin hardener because the hardener acted as an acid catalyst for the curing reaction of the UF resin [18].

The sludge and the wood particles had moisture contents of 9% and 11%, respectively. A granulometry curve was created for WTP sludge particles size distribution and indicates that the size particle distribution was between 0.001 and 1 mm (Fig. 1).

The distribution of wood particle size is presented in Fig. 2. The particles in group A had a size between 0.08 and 2.0 mm (Fig. 2a) with the largest mass fraction represented by mesh size 16. The particles in group B had a size distribution between 0.08 and 9.5 mm, and the largest mass fraction was represented by mesh size 10 (i.e., 2 mm).

Particle size was classified by the opening size in perforated metal plates (i.e., mesh size) in this study and is an important factor affecting the final characteristics of particleboard panels. Large particles create difficulties with compression of the particleboard panel and small particles have large surface area requiring greater quantities of adhesives to cover the particles adequately [23]. Thus, the UF resin-bonded boards were fabricated using only two particle sizes (Group A and B particles) in our study.

The concentrations of heavy metals in the WTP sludge particle and wood particles are presented in Table 2.

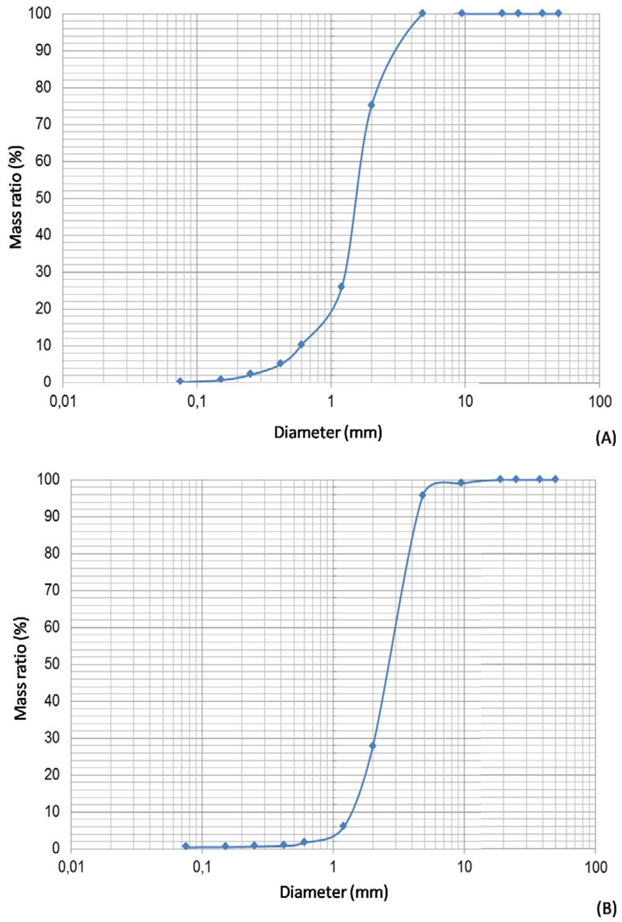

Table 2
WTP sludge and wood particle metal concentrations

Element	Metal concentration (mg kg^{-1})	
	WTP sludge particle	Wood particle
Al	56,220.07	532.85
K	956.67	714.31
Ca	3,343.24	2,622.63
Cr	142.90	6.16
Mn	1,917.96	133.10
Fe	128,644.59	2,476.70
Cu	328.77	32.89
Zn	141.97	46.03
Se	2.65	n.d.
Br	13.21	0.65
Sr	27.05	8.33
Ag	n.d.	n.d.

n.d. – not detected.

The WTP sludge had a large concentration of Al and Fe, likely resulting from the chemical coagulants used in the water treatment process. The Fe concentration may also originate from the surface water or soil in the area. The wood particles samples had greater concentrations of Ca and Fe.

Metal concentrations in the leachate and solubilized particles determined according to ABNT NBR 10.004/2004 [24] are presented in Table 3. No metal concentration exceeded the maximum allowable limits indicating that the samples are nontoxic.

Fig. 3 presents a photomicrograph and scanning electron EDS of raw WTP sludge used to construct the particleboards. Particles had highly variable size and irregular shapes resulting from the trituration process without granulometry selection (Fig. 3a). The scanning electron EDS (Fig. 3b) indicates the C, O, Fe Na, Mg, Al, and Si contents in the WTP sludge composition.

The wood particles used in particleboard production were also subjected to SEM photomicrography and scanning electron EDX analysis (Fig. 4). The fibres of the wood particles surface had a rough surface due to the trituration process Fig. 4a). The EDS spectrum with wood particles indicated the presence of C, O, Na, Mg, and Si (Fig. 4b).

3.2. Characterization of wooden particleboards manufactured

Particleboard density, moisture content (MC), water absorption (WA) within 2 and 24 h, and thickness swelling (TS) were characterized (Table 4). The particleboard densities ranged from 362.24 ± 15.24 (type 09) to 531.64 ± 16.47 kg m^{-1} (type 06). The lightest particleboards with densities ranging from 362 to 398 kg m^{-3} were produced without WTP sludge and with 7 min and 110°C manufacturing parameters. The highest density (531.64 kg m^{-3}) particleboards were obtained with the 20% WTP sludge and 7 min and 160°C manufacturing parameters (Type 6). Among the particleboard types, those that had greater WTP (20%) sludge incorporation had higher densities in comparison with the panels without sludge and manufactured under the same conditions of time and temperature of pressing.

Wang and Sun [14] incorporated wheat straw and corn piths into particleboard agglomerate and obtained a density of 340 kg m^{-3}. Monteiro et al. [15] used cassava sour starch residue and obtained plate densities of 207–407 kg m^{-3}. Liao et al. [16] incorporated sugarcane bagasse into the agglomerate and obtained a density of 400 kg m^{-3} and Martins et al. [17] used soy residues to make the plates with a density of 500 kg m^{-3}.

The Brazilian normatization establishes that moisture content (MC) (humidity) should be greater than 5% and less than 11%. The MC of particleboards created here varied between 8.16 ± 7.47% (type 3) and 18.66% (type 10). The treatments 3, 6, 12 and 16 were within the limits established by ABNT NBR 14810-2/2006 [22]. When compared with the European Standard EM 312 [25], which establishes an MC between 5% and 13%, the treatments 1, 3, 6, 12, 14, 15, and 16 are within the established limit.

The treatments 1, 3, and 15 were made with no WTP sludge, while treatments 6, 12, 14, and 16 were produced with sludge. Sludge incorporation contributed to MC of the wooden particleboards, however the primary variable influencing particleboard MC was the pressing temperature since the majority of the particleboards produced with adequate MC, were manufactured at 160°C (treatments 6, 12, 14, 15, and 16).

The lowest mean TS percentage was with treatment 6 where TS was 2.88 ± 0.71% after 2 h and 5.53 ± 0.51% after 24 h.

Table 3
Metal content in the leachate and solubilized particles from WTP sludge particles and wood particles (WP) samples

Metals	Leachate particles (mg L^{-1})		Limit NBR 10.004 (mg L^{-1})	Solubilized particles (mg L^{-1})		Limit NBR 10.004 (mg L^{-1})
	Sludge	WP		Sludge	WP	
Al	0.967	0.675	-	0.41	0.535	0.2
As	0.615	0.585	1	0.405	0.405	0.01
Ba	n.d.	n.d.	70	n.d.	n.d.	0.7
Cd	n.d.	n.d.	0.5	n.d.	n.d.	0.005
Pb	n.d.	n.d.	1	n.d.	n.d.	0.001
Cu	*	*	*	n.d.	0.08	2
Cr	0.005	0.004	5	0.017	0.021	0.05
Fe	*	*	*	0.039	n.d.	0.3
Mn	*	*	*	3.744	1.345	0.1
Hg	n.d.	n.d.	0.1	n.d.	n.d.	0.001
Ag	0.008	0.004	5	n.d.	n.d.	0.05
Se	0.451	0.463	1	0.292	0.162	0.01
Na	*	*	*	7.417	1.523	200
Zn	*	*	*	n.d.	0.34	5

*– Heavy metal not analyzed, n.d. – not detected.

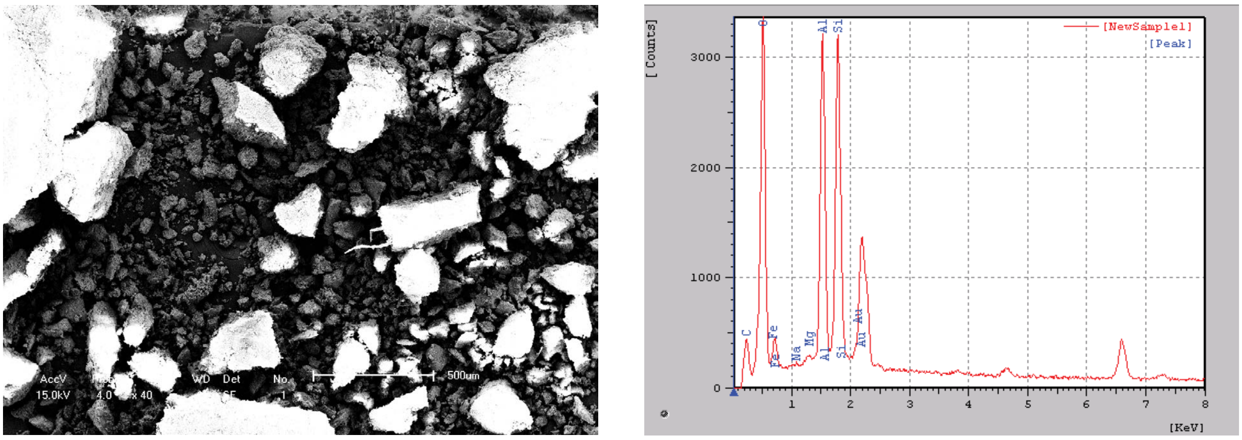

Fig. 3. WTP sludge characterized in a SEM photomicrograph (40X) (a) and scanning electron EDS (b).

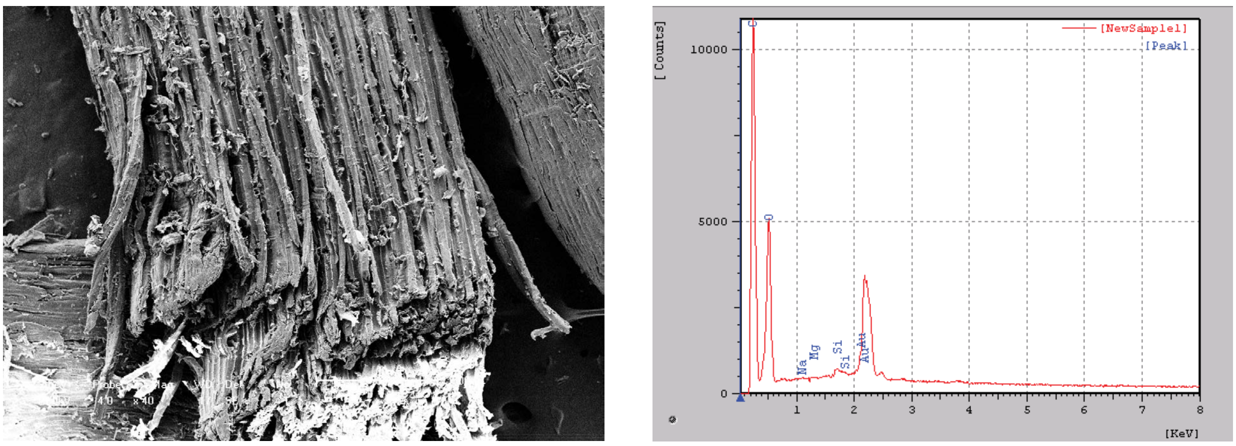

Fig. 4. Surface characterization of wood particles in a SEM photomicrograph (40X) (a) and with scanning electron EDS (b).

Table 4
Physical analysis of particleboards produced with WTP sludge and wood particles and at different pressing times and temperatures

Type	Granulometry	%WTP sludge	Wood particles	Time (min)	Temperature (°C)	Density (kg/m³)	MC (%)	TS (%) after 2 h	TS (%) after 24 h	WA (%) after 2 h	WA (%) after 24 h
1		0	100	7	110	425.17 ± 11.50	12.16 ± 4.91	5.45 ± 0.39	8.24 ± 0.60	72.19 ± 0.34	85.61 ± 0.24
2		20	80	7	110	444.24 ± 17.35	15.75 ± 6.13	5.51 ± 0.23	7.32 ± 0.79	78.56 ± 0.17	82.66 ± 0.65
3		0	100	12	110	412.94 ± 9.05	8.16 ± 7.47	5.79 ± 0.53	7.45 ± 0.51	87.78 ± 0.09	98.40 ± 0.32
4	Particle A	20	80	12	110	421.33 ± 16.44	14.40 ± 3.89	5.31 ± 0.27	7.39 ± 0.49	75.17 ± 0.26	83.91 ± 0.87
5	0.08 mm < d < 2.0 mm	0	100	7	160	379.62 ± 19.22	14.70 ± 7.43	3.98 ± 0.02	5.56 ± 0.45	51.15 ± 0.65	83.87 ± 8.76
6		20	80	7	160	531.64 ± 16.47	7.26 ± 9.29	2.88 ± 0.71	5.53 ± 0.51	42.04 ± 0.75	60.26 ± 0.22
7		0	100	12	160	433.67 ± 14.21	15.54 ± 2.76	3.43 ± 0.13	5.47 ± 0.46	24.32 ± 0.09	54.76 ± 0.18
8		20	80	12	160	531.37 ± 26.24	15.31 ± 5.62	4.59 ± 0.36	6.16 ± 0.19	42.58 ± 0.98	59.80 ± 0.48
9		0	100	7	110	362.24 ± 15.24	18.51 ± 3.45	7.59 ± 0.15	13.71 ± 0.09	54.34 ± 0.69	97.33 ± 0.34
10		20	80	7	110	496.01 ± 7.84	18.66 ± 4.29	3.46 ± 0.26	6.34 ± 0.35	53.61 ± 0.44	68.23 ± 0.60
11		0	100	12	110	374.13 ± 17.25	15.54 ± 5.21	7.66 ± 0.63	13.41 ± 0.27	70.41 ± 0.76	106.20 ± 1.29
12	Particle B	20	80	12	110	461,02 ± 20.60	9.47 ± 8.52	3.52 ± 0.30	5.94 ± 0.06	67.04 ± 0.21	75.41 ± 0.63
13	0.08 mm < d < 9.5 mm	0	100	7	160	398.02 ± 21.63	15.17 ± 3.98	4.41 ± 0.43	6.94 ± 0.46	67.82 ± 0.77	75.99 ± 0.88
14		20	80	7	160	439.84 ± 27.67	11.56 ± 3.08	4.65 ± 0.41	5.68 ± 0.59	70.26 ± 0.03	65.67 ± 0.07
15		0	100	12	160	414,18 ± 28.01	12.83 ± 0.45	9.13 ± 0.33	12.32 ± 0.46	52.39 ± 0.09	76.91 ± 0.15
16		20	80	12	160	526.44 ± 17.75	9.62 ± 0.84	4.70 ± 0.16	8.04 ± 0.54	52.92 ± 0.66	64.87 ± 0.53

Note: MC is moisture content, TS is thickness swelling, WA is water absorption.

The highest mean TS was 9.13 ± 0.33% after 2 h for treatment 15 and 13.71 ± 0.09% after 24 h for treatment 9. The ABNT NBR 14810-2/2006 [22] establishes a maximum TS of 8% after 2 h and all treatments (except Treat. 15, without sludge) presented within the parameters established by the regulations. A maximum TS value of 15% is allowed for particleboards used in load-bearing applications in dry conditions [18,25].

The ABNT NBR 14810-2/2006 [22] establishes a maximum TS of 8% after 2 h. Comparing this limit with the values obtained in this study, it can be observed that the all treatments presented within the parameters were established by the regulations. A maximum TS value of 15% is allowed for particleboards used in load-bearing applications in dry conditions [18,25].

The treatment with the lowest WA was 7 with 24.32 ± 0.09% after 2 h and 54.76 ± 0.18% after 24 h (Table 4). Treatment 3 had the highest WA percentage after 2 h with 87.78 ± 0.09% and treatment 11 after 24 h with 106.20 ± 1.29%.

In the particleboards obtained, no great differences was observed in the results of the physical analyzes in relation to the evaluated parameters of time and temperature of pressing and particle size of wood sieves.

The incorporation of WTP sludge into agglomerated wooden particleboards did not influence the quality of the panel obtained. That is, WTP sludge did not diminish the quality of the particleboard relative to the product obtained without sludge incorporated. Therefore, the incorporation of the sludge waste into panels provides an environmentally advantageous disposal method.

The modulus of rupture (MOR) and modulus of elasticity (MOE) provide parameters that relate to the mechanical analysis of static bending performance (Table 5). The MOR limit established by ABNT NBR 14810-2/2006 [22] for a medium density panel with a thickness between 14 and 20 mm is 16 MPa. The Brazilian standard does not establish a limit for MOE.

All treatments had MOR below the minimum limit established by ABNT NBR 14810-2/2006 [22]. The constructed panels had densities categorized as low-density agglomerate, so the mechanical strength of the panel in relation to the static bending analysis was below the expected value. When comparing treatments with and without WTP sludge incorporation created under the same pressing time and temperature conditions, the treatments that had sludge added had higher MOR and MOE. The density of the particleboards had a direct influence on the mechanical strength of the panels.

Table 5
Modulus of rupture (MOR) and modulus of elasticity (MOE) for the particleboards created provide an analysis of their static bending capacity

Particleboard types	MOR (Mpa)	MOE (Mpa)
1	0.51	42.44
2	0.58	54.56
3	0.32	23.79
4	0.40	37.18
5	1.00	88.34
6	2.21	293.19
7	1.60	176.46
8	1.93	276.61
9	0.22	27.30
10	0.73	106.88
11	0.36	42.34
12	0.65	82.32
13	0.88	81.82
14	1.03	132.89
15	0.68	92.42
16	1.56	223.99

4. Conclusion

The agglomerated wood panels incorporating WTP sludge had physical and mechanical parameters that classified it as low-density wooden particleboards. The treatments that presented the highest densities were the treatments that had WTP sludge incorporated. The low-density panels obtained in this work may have some commercial applications that do not require high mechanical resistance, such as for use in insulation.

The incorporation of WTP sludge into wood particleboards did not influence the final quality of panels obtained; WTP sludge did not diminish the quality of the particleboard when compared with the panels without WTP residues.

Developing a suitable final disposal for WTP sludge is extremely important because it is generated continuously and in large quantities. The incorporation of WTP sludge into wooden particleboards is a promising alternative for final disposal for this waste, providing a useful product with a waste that encourages sustainable development, collaborating with society and the environment.

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References

[1] K.-Y. Chiang, P.-H. Chou, C.-R. Hua, K.-L. Chien, C. Cheeseman, Lightweight bricks manufactured from water treatment sludge and rice husks, J. Hazard. Mater., 171 (2009) 76–82.
[2] M.-J. Wang, Land application of sewage sludge in China, Sci. Total Environ., 197 (1997) 149–160.
[3] K.B. Dassanayake, G.Y. Jayasinghe, A. Surapaneni, C. Hetherington, A review on alum sludge reuse with special reference to agricultural applications and future challenges, Waste Manage., 38 (2015) 321–335.
[4] S. Bittencourt, B.M. Serrat, M.M. Aisse, L. Marin, C.C. Simão, Aplicação de lodos de estações de tratamento de água e de tratamento de esgoto em solo degradado, Eng. Sanit. Ambiental, 17 (2012) 315–324.
[5] C. Huang, J.R. Pan, K.-D. Sun, C.-T. Liaw, Reuse of water treatment plant sludge and dam sediment in brick-making, Water Sci. Technol., 44 (2001) 273–277.

[6] R.R. Zamora, F.E. Ayala, M.S. López, O.G. Barceló, R. Gómez, J.P. Mazariego, R. Navarro-González, R. Schouwenaars, Optimisation and analysis of the synthesis of a cellular glass-ceramic produced from water purification sludge and clay, Appl. Clay Sci., 123 (2016) 232–238.
[7] H.A. Elliott, L.M. Singer, Effect of water treatment sludge on growth and elemental composition of tomato (*Lycopersicon esculentum*) shoots, Commun. Soil Sci. Plant Anal., 19 (1988) 345–354.
[8] T. Skene, J. Oades, G. Kilmore, Water treatment sludge: a potential plant growth medium, Soil Use Manage., 11 (1995) 29–33.
[9] M.H. Kim, H.B. Song, Analysis of the global warming potential for wood waste recycling systems, J. Cleaner Prod., 69 (2014) 199–207.
[10] G. Nemli, A. Aydın, Evaluation of the physical and mechanical properties of particleboard made from the needle litter of *Pinus pinaster* Ait, Ind. Crops Prod., 26 (2007) 252–258.
[11] T. Tabarsa, S. Jahanshahi, A. Ashori, Mechanical and physical properties of wheat straw boards bonded with a tannin modified phenol–formaldehyde adhesive, Compos. Part B, 42 (2011) 176–180.
[12] R. da Rosa Azambuja, V.G. de Castro, R. Trianoski, S. Iwakiri, Utilization of construction and demolition waste for particleboard production, J. Build. Eng., 20 (2018) 488–492.
[13] R. Kozlowski, M. Helwig, Lignocellulosic Polymer Composites. Science and Technology of Polymers and Advanced Materials, Springer, 1998, pp. 679–698.
[14] D. Wang, X.S. Sun, Low density particleboard from wheat straw and corn pith, Ind. Crops Prod., 15 (2002) 43–50.
[15] S. Monteiro, J. Martins, F. Magalhães, L. Carvalho, Low density wood-based particleboards bonded with foamable sour cassava starch: preliminary studies, Polymers, 8 (2016) 354–365.
[16] R. Liao, J. Xu, K. Umemura, Low density sugarcane bagasse particleboard bonded with citric acid and sucrose: effect of board density and additive content, BioResources, 11 (2016) 2174–2185.
[17] E.H. Martins, A.P. Vilela, R.F. Mendes, L.M. Mendes, L.E.V.d.S. Vaz, J.B. Guimarães Junior, Soybean waste in particleboard production, Cienc. Agrotecnol., 42 (2018) 186–194.
[18] İ. Atar, G. Nemli, N. Ayrilmis, M. Baharoğlu, B. Sarı, S. Bardak, Effects of hardener type, urea usage and conditioning period on the quality properties of particleboard, Mater. Des., 56 (2014) 91–96.
[19] ABNT, ABNT NBR 10.005, in Procedimento para obtenção de extrato lixiviado de resíduos sólidos, Associação Brasileira de Normas Técnicas, Rio de Janeiro, 2004.
[20] ABNT, ABNT NBR 10.006, in Procedimento para obtenção de extrato solubilizado de resíduos sólidos, Associação Brasileira de Normas Técnicas, Rio de Janeiro, 2004.
[21] E. Pendlebury, H. Lei, M. L. Antoine, A. Pizzi, Melanine – Formaldehyde Resins without Urea for Wood Panels, in: A. Pizzi, K.L. Mittal, Eds., Wood Adhesives, CRC Press, London, p. 462, 2011.
[22] ABNT, NBR 14.810, in Chapas de madeira aglomerada, Associação Brasileira de Normas Técnicas, Rio de Janeiro, 2006.
[23] Z. Pan, Y. Zheng, R. Zhang, B.M. Jenkins, Physical properties of thin particleboard made from saline eucalyptus, Ind. Crops Prod., 26 (2007) 185–194.
[24] ABNT, NBR 10004 - Resíduos sólidos – Classificação, Associação Brasileira de Normas Técnicas, Rio de Janeiro, 2004.
[25] S. ECf, EN 312 - European Committee for Standardization, Brussels, 2003.