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Influence of the addition of carbon black to the mixed adhesive based on vegetable oils used to manufacture *Pinus* sp. composite panels

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ABSTRACT

This study analyzes the influence of carbon black (CB) addition to a mixed adhesive based on vegetable oils, used in manufacturing *Pinus* sp. wood composite panels. To this end, test specimens were made to evaluate the following concentrations of carbon black (CB) was added at concentrations ranging from 0% to 100%. For each class of CB concentration, 6 specimens were made for physical and mechanical characterization in accordance with ABNT NBR 14810:2018 and used for microstructural analysis using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) of the panels. As a result, the addition of CB to the vegetable oil-based mixed adhesive resulted in statistically higher average values for the mechanical properties of the panels with 30% CB, achieving the same level of significant increase as the panels with 60% CB and 100% CB in their strength values. According to the ABNT NBR 14810:2018 standards, the panels from 0% CB to 5% CB were classified as P6 (structural panels for use in severe load conditions, in dry conditions) and the panels from 10% CB to 100% CB were classified as P7 (structural panels for use in severe load conditions, in humid environments).

Keywords: Wood composite panels; Carbon black; Physical-mechanical properties; Microstructural characterization.

1. INTRODUCTION

Wood-based composite panels have emerged as an alternative to the problems presented in using solid wood, mainly from low to medium density species, such as low durability against wood biodeteriorating organisms, low mechanical strength, anisotropy and limited dimensions [1–5]. Among these composites, reconstituted wood panels such as plywood, MDP (Medium Density Particleboard), MDF (Medium Density Fiberboard), and OSB (Oriented Strand Board) stand out.

A significant portion of wood processed in sawmills, estimated at 40% to 60%, becomes waste, especially sawdust, which is frequently discarded improperly, contributing to environmental degradation [6–11]. This context highlights the need to develop sustainable technologies that incorporate wood residues and environmentally friendly binders [6–11].

Wood particleboards are produced by binding particles or plant fibers with a synthetic or natural polymer adhesive through hot pressing. Their applications include walls, floors, ceilings, office partitions, cabinets, furniture, and countertops [2, 12–14]. Panels are pressed under predetermined pressure and temperature to ensure complete adhesive curing and good interaction between the constituent [14–16].

Adhesive is a determining factor in wood-based composite panels production process, as it greatly influences compation degree, fixation and wetting between wood particles, as well as the final product price. Therefore, it is essential to define type and quantity of adhesive to be used during the process, ensuring optimization and quality of production [17].

Urea-formaldehyde is the most widely used polymeric adhesive for these composites production due to its low cost, high curing speed, and good flame resistance. However, due to formaldehyde emission during hot

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pressing, which generates environmental burdens for industries as it is a toxic gas to human health, the demand for not-toxic alternative adhesive to health and environment has grown, such as castor oil-based polyurethane adhesive (PU-Camona) and mixed polyurethane adhesive based on vegetable oils [18, 19].

Brazilian industries have used a large number of reforested wood species, such as those from Pinus and Eucalyptus genera, which have well adapted to planting system and are the most used for wood composite panels production, once are of medium density and allow good physical and chemical adhesion with polymeric adhesives [20].

Currently, with nanotechnology applied in materials science and engineering fields, polymers reinforced with nanometric particles have received attention of many scientific and industrial societies [21]. Nanometric particles, generally ceramic in nature, are compatible with polymeric adhesives used in wood composite panels manufacture, and have a great capacity to fill voids and improve physical-mechanical performance of these composites [22, 23].

Carbon black is a material classified as ceramic and characterized by its particles nanometric dimensions, with a large surface area. When added as a filler in polymer composites, it can provide a great improvement in physical-mechanical properties. This can be explained by its great capacity to fill voids and by providing good chemical interaction between the phases, improving polymer composites performance, such as wood panels. For this reason, it is commonly used as a filler in polymeric materials and, when added to a polymeric matrix, it is used to improve its physical-mechanical, electrical, and chemical properties and, in addition, it is capable of improving the thermal and UV stability of the materials [23].

Industrial waste use in various engineering materials has been evaluated by many researchers with a view to environmental sustainability. Thus, inclusion of reinforcements such as natural fillers in different formulations treated and untreated, nucleating agents and organic pigments such as carbon black in recycled polymer composites, are alternative approaches to develop materials meeting the requirements of most engineering and commercial applications [17, 24–26].

Researchers such as MENSAH *et al*. [27], GONÇALVES *et al*. [28] and FARIA *et al.* [29] have been engaged in the search for improvements in the production and performance of this material. They have also sought to assess the technical and environmental viability of using new adhesives and materials that would otherwise be indiscriminately discarded into the environment, with the aim of using them as alternative materials for reinforcement/load in panels, or in conjunction with wood particles.

Even with the widespread use of carbon black to improve the physical and mechanical properties of polymer matrix composites, as it provides significant void filling and increases the chemical bonding between particles, no research has been found on the addition of this material to polymer adhesives in wood composite panels [23–26]. This fact proves the originality of the work, combining sustainability issues and the improvement of a product that many researchers call the "material of the future" and that should be increasingly explored by scientific research.

In this context, the present study aims to investigate the influence of incorporating carbon black into a mixed polyurethane adhesive based on vegetable oils in the production of *Pinus* sp. particleboards. The research evaluates the panels' physical-mechanical properties and microstructural characteristics to establish correlations between filler content, composite performance, and potential for structural applications.

2. MATERIALS AND METHODS

2.1. Description of materials

For panel production, *Pinus* sp. wood particles without preservative treatment were used, stored in Wood and Timber Structures Laboratory (LaMEM), of the Department of Structural Engineering (SET), São Carlos School of Engineering (EESC/USP), with a moisture content close to 10% and dimensions between 0.8 mm and 2.8 mm, as pointed out by SHIROSAKI [30].

In composite panels manufacturing process, a mixture of two-component polyurethane adhesive derived from a mixture of vegetable oils supplied by the IMPERVEG industry (Aguaí-SP) and carbon black supplied by the distributor BANDEIRANTE BRAZMO was used, as shown in Figure 1.

The choice of carbon black type was made in conjunction with the Materials Engineering and Research and Development team at CABOT CORPORATION, since carbon black application for this specific purpose had never been carried out.

2.2. Methods

2.2.1. Panel manufacturing

Particle boards (400 × 400 × 10 mm) were manufactured in accordance with ABNT NBR 14810:2018 [31–33]. Each board was produced using 640 g of kiln-dried *Pinus* sp. particles with 15% (by dry weight) polyurethane

Figure 1: Sample of carbon black.

adhesive. Carbon black was added in concentrations of 0%, 2.5%, 5%, 10%, 15%, 30%, 60% and 100% in relation to the adhesive mass. Six replicate panels were produced for each formulation.

To facilitate the reading of the next sessions of this paper, the types of panels are identified according to Table 1.

All panel production was conducted at LaMEM/SET/EESC/USP, using equipment including a semi-analytical balance (OHAUS Adventurer AR3130), orbital mixer (Fiochi), and thermal press (Marconi MA 098/50) (Figure 2).

Table 1: Type of panel made and simplification/acronyms used.

TYPE OF PANEL	SIMPLIFICATION/ACRONYM
0% of carbon black added to 96g of adhesive.	0% carbon black/0% CB
2.5% of carbon black added to 96g of adhesive.	2.5% carbon black/2,5% CB
5% of carbon black added to 96g of adhesive.	5% carbon black/5% CB
10% of carbon black added to 96g of adhesive.	10% carbon black/10% CB
15% of carbon black added to 96g of adhesive.	15% carbon black/15% CB
30% of carbon black added to 96g of adhesive.	30% carbon black/30% CB
60% of carbon black added to 96g of adhesive.	60% carbon black/60% CB

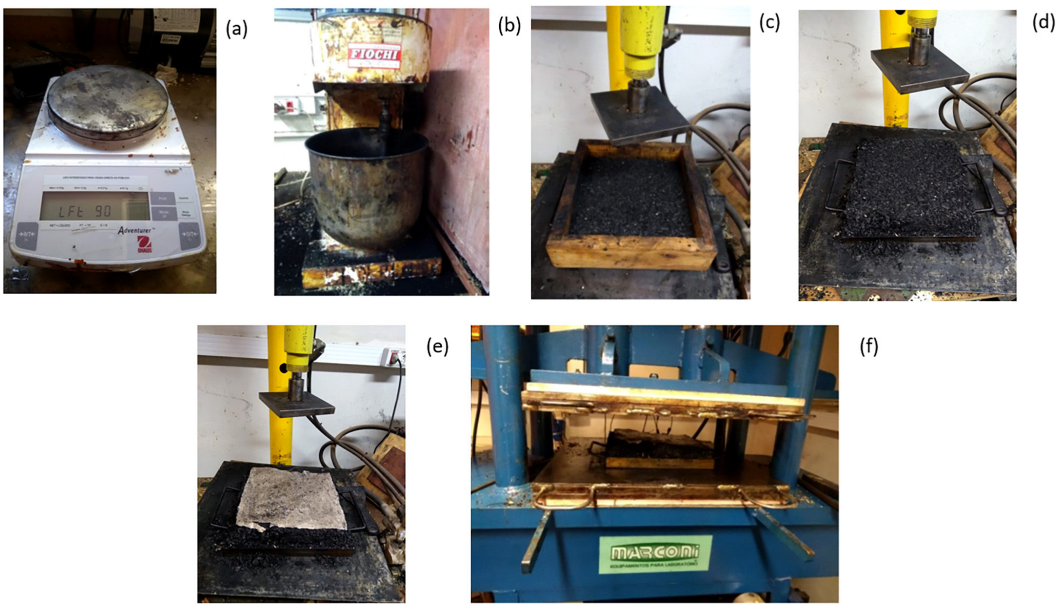

Figure 2: Production of particleboards: (a) OHAUS Adventurer AR3130 semi-analytical balance, (b) Fiochi orbital mixer, (c) hydraulic press for pre-forming, (d) pre-pressed panel on sheet metal, (e) preparation with heat protector, (f) a Marconi Model MA 098/50 thermal press.

After particles mixing with adhesive and was homogeneous, it was placed in a metal mold and subjected to pre-pressing at 0.01 MPa, carried out in a hydraulic press for pre-forming. The pre-pressed mixture was then sent for hot pressing in a Marconi Model MA 098/50 thermal press, temperature of 100 °C, pressure 4 MPa, for 10 minutes, still according to parameters adopted by SHIROSAKI [30]. For stabilization and complete adhesive curing, the panels produced were stored at room temperature for 48 hours.

2.2.2. Physical-mechanical characterization of the panels

Physical and mechanical properties were determined according to ABNT NBR 14810:2018 [31–33], including density, thickness swelling (TS), water absorption (WA), modulus of elasticity (MOE), modulus of rupture (MOR), internal bond strength (IB), and screw pullout tests (surface and top). This research addressed determining the properties:

- Physical properties: density (D), thickness swelling (IE) and water absorption (AA).
- Mechanical properties: modulus of elasticity (MOE), modulus of rupture (MOR), tensile strength perpendicular to the faces (TP), surface bolt pullout (APS) and top bolt pullout (APT).

With the values obtained in panels characterization, it was possible to compare them with the values found in literature regarding conventionally used and already studied panels, as well as the comparison of the values obtained with national and international normative documents for particle panels.

Figure 3 shows values of static bending, tension perpendicular to faces and screw pullout tests.

2.2.3. Microstructural characterization of the panels

Microstructural analysis was performed using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and Fourier Transform Infrared Spectroscopy (FTIR) tests. Thus, it was possible to analyze the mechanical strength from a molecular point of view and interaction of carbon black mixed with adhesives, drawing a parallel between these analyses and results of panels physical-mechanical characterization.

- Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS).

Scanning Electron Microscopy (SEM) allowed samples examination by scanning an electron beam across its surface. The reflected electron beam is collected and displayed at the same scanning rate on a cathode ray tube. Thus, an image representing samples surface characteristics is generated on the computer screen and can be photographed for the respective analysis [34, 35].

Specimens with nominal dimensions 1 × 1 × 1 cm were tested, after metallized with gold for SEM and EDS to be performed. Figures 4 and 5 show specimens before and after metallization. SEM photomicrographs and their respective EDS spectra, which allowed the qualitative analysis of the constituent carbon in the carbon black added to panels, were performed at Instrumental Chemical Analysis Center of the Chemistry Institute of São Carlos (CAQI/IQSC/USP).

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

Figure 3: (a) static bending test on the 2.5% CB in EMIC, (b) tension perpendicular to faces of a CP with 60% CB, (c) screw pullout test (side) of a sample with 2.5% CB, (d) screw pullout test (surface) of a sample with 2.5% CB.

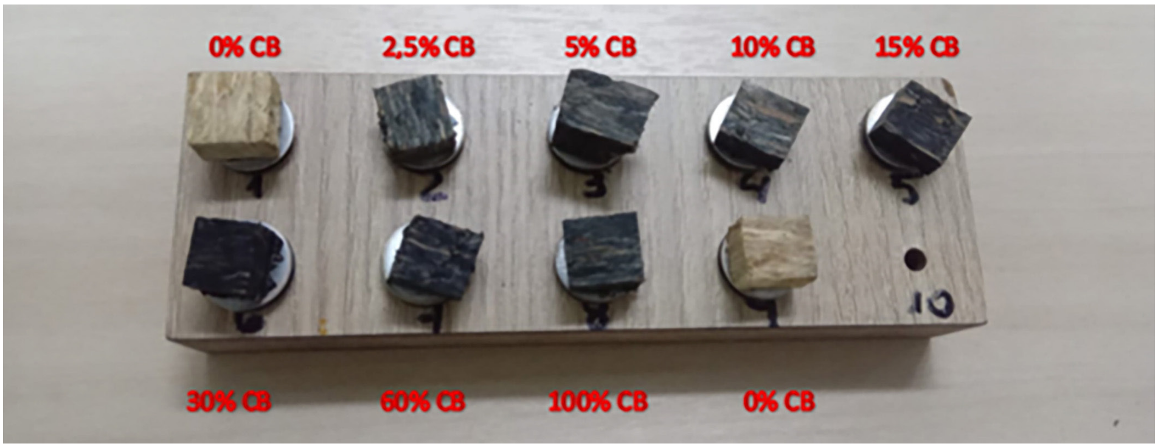

Figure 4: Test specimens used in the SEM and EDS tests.

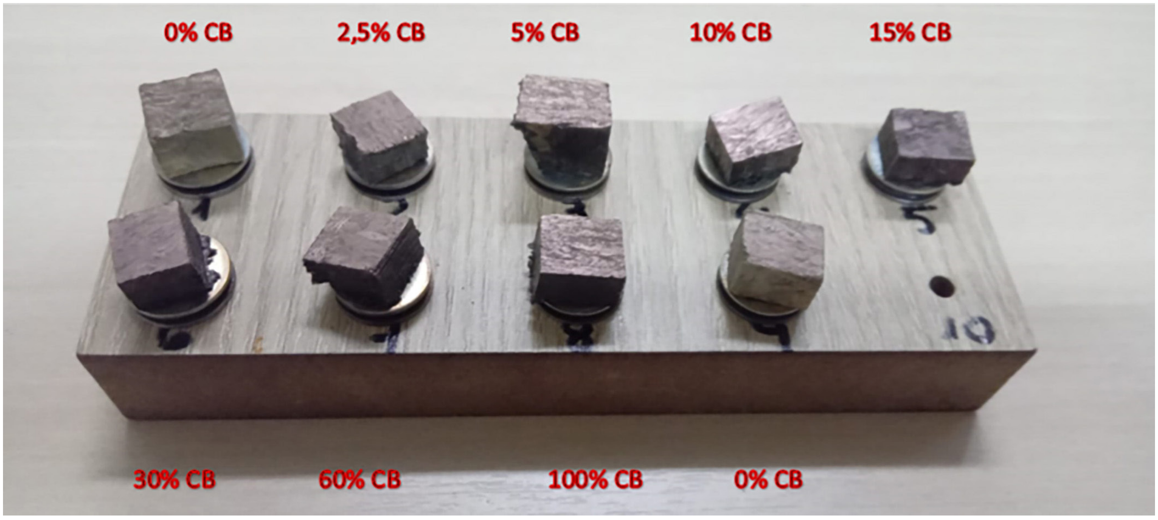

Figure 5: Metallized test specimens in SEM and EDS tests.

For SEM and EDS analyses, ZEISS LEO 440 equipment (Cambridge, England) with OXFORD detector (model 7060) was used, operating with an electron beam of 20 kV, current 2.82 A and I probe 200 pA. Samples were metallized in the Coating System BAL-TEC MED 020 equipment (BAL-TEC, Liechtenstein) and kept in a desiccator (vacuum) until analysis.

- Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) typically uses transmission, external reflection, and ATR modes. In a transmission measurement, infrared light passes through a sample; in external reflection and ATR modes, infrared light is reflected from external or internal surfaces of the sample.

In order to analyze carbon black interaction with polymer matrix and wood particles, Fourier Transform Infrared Spectrocopy (FTIR) analysis was performed on FTIR-Bruker Spectrophotometer with ATR, as shown in Figure 6, from the Instrumental Chemical Analysis Center of the São Carlos Chemistry Institute (CAQI/IQSC/USP).

Samples shown in Figure 7 were placed in a plastic container, each containing 10 g of the powdered material and 3 test specimens in the form of 5 × 5 cm plates with a flat surface, since during the test, the quality of the results for the two types of material analysis (powder or plates) would be evaluated. Given that the spectra quality in powder format permitted better resolution than in blocks, and in order to save costs, with the exception of group with 60% carbon black, the others were analyzed in powder form.

Figure 6: FTIR-Bruker spectrophotometer.

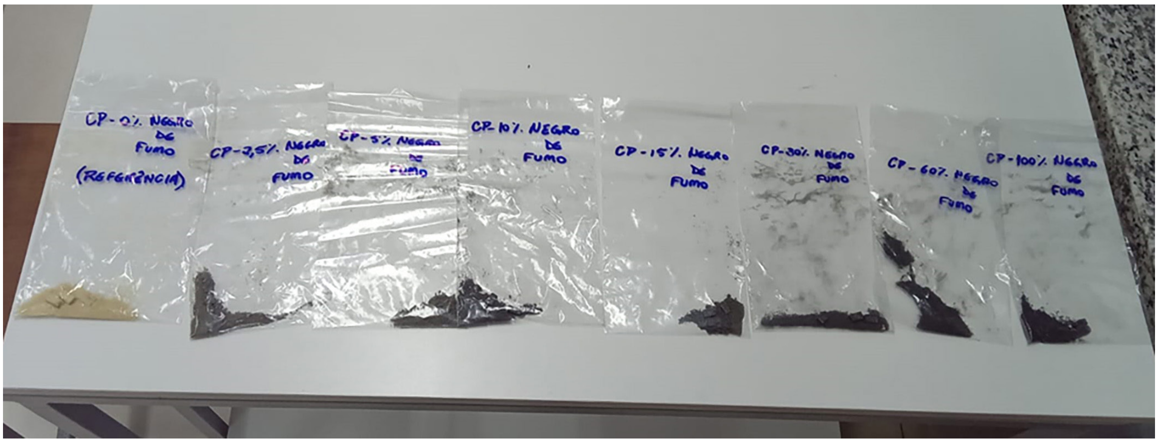

Figure 7: Samples for the FTIR test, where each plastic container contained 10 g of the powdered material and 3 test specimens in the form of 5 × 5 cm plates with a flat surface.

- Statistical analyses

Statistical analysis was elaborated using JMP® software, with a t-value below the significance level ($\alpha = 0.5$), i.e., all regression models were considered significant by ANOVA (P-value < 0.05). Thus, even with the great variability of results, which directly reflected on the quality of the adjustment and the coefficients of determination, the models generated captured behavioral trends between the factors evaluated and carbon black concentration added to the polymeric adhesive. Thus, Tukey test was performed to assess whether there was a significant difference between the mean values of the properties verified for the different carbon black contents in panels evaluated.

3. RESULTS AND DISCUSSION

In order to investigate the physical-mechanical properties of *Pinus* sp. wood panels produced additioning carbon black in the mixed polyurethane adhesive based on vegetable oils, experimental mean values obtained for the referred panels made with 0% (reference) of carbon black (CB) in adhesive percentage, 2.5% CB, 5% CB, 10% CB, 15% CB, 30% CB, 60% CB and 100% CB are presented.

Finally, results here obtained are compared with literary values found by SHIROSAKI [30], who also evaluated behavior of mixed adhesive based on vegetable oils in *Pinus* sp. composites.

Due to this work originality, a more direct results discussion in this context was not possible, limiting comparisons with more general factors of the panels that obtained better properties made by SHIROSAKI [30], which were the *Pinus* sp. panels treated with saline solution of CCB (Chromated Copper Borate preservative) and 15% adhesive.

Table 2: Mean experimental values obtained and results of Tukey test for density (D).

TYPE OF PANEL	D (kg/m^3)	TUKEY TEST
0% CB	909.2	A
2.5% CB	936.6	AB
5% CB	918.7	AB
10% CB	918.6	AB
15% CB	814.2	AB
30% CB	858.1	AB
60% CB	1031.0	B
100% CB	919.3	B

3.1. Physical properties

This item presents in Tables 2 to 4 the mean experimental values obtained and results of Tukey Test for density (D), thickness swelling (IE), water absorption (AA).

3.1.1. Density

Experimental mean reference value for density was close to that found by SHIROSAKI [30]: 888 kg/m^3. Experimental values found for panels with carbon black addition resulted in statistically different mean values between panels with 60% CB. This is the one with highest density value, and the panels with 30% and 15% CB, with significantly lower values compared to the panels with 60% carbon black added to the adhesive (Table 2).

3.1.2. Thickness swelling and water absorption

From Tables 3 and 4, there is a greater similarity between mean values of thickness swelling and water absorption, panels with 2.5% CB and the panels evaluated by SHIROSAKI [30], which presented values for thickness swelling and water absorption of 9% and 13%, respectively. The other panel varieties showed a better performance in thickness swelling than SHIROSAKI [30].

Table 3: Mean experimental values obtained and results of Tukey test for thickness swelling (IE).

TYPE OF PANEL	IE (%)	TUKEY TEST
0% CB	7.1	A
2.5% CB	9.0	AB
5% CB	6.5	BC
10% CB	5.5	BC
15% CB	6.6	BC
30% CB	6.4	BC
60% CB	4.5	C
100% CB	4.7	C

Table 4: Mean experimental values obtained and results of Tukey test for water absorption (AA).

TYPE OF PANEL	AA (%)	TUKEY TEST
0% CB	11.3	A
2.5% CB	13.1	AB
5% CB	14.25	B
10% CB	12.9	B
15% CB	13.8	B
30% CB	22.4	B
60% CB	11.4	B
100% CB	16.7	B

Table 5: Mean experimental values obtained and results of Tukey test for modulus of elasticity (MOE).

TYPE OF PANEL	MOE (MPa)	TUKEY TEST
0% CB	3203	A
2.5% CB	3235	AB
5% CB	3345	ABC
10% CB	3399	BCD
15% CB	3483	CDE
30% CB	3598	CDE
60% CB	3745	DE
100% CB	3807	E

According to Table 3, panels with 0% CB and 2.5% CB are statistically different, with means for thickness swelling higher than those obtained for panels with 60% CB and 100% CB. Tukey test shows that addition of 60% and 100% carbon black to the adhesive improved panels dimensional stability.

As shown in Table 4, mean value for water absorption of panels with 30% CB is significantly higher than that of panels with 5%, 15%, 2.5%, 10%, 60% and 0% carbon black added to adhesive.

According to WANG and SUN [36] and PFAFF [37], surface area is one of the most important characteristics that influence carbon black performance, as it determines interfacial area between carbon black and matrix in which it is dispersed. The large specific surface area is the reason for high adsorption capacity of carbon blacks for water, organic solvents and binders. Adsorption is important for wettability and dispersibility of carbon black particles in different applications, having an important meaning for the decision on whether to use a type of carbon black as a pigment or as a filler in rubber.

3.2. Mechanical properties

This item presents in Tables 5 to 9 the mean valuer of modulus of elasticity (MOE), modulus of rupture (MOR), tension perpendicular to faces (TP), surface screw pullout (APS) and top screw pullout (APT). Furthermore, Table 10 presents the classification of the panels manufactured in this research, according to ABNT NBR 14810:2018 [31–33].

3.2.1. Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

According to Tables 5 and 6, panels with carbon black addition of 0% to 15% in relation to adhesive presented MOR values slightly lower than, that found by SHIROSAKI [30], 31 MPa, and, still within this carbon black concentration range, MOE values higher than those in the cited literature (3115 MPa). Thus, the addition of nanometric ceramic particle increased composite stiffness.

According to Tables 5 and 6, values for these properties of panels with 30% to 100% carbon black were higher than those showed in literature. Through Tukey test, it can be observed that MOR mean values of the panels with 100% CB, 60% CB and 30% CB are statistically higher than those of panels with 15% CB, 10% CB, 5% CB, 2.5% CB and 0% CB. For MOE, it can be stated that panels with 100% CB, 60% CB and 30% CB have significantly higher average values than the other panels evaluated.

Therefore, from the concentration of 30% carbon black, MOE and MOR mean values of properties remained at a level and reached the highest values for these properties, and it can be concluded that addition

Table 6: Mean experimental values obtained and results of Tukey test for modulus of rupture (MOR).

TYPE OF PANEL	MOR (MPa)	TUKEY TEST
0% CB	24	A
2.5% CB	26	A
5% CB	28	A
10% CB	29	B
15% CB	30	C
30% CB	32	C
60% CB	33	D
100% CB	33	E

of 30% carbon black in mixed adhesive helps to increase mean values for the bending properties, as well as improving dimensional stability.

The observed behavior is explained by the ability of carbon black nanoparticles to increase interaction between long polymer chains, aiding in their coiling and increasing stiffness, since polymer chains present physical-chemical bonds when they come into contact and coil in the carbon black nanoparticles.

3.2.2. Tension perpendicular to faces

According to Table 7, the experimental values found for the panels evaluated for tension perpendicular to the face followed the same behavioral trend verified for MOE and MOR tests, with a noticeable increase in mean value from 30% CB. In addition, all experimental values were higher than that found by SHIROSAKI [30], 3.64 MPa.

Tukey test presented in Table 7 proves that from 30% of carbon black added to adhesive, mean values for tension perpendicular to faces increase significantly, with the panels with 100% CB and 60% CB being those that gained the most strength to this mechanical stress.

3.2.3. Screw pullout resistance

According to Tables 8 and 9, experimental values obtained for surface screw pullout property were all higher than that found by SHIROSAKI [30], 1160 N. As for the top screw pullout property, only the panels of 30–100% CB presented values higher than 2613 N in literature.

Tukey test values for screw pullout from surface show that panels with 100% CB have a significantly higher mean value than the other panels evaluated. Panels with 5% CB and 0% CB have significantly lower mean values, while the other types, such as 60% CB, 30% CB, 15% CB, 10% CB and 5% CB, are statistically higher than those with 5% CB and 0% CB, without significant differences between them.

Also, according to Tukey test, panels with 100% CB presented a significantly higher mean value than the other panels evaluated. Panels with 0% CB, 2.5% CB, 5% CB and 10% CB showed significantly lower mean values, and close to each other.

Table 10 presents classification of the panels manufactured in this research, according to ABNT NBR 14810:2018 [31–33].

According to ABNT NBR 14810:2018 [31–33], panels with 0% CB to 5% CB were classified as P6 (Structural panels for use in severe load conditions, in dry environments) and panels with 10% CB to 100% CB

Table 7: Mean experimental values obtained and results of Tukey test for tension perpendicular to faces (TP).

TYPE OF PANEL	TP (MPa)	TUKEY TEST
0% CB	4.10	A
2.5% CB	4.82	A
5% CB	4.98	AB
10% CB	5.35	BC
15% CB	5.69	CD
30% CB	6.28	CD
60% CB	6.47	DE
100% CB	6.50	E

Table 8: Mean experimental values obtained and results of Tukey test surface screw pullout (APS).

TYPE OF PANEL	APS (N)	TUKEY TEST
0% CB	1608	A
2.5% CB	1504	B
5% CB	1895	B
10% CB	1746	B
15% CB	1605	B
30% CB	2015	B
60% CB	2373	C
100% CB	2457	C

Table 9: Mean experimental values obtained and results of Tukey test for top screw pullout (APT).

TYPE OF PANEL	TUKEY TEST
0% CB	A
2.5% CB	AB
5% CB	BC
10% CB	CD
15% CB	CDE
30% CB	CDE
60% CB	DE
100% CB	E

Table 10: Classification of the panels manufactured in this research, according to ABNT NBR 14810:2018 [31–33].

TYPE OF PANEL	ABNT NBR 14810:2018
0% CB	P6
2.5% CB	P6
5% CB	P6
10% CB	P7
15% CB	P7
30% CB	P7
60% CB	P7
100% CB	P7

were classified as P7 (Structural panels for use in severe load conditions, in humid environments), with results significantly higher than the performance limits of the aforementioned standard. This demonstrates the great versatility of composites produced with carbon black, which can be widely used in civil construction, furniture, packing, and naval industry, as examples.

3.3. Microstructural characterization

3.3.1. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)

Figures 8 to 23 are SEM photomicrographs and EDS graphs of the panels evaluated in this research.

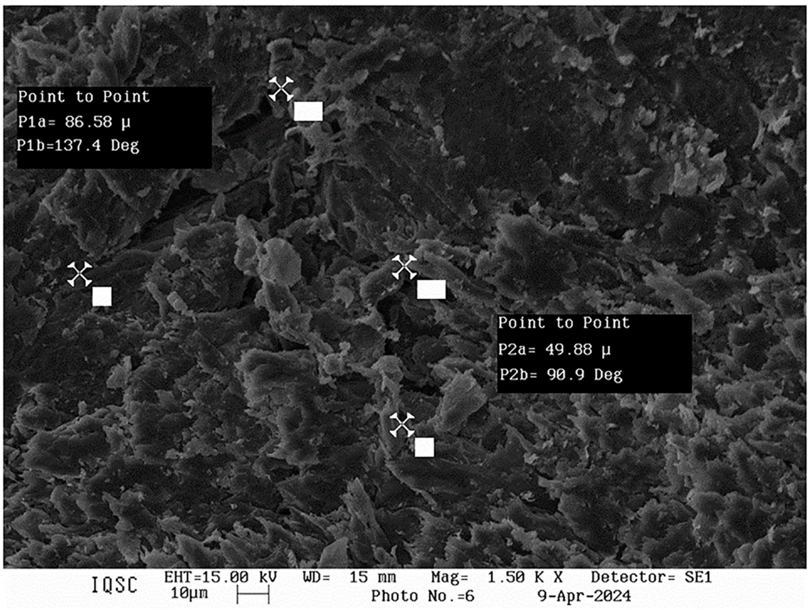

Figure 8: SEM photomicrograph at 1500× magnification of the panel sample with 0% carbon black in adhesive percentage.

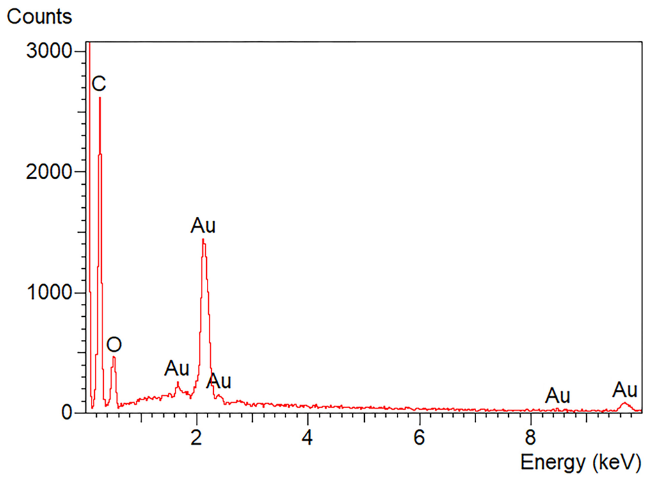

Figure 9: EDS spectrum of the panel sample with 0% carbon black in adhesive percentage.

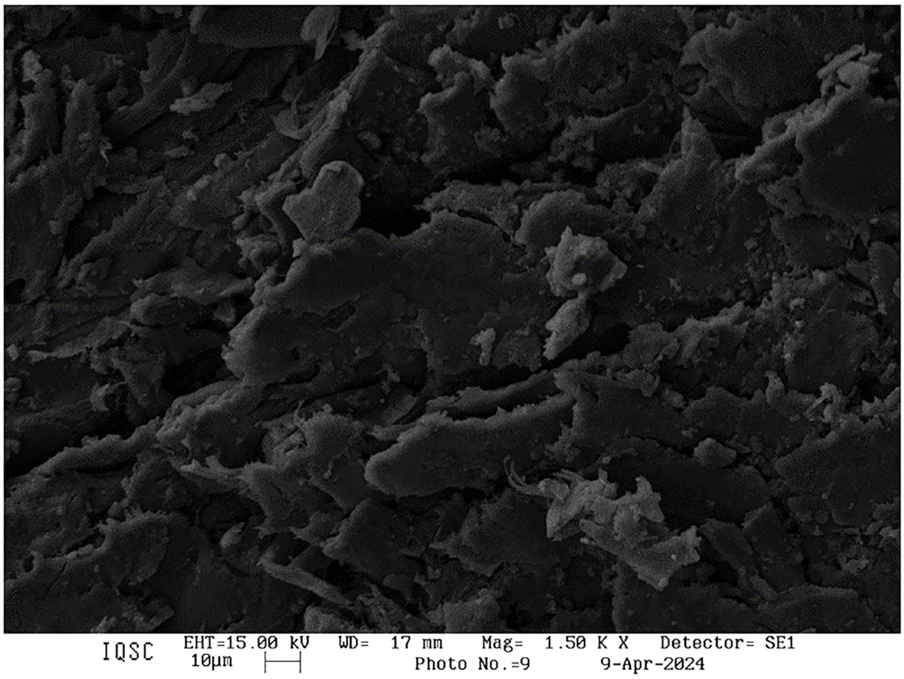

Figure 10: SEM photomicrograph at 1500× magnification of the panel sample with 2.5% carbon black as a percentage of adhesive.

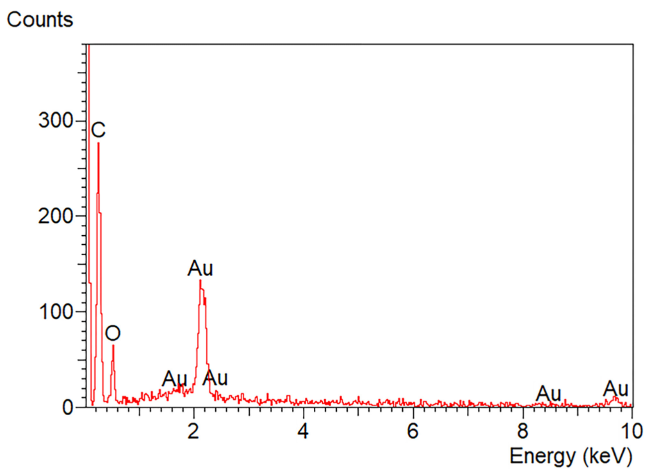

Figure 11: EDS spectrum of the panel sample with 2.5% carbon black in adhesive percentage.

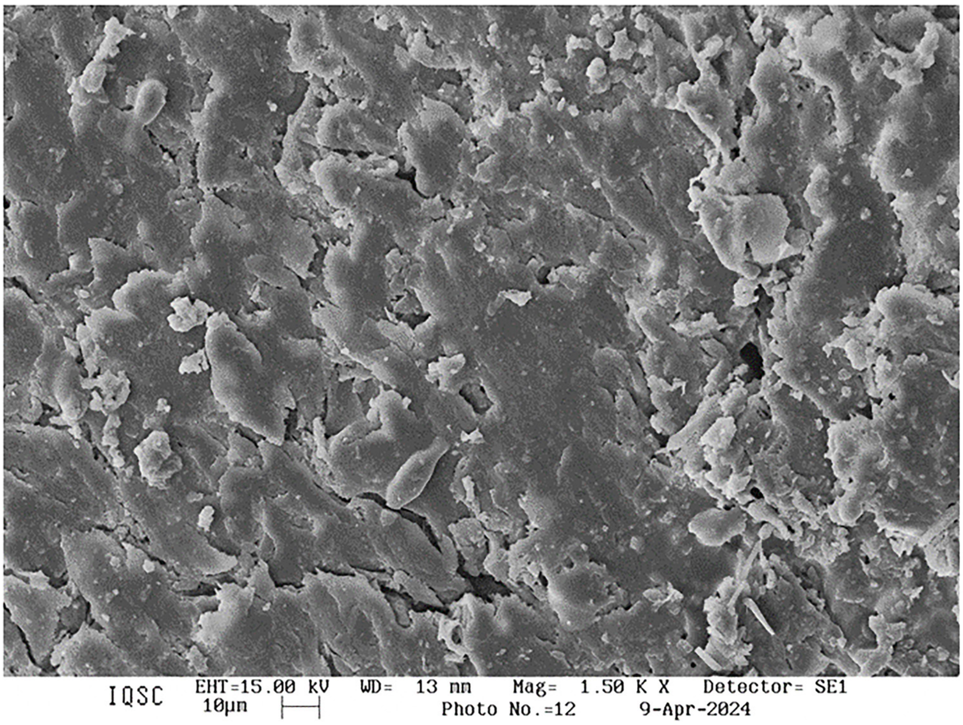

Figure 12: SEM photomicrograph at 1500× magnification of the panel sample with 5% carbon black as a percentage of adhesive.

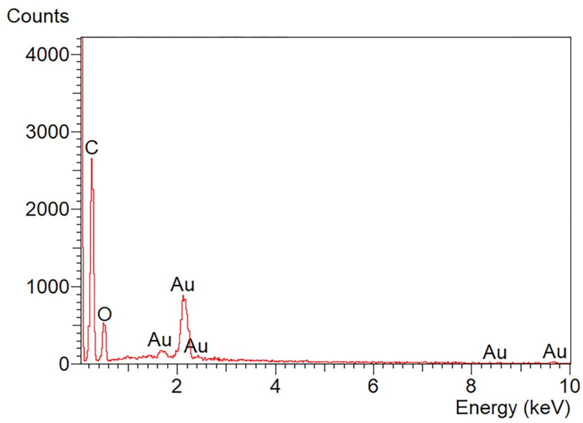

Figure 13: EDS spectrum of the panel sample with 5% carbon black in adhesive percentage.

Through SEM photomicrographs, it is possible to note that, in samples corresponding to panels with 0% to 15% CB, the surface quality is noticeably lower when compared to the same characteristic with the other photomicrographs, samples with 30% to 100% CB. Considering that the first group of samples contains a significantly lower amount of carbon black when compared to the second group, therefore, surface quality presents an improvement directly proportional to increase in carbon black amount added to the mixed adhesive.

Analyzing photomicrographs from 0 to 15% CB, it is observed a gradual improvement in the filling of voids, as well as a decrease in defects resulting from sample preparation, evidencing a growing mechanical interaction with increase in carbon black percentage in panels. When comparing samples with quantities lower than 15% CB with the last three samples (30% CB, 60% CB and 100% CB), decrease in the number of voids is noticeable, as well as the decrease in defects, such as: pores, cracks and lacerations.

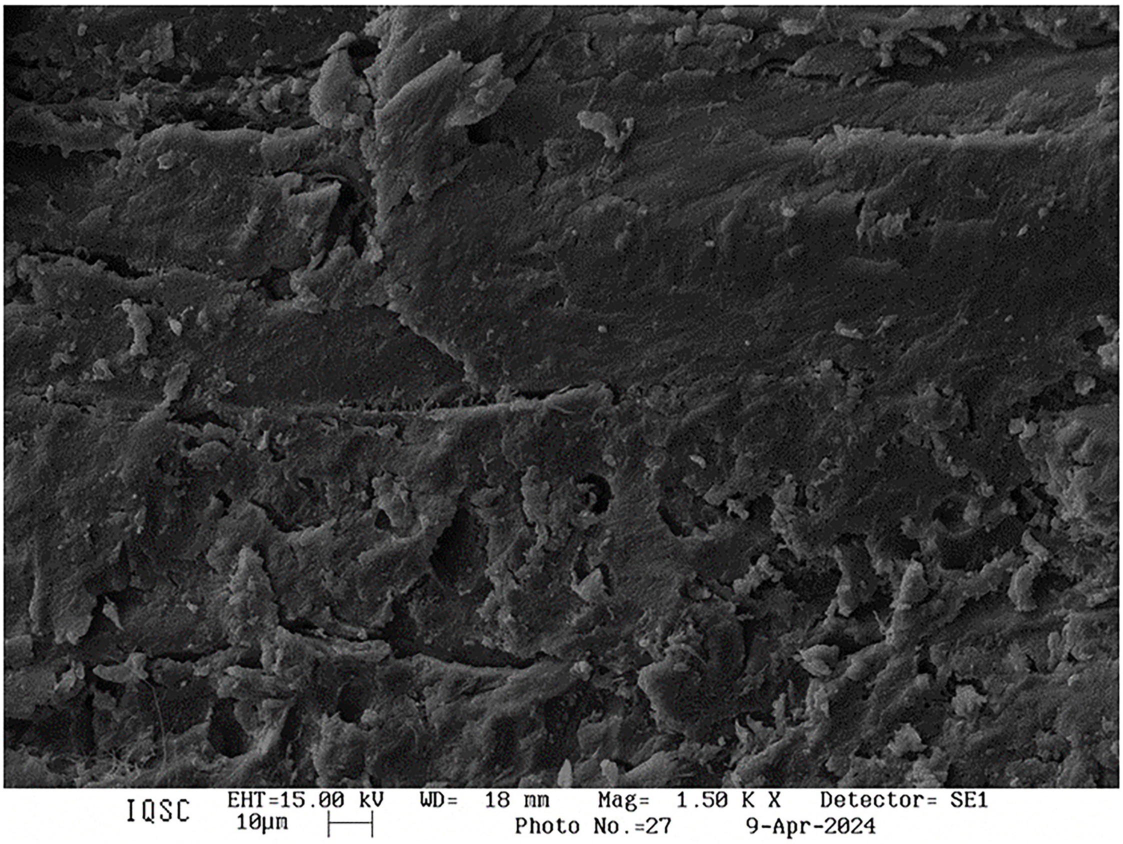

Figure 14: SEM photomicrograph at 1500× magnification of the panel sample with 10% carbon black as a percentage of adhesive.

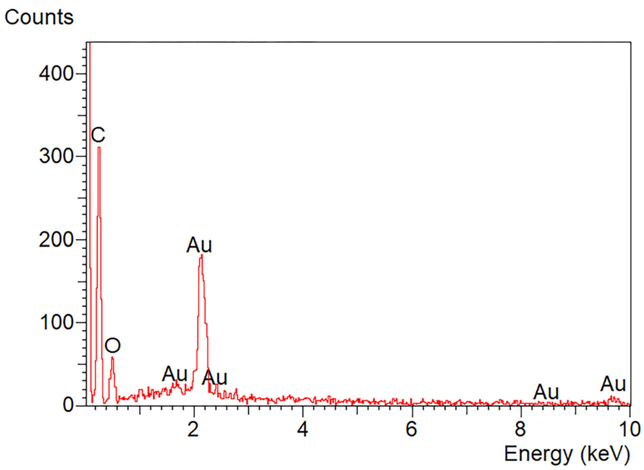

Figure 15: EDS spectrum of the panel sample with 10% carbon black in adhesive percentage.

3.3.2. Fourier Transform Infrared

Figures 24 to 30 show Fourier Transform Infrared (FTIR) Spectrum of panels evaluated in this research, discussed based on the characterizations of the chemical component bands.

Depending on carbon black production process, chemical structure of this material may contain surface functional groups, such as hydroxyls, carboxyls, phenols and quinones, which confer specific surface properties to the material. These chemical properties are important in interaction of carbon black with other molecules, such as polymers and solvents, which can be used to modify properties of the materials to which carbon black is added [22].

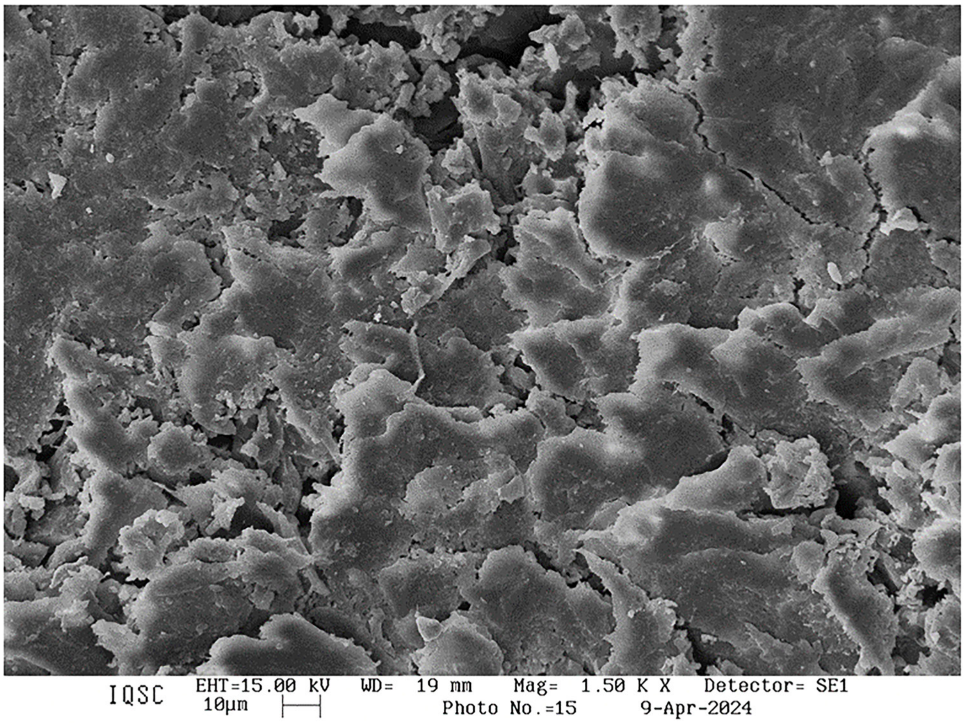

Figure 16: SEM photomicrograph at 1500× magnification of the panel sample with 15% carbon black as a percentage of adhesive.

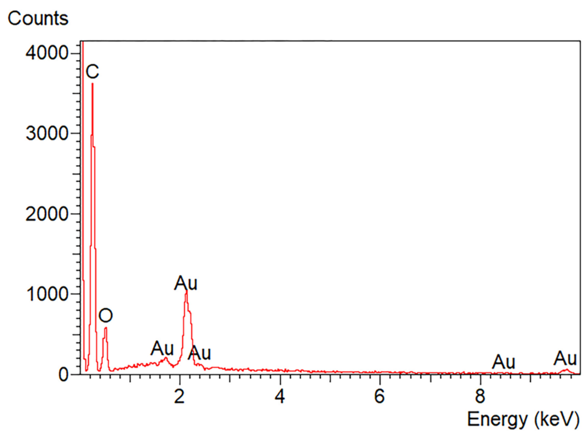

Figure 17: EDS spectrum of the panel sample with 15% carbon black in adhesive percentage.

However, carbon black absorbs not only electromagnetic radiation in visible region, but also in infrared and ultraviolet ranges. Absorption of ultraviolet radiation in carbonaceous materials is caused by electronic transitions between bonding and antibonding π orbitals. The (σ-σ*) transitions are expected in far ultraviolet between 60 and 100 nm, while the (π-π*) transitions are located in range between 180 and 260 nm. Incorporation of hydrogen into the internal structure of carbon black leads to an increase in sp^3 hybridized carbon [22].

The band in ultraviolet region caused by transitions (π-π*) can disappear at sp^2/sp^3 hybridized carbon ratios smaller than 1. In this case, absorption band (π-π*) loses intensity and is overlapped by the more intense band (σ-σ*). The characteristic spectrum of ultraviolet region is extremely sensitive to small changes in carbon black preparation conditions, which correspond to small changes in electronic structure of carbon black particles [22].

Through the spectra of samples with carbon black, it is possible to observe attenuation of absorption peaks, which is result of interaction of carbon black with the entire spectrum curve that had its peaks modified.

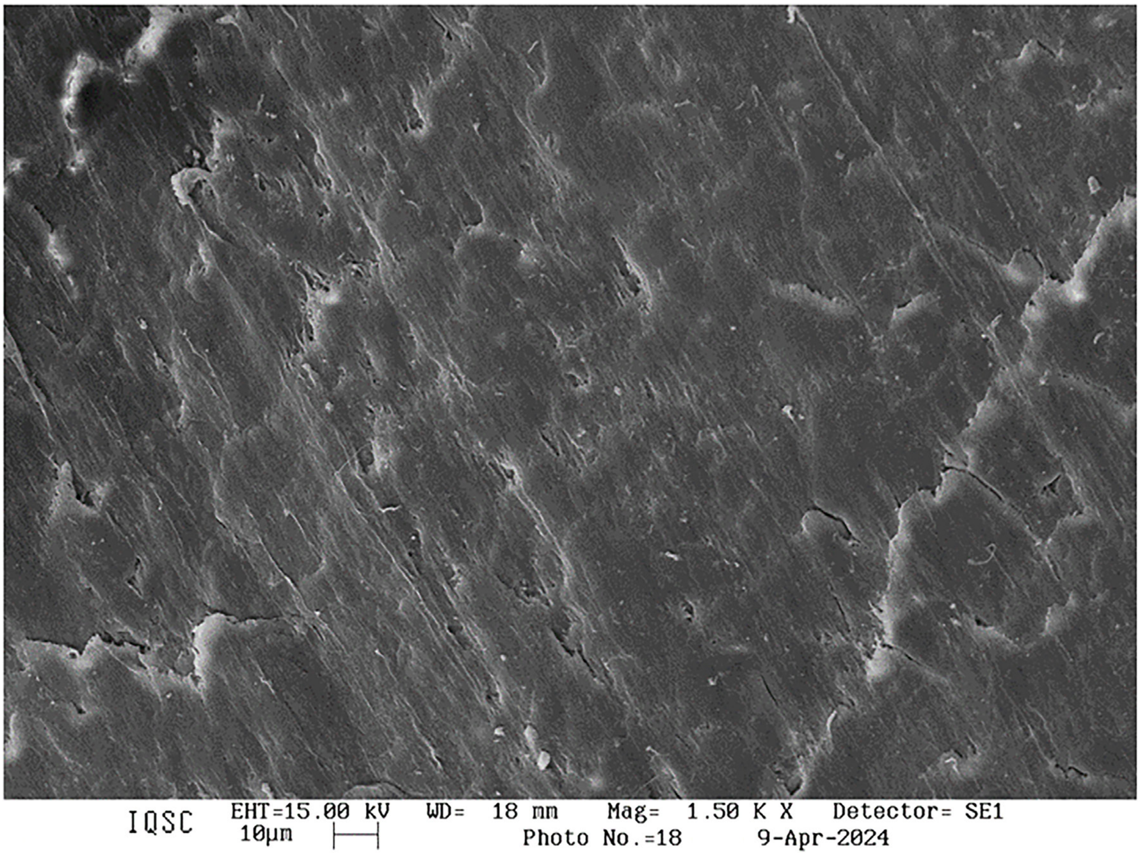

Figure 18: SEM photomicrograph at 1500× magnification of the panel sample with 30% carbon black as a percentage of adhesive.

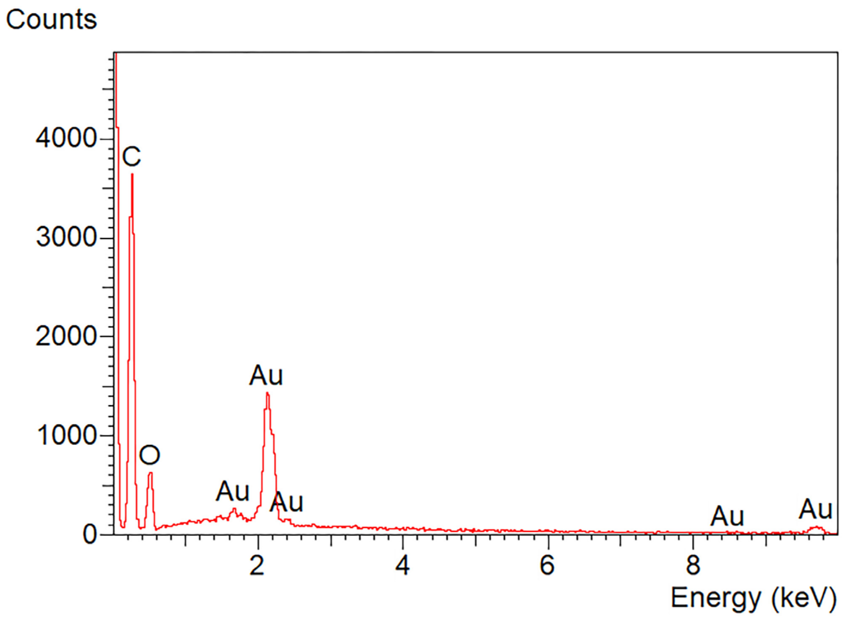

Figure 19: EDS spectrum of the panel sample with 30% carbon black in adhesive percentage.

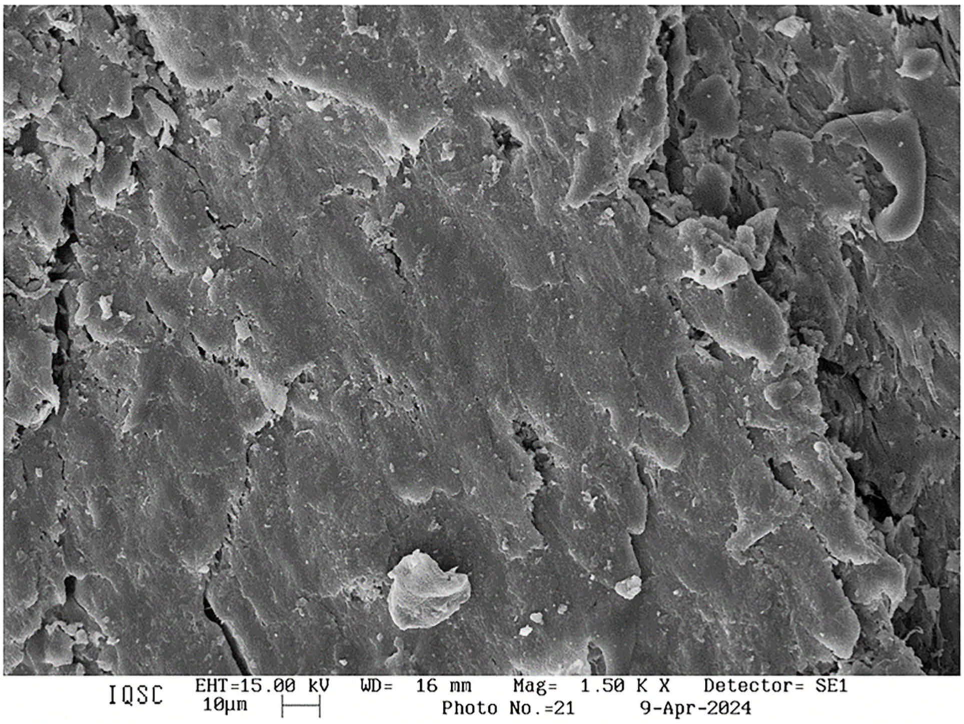

Figure 20: SEM photomicrograph at 1500× magnification of the panel sample with 60% carbon black as a percentage of adhesive.

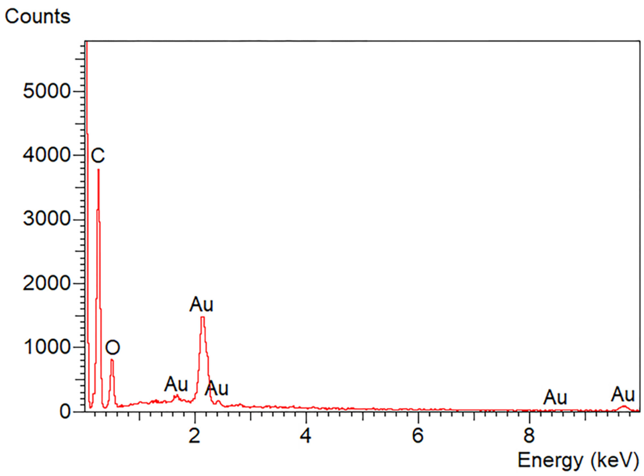

Figure 21: EDS spectrum of the panel sample with 60% carbon black in adhesive percentage.

It's possible to conclude that carbon black interacted with both adhesive and wood particles of the panels, causing new chemical structure formed by it not to absorb light emitted during FTIR test.

Considering Figure 24 as reference for characterization of the chemical groups present in samples, the wavelength range between 3610–3200 cm^{-1} is represents the cellulose present in wood particles. At wavelength of 1030 cm^{-1}, there are the cell wall compounds and, in range of 2960–2870 cm^{-1}, there are N-H groups present in cellulose and in mixed polyurethane adhesive. In wavelength range of 1450–1600 cm^{-1}, there are C-C bonds of wood aromatic groups and, in range of 1230–890 cm^{-1}, there is the representation of C-O and C-H groups of lignocellulosic particles.

With 2.5% carbon black added to polyurethane adhesive, it is possible to observe interaction of the manometric material with both adhesive and lignocellulosic particles, as can be seen in the difference in transmittance,

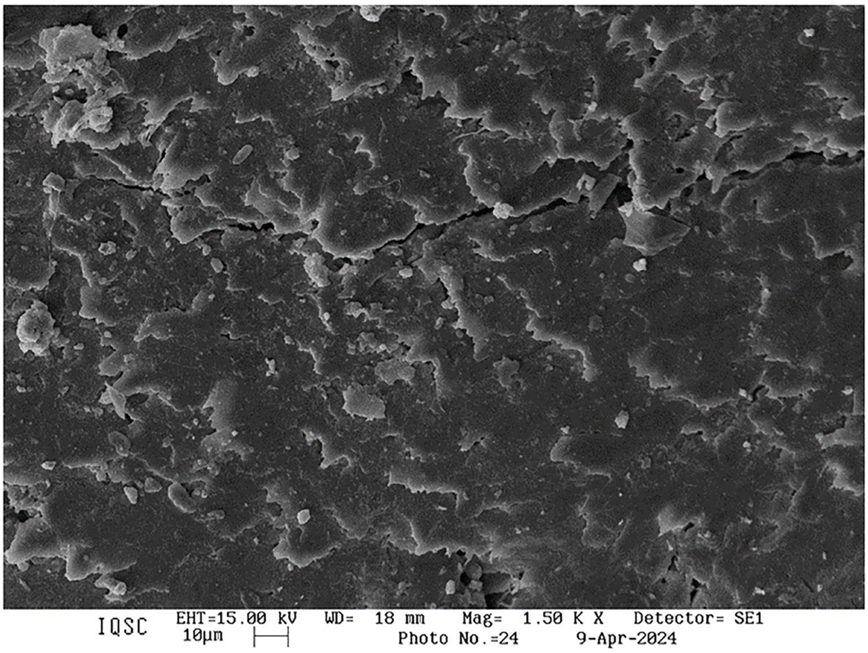

Figure 22: SEM photomicrograph at 1500× magnification of the panel sample with 100% carbon black as a percentage of adhesive.

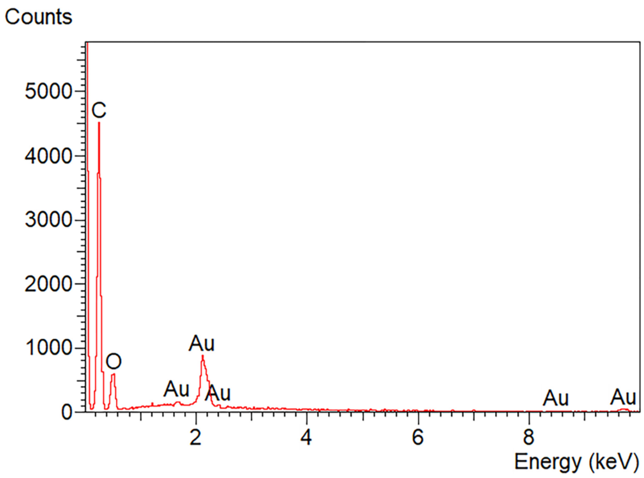

Figure 23: EDS spectrum of the panel sample with 60% carbon black in adhesive percentage.

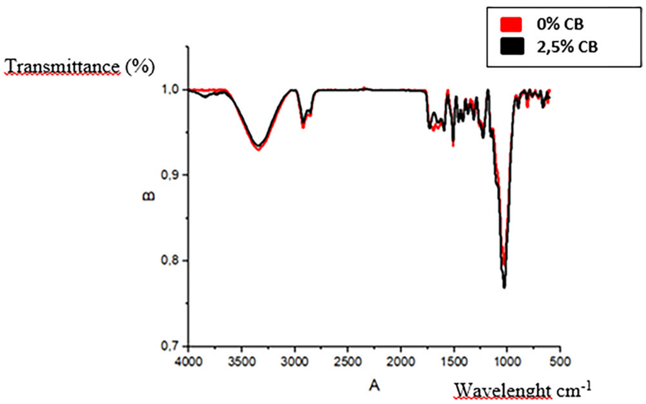

Figure 24: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 2.5% carbon black added to the adhesive.

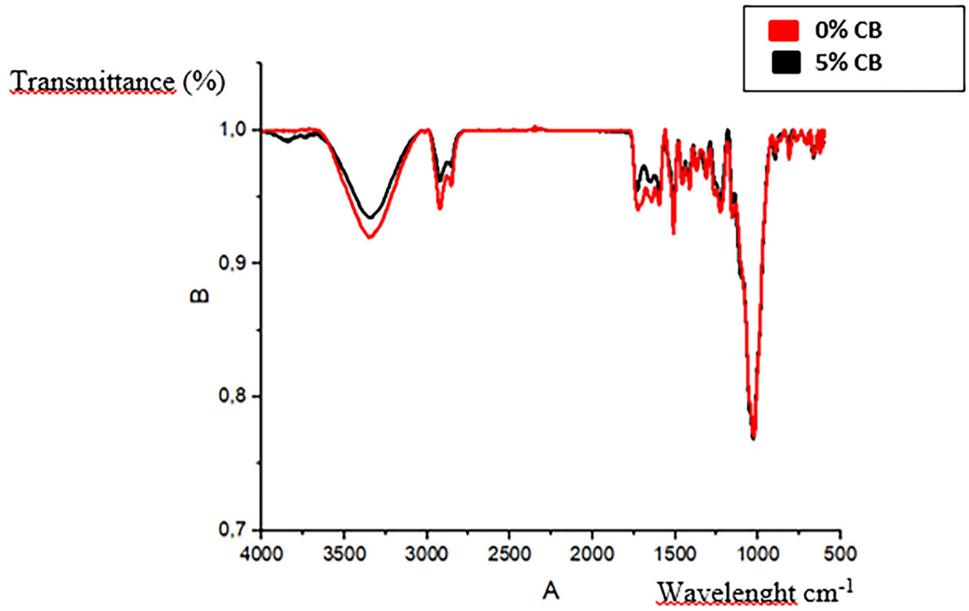

Figure 25: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 5% carbon black added to the adhesive.

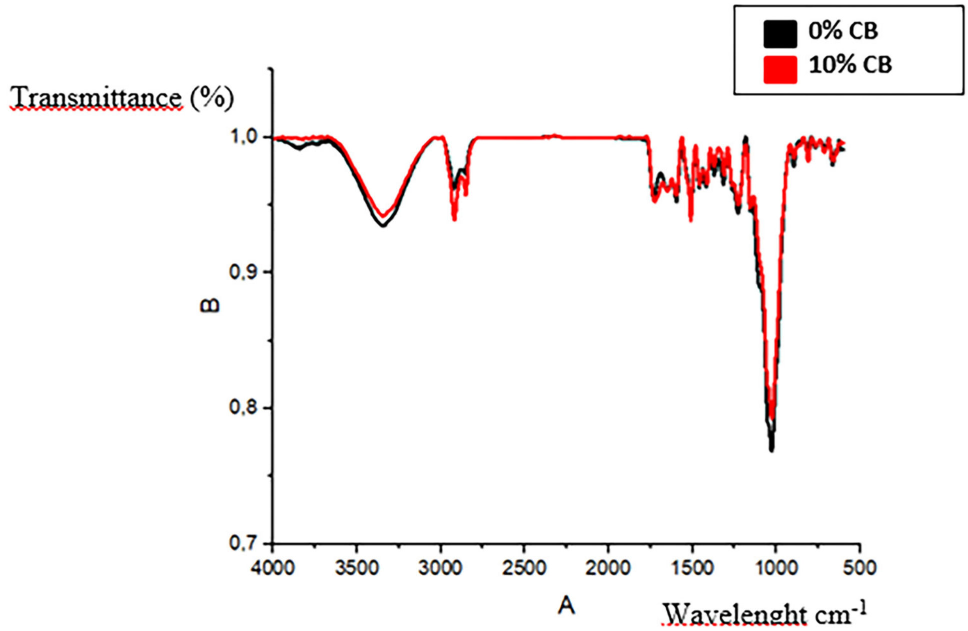

Figure 26: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 10% carbon black added to the adhesive.

which intensity is reduced by interaction of carbon black with both composite filler and its polymer matrix. This behavior is explained because carbon black does not absorb light used in spectroscopy test. By increasing carbon black concentration, spectroscopy peaks tend to decrease due to the increased interaction of carbon black with the composite phases.

As shown in Fourier transform infrared spectrometers, the higher the concentration of carbon black added, the greater its interaction with polyurethane adhesive and lignocellulosic particles. Thus, addition of carbon black to *Pinus* sp. wood panel was responsible for increasing values of panels mechanical properties, helping to classify them as the highest according to the regulations. Panels with 10% CB to 100% CB can be classified as P7 (Structural panels for use in severe load conditions, in humid environments).

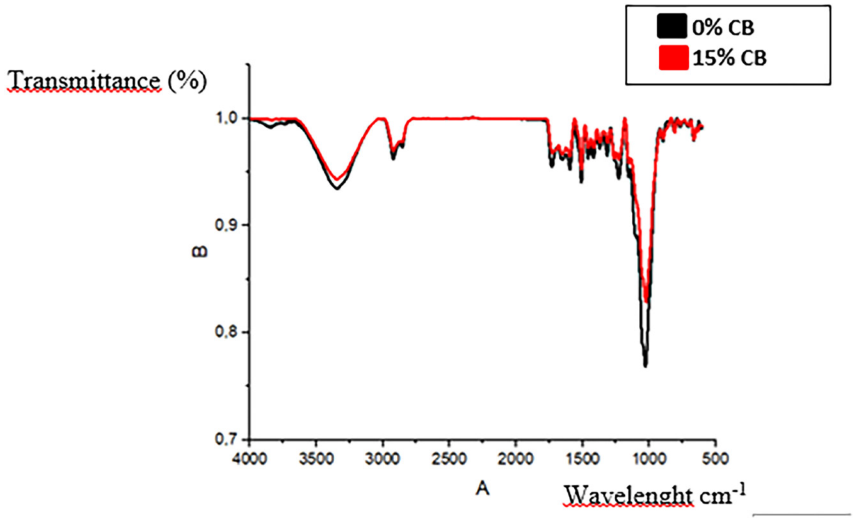

Figure 27: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 15% carbon black added to the adhesive.

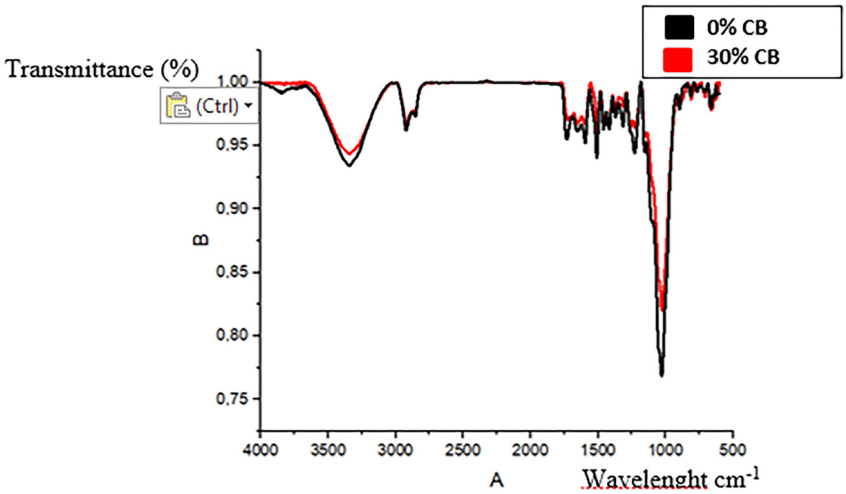

Figure 28: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 30% carbon black added to the adhesive.

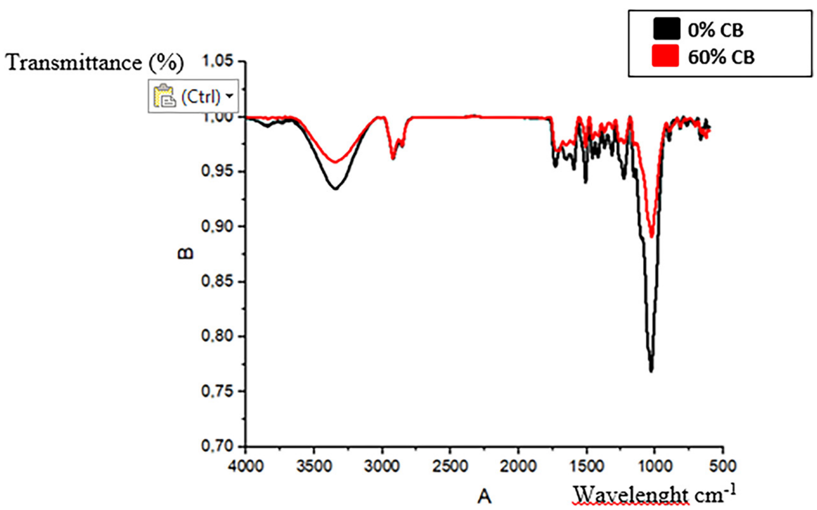

Figure 29: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 60% carbon black added to the adhesive.

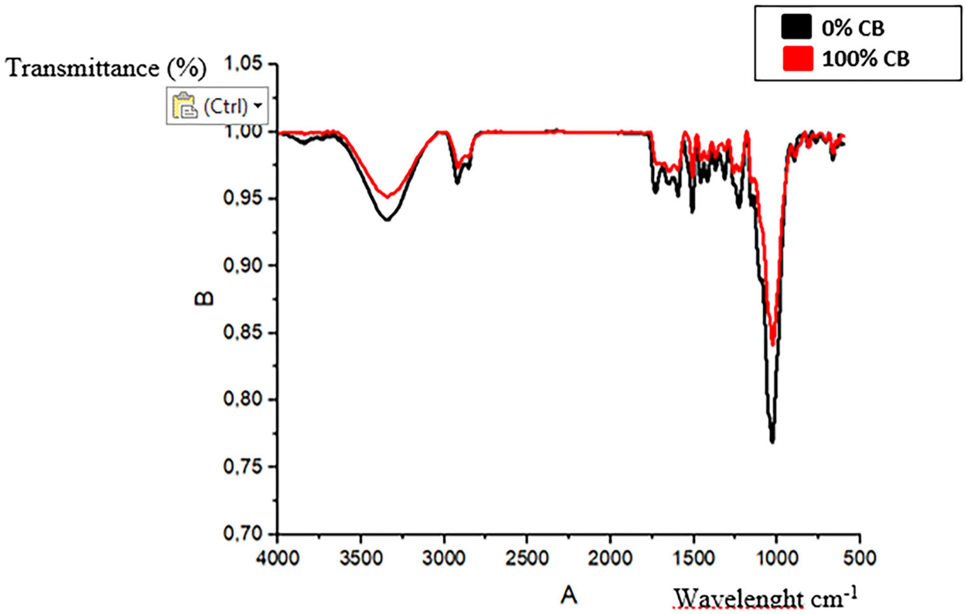

Figure 30: FTIR spectrum of *Pinus* sp. panel made with mixed polyurethane adhesive based on vegetable oils and with 100% carbon black added to the adhesive.

4. CONCLUSIONS

This study, aiming to investigate the influence of carbon black addition in mixed adhesive based on vegetable oils used to manufacture composite panels of *Pinus* sp. allows us to conclude that the referred addition resulted in statistically higher mean values for mechanical properties of the panels made with 30, 60 and 100% carbon black in adhesive percentage. Panels containing 30% CB showed comparable mechanical performance to panels with 60% and 100% CB, indicating no significant advantage in using higher CB contents.

Therefore, panels with 30% CB were the best evaluated, even with increase in water absorption, which in theory would harm dimensional stability of composite studied, classified as P7 (Structural panels for use in severe load conditions, in humid environments).

Carbon black, a nanometric by-product derived from end-of-life tires, shows potential as a reinforcing filler in the manufacture of sustainable wood composites, contributing to environmental sustainability. This research shows how important lignocellulosic composite panels are and how they contribute to sustainability, as they are composites produced with processed wood waste that is commonly discarded in the environment indiscriminately. Thus, wood panels are presented as a sustainable alternative to traditional materials used in civil construction, such as concrete, masonry and steel.

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