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Novel Sustainable Castor Oil-Based Polyurethane Biocomposites Reinforced with Piassava Fiber Powder Waste for High-Performance Coating Floor

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Abstract: The search for new greener materials that contribute to a more sustainable world motivated the present study in which novel biocomposites with 10, 20 and 30 vol% of piassava fiber powder waste reinforcing castor oil-based polyurethane (COPU) intended for a high-performance coated floor (HPCF) were developed. The novel biocomposites were characterized by flexural, Izod impact and wear standard tests as well as Fourier transform infrared spectroscopy (FTIR) and fracture analysis using scanning electron microscopy (SEM). Both flexural modulus and strength displayed marked increases reaching more than 800 and 500%, respectively, compared to plain COPU for 30 vol% piassava powder incorporation. FTIR bands indicated the existence of interaction between the piassava constituents and COPU. However, SEM fractographs disclosed the presence of bubbles attributed to retained gases during the COPU curing. Consequently, the Izod impact resistance showed a 50% decrease while the wear was more than three times accentuated for 30 vol% piassava powder biocomposite. These results met the specified values of corresponding standards and revealed a promising new greener material for HPCFs.

Keywords: castor oil polyurethane; natural fiber biocomposite; piassava fiber powder; high-performance coating; high-performance coating floor

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1. Introduction

In different kinds of activities, coatings are used to protect structures, goods and packaging from the aggressiveness of the environment mostly by providing special characteristics to the associated material. High-performance coatings is a generic term used to define coatings that provide great mechanical resistance along with other interesting features. These coatings must have particular properties in addition to mechanical resistance to ensure good protection against corrosion or to avoid the occurrence of cracks and fissures among other anomalies [1,2] without loss of performance throughout their life cycle. In particular, polymer resins are widely used as coatings in many industries from aerospace and automobile to pharmaceutical and food industries [3–5]. Resins normally used as high-performance coatings are actually polymer matrix composites reinforced by mineral aggregates, natural or synthetic fibers, as well as other fillers that provide great mechanical resistance along with high durability and waterproof conditions, together with any property of specific interest [6–8].

A particular case related to the civil construction common in Brazil is the high-performance coated floor (HPCF). Traditional floors are made of concrete plates with or without mortar and ceramic tiles. The joints in these floors pose problems such as biohazard contamination. This can be bothersome in places such as hospitals, and pharmaceutical

and food processing buildings. In contrast, polymer-based HPCFs are easy to apply and do not need a previously prepared surface when compared to traditional ceramic tiles. Moreover, HPCFs do not have joints as the polymer is primarily applied in the form of liquid resin over the entire floor. In fact, not only do HPCFs improve the floor's durability, provide oil or waterproof characteristics, and maintain its cleanliness, but they also enhance sports performance because of their good adherence properties when applied on stadium floors [9].

Although it is common to find marketing information for HPCFs, to our knowledge, studies on this subject are scarce and no relevant work has been reported in the literature for their use in civil construction. Therefore, the main objective of this work was to evaluate the potential viability of using the piassava fiber waste in such an application. Although some nanocomposites have shown promising results for HPCFs [9], the reinforcements used are usually from synthetic, non-renewable origins. The use of biocomposites reinforced by natural and renewable piassava fibers for this application would be directly beneficial for the environment. The Brazilian standard NBR 14050 [10] regulates the use of HPCFs made with epoxy resins and provides the requirements for their application, as shown in Table 1. In this table, the "critical" requirements are properties that can be found in other kinds of polymers and their composites.

Table 1. Summarized requirements of the NBR 14050 [10] standard for a material to be used as HPCFs.

Requirements	Value Recommendations
Thickness	3 to 10 mm
Maximum Water Absorption	1.0%
Minimum Compressive Strength	45 MPa
Minimum Flexural Strength	20 MPa
Maximum Abrasion	2.30 mm/km

Epoxy resins are the most common choice not only for HPCFs but also for paints, car components and aerospace parts because of their well-known properties and reliable characteristics [11–13]. However, the production of epoxy-based HPCFs generates the evaporation of large amounts of volatile organic compounds [14]. Moreover, the use of non-renewable source materials poses a long-term problem. Both the academic and the industrial communities have been striving to develop new sustainable materials [15–18].

An alternative to the use of petroleum-derived resins such as epoxy is material from natural sources. One example is polyurethane (PU) synthesized from oilseed plants. The synthesis of PU occurs in stages of polyaddition and from hydroxyl compounds and isocyanates. Hydroxyl monomers can be obtained from vegetable oils [19]. This is the case for castor oil-based polyurethane (COPU). The oil is extracted from the fruit of the "castor oil plant" (*Ricinus communis* L.) a relatively tall shrub from tropical regions that has been successfully used to obtain the COPU polymer [19,20].

Studies have shown some interesting properties of COPU. Santan et al. [21] created an adhesive based on COPU and evaluated both the microstructural relationships and mechanical properties of the new material. Zeng et al. [22] modified the asphalt used for paving roads with COPU and noticed improvements in performance and a reduction in the deformations of these coatings. In fact, COPU is a bi-component polymer composed of prepolymer and polyol, both of them easily found commercially, and characterized by not emanating toxic substances [23,24].

In parallel, several researchers in past decades have suggested natural lignocellulosic fibers (NLFs) [25–32] as composite reinforcement material, mostly owing to its attractive features such as good mechanical properties, low density cost-effective production and sustainable motivation. The environmental appeal of these materials can be further enhanced by adding industrial, residential or agricultural wastes as reinforcement of these composites [32–36]. Usually, natural lignocellulosic fiber (NLF) waste is burned during its

end-of-life cycle, and not only does the use of waste as a composite reinforcement or filler in natural source-derived resins directly reduce the cost associated with its disposal, but it also presents itself as a good alternative to materials with carbon neutral emissions.

One specific NLF commonly used in Brazil as a raw material in the manufacture of brooms for households is the piassava fiber. In the manufacturing process, the fibers are cut to a standard length, and those shorter are discarded and become disposable waste. These piassava fiber wastes have limited commercial use and are normally burned [37]. As an alternative, this fibrous waste can be further processed and ground to powder to be incorporated into polymer composites.

The use of piassava fiber powder, here referred as piassava powder for short, has shown some promising results. Borges et al. [38] initially ground the piassava fibers in a knife mill and sieved them at 50 mesh to incorporate as composite filler in a co-polypropylene matrix. They achieved satisfactory results of 35.5 MPa for the flexural strength, while those incorporated into a homopropylene matrix showed an even greater resistance of 47.7 MPa. These results revealed the possibility of using piassava powder as a reinforcement in polymer composites to be applied as an HPCF. Furthermore, a preliminary study [39] disclosed the great potential of the piassava fibers to be used as HPCFs. Indeed, the compressive strength obtained was around 50 MPa, and 0.8% of water absorption was found in 20 vol% of piassava powder-reinforced COPU.

Therefore, the present work aimed to continue the investigation into the use of piassava powder waste obtained as a processed material from a Brazilian broom factory, reinforcing a COPU biocomposite to be applied as an HPCF. In this study a comprehensive investigation was conducted not only to meet the NBR 14050 [10] standard recommendations, but also to perform a more extensive characterization of this HPCF material since, so far, there are no results to compare it to in the literature.

2. Materials and Methods

2.1. Materials

The piassava fibers used in this work were obtained as an industrial waste from a broom factory in the city of Campos dos Goytacazes, Brazil. After they were received, the fibers were washed in running water to eliminate any contaminant and put to dry in a stove for 24 h at 60 °C. For use as reinforcement material in HPCFs the piassava fibers were processed in a knife mill until the ground powder material passed through a 16-mesh sieve in accordance with the NBR 14050 standard [10]. Prior to the ground processing, however, a group of fibers was separated and went through preliminary characterization.

The polymeric matrix used in this study was the castor oil-based polyurethane (COPU) produced and commercially supplied by Imperveg, Brazil (Commercial tag AGT 1315). The COPU consisted of a bi-component. Both components—"A" (polyol) derived from castor oil and "B" (isocyanate)—were obtained as liquid. When the initiator (B) was added in A with 55% mass fraction, the polymerization process occurred and the resin hardened.

2.2. Methods

2.2.1. Characterization of the Piassava Fiber

The density, length and diameter distributions of the piassava fiber waste m reported in a previous work [39]. The density value of 1.42 g/cm^3 was used to calculate the volume fraction of reinforcement used on each composite in this work.

Initially, 100 fibers were randomly selected from the received batch (after the cleaning process) and had, one by one, their dimensions measured in a profile projector model PJ3150 made by Pantec (São Paulo, Brazil). These fibers were subjected to tensile tests in an Instron model 5582 universal machine with a 2.0 mm/min test speed at a controlled temperature of 20 °C. The test was conducted according to ASTM D3822-7 [40]. Adhesive tape was used on both ends of these fibers to avoid slipping as well as any damage that the machine grips may cause during the tensile test.

Images of the fiber surface morphology were obtained by scanning electron microscopy (SEM) on a microscope model SSX 550 made by Shimadzu (kyoto, Japan).

2.2.2. Biocomposites and Resin Processing

The biocomposites were made by adding the processed piassava powder in an already mixed component A and B resin, then leaving it at room temperature for 24 h in specific molds for the polymer cure to occur. Figure 1 illustrates the materials used in this study by showing the plain COPU Figure 1a and 30 vol% piassava powder Figure 1b,c biocomposites used for the abrasive wear tests as well as the material applied over a concrete surface. The piassava powder is black and the higher percentage of it added, the darker the biocomposites become. When applied over larger surfaces the material tends to form a smooth and even surface.

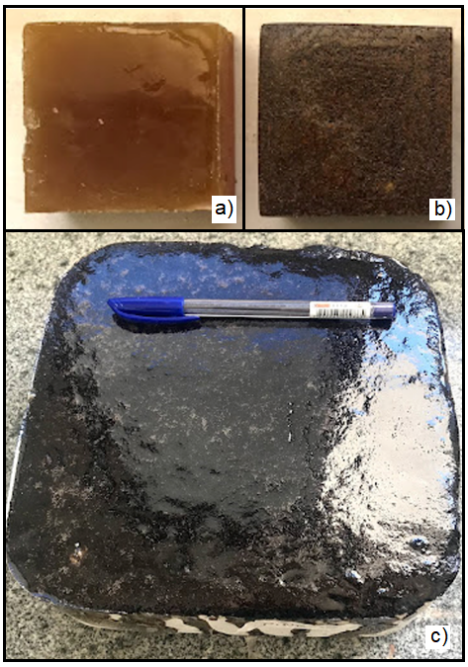

Figure 1. Plain COPU (**a**) and 30 vol% piassava powder biocomposite (**b**) samples used for abrasive wear tests, and 30 vol% piassava powder biocomposite applied over a concrete surface (**c**).

Biocomposite specimens were produced inside an open silicone mold. The molds were made according to the dimensions indicated by specific standards [40–42]. The piassava powder used in the preparation of the composites was dried in a stove for 24 h at 60 °C before the biocomposite preparation. To avoid excessive moisture absorption, the piassava powder was mixed with polymer, still heated to the polymer and finally poured inside silicone molds. After the 24 h period of curing, neat COPU, control with 0 vol% of piassava powder, and biocomposites made with 10, 20 and 30 vol% were demolded and the tests were carried out.

2.2.3. Tree Point Flexural Tests

The flexural tests were conducted according to ASTM C580 standard [40] on a universal machine model 5582 made by Instron (Norwood, MA, USA). For these tests, 10 rectangular cross-section samples with dimensions of 13 cm × 1.5 cm × 1.5 cm were used for each volume fraction of the biocomposites and the neat COPU resin, with a distance between the cleavers of 100 mm and a test speed of 1.3 mm/min.

2.2.4. Izod Impact Tests

For Izod tests, specimens were machined with dimensions of 150 mm × 120 mm × 10 mm. The specimens were then cut and polished to comply with the ASTM D256 standard [41] recommendations of 62 mm × 12 mm × 10 mm. Later a notch of 45° was made using a milling cutter and tests were conducted in a pendulum model XC-50 made by Pantec with a 22 J hammer. For each biocomposite studied a total of 10 samples were used.

2.2.5. Abrasive Wear Tests

Wear tests were conducted to determine the abrasion resistance of the material. Following the recommendations of the NBR 12042 standard [42], 70 mm × 70 mm × 30 mm samples were compressed with a constant and standard force against a circular-shaped track covered with sand, which ran at a specific speed. After a 500 and a 1000 m run the dimension difference was observed on the original 70 mm × 70 mm × 30 mm samples and the resistance was determined by the amount of material lost per distance.

2.2.6. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analyses were performed using attenuated total reflectance (ATR) on the piassava powder samples, COPU resin and its biocomposites. The equipment used was a spectrophotometer model IR-Affinity-1 made by Shimadzu, with a range interval of 4000–400 cm^{-1} and a resolution of 4 cm^{-1}, 32 scans. The preparation consisted of mixing the materials with KBr in order to increase the absorption signal.

2.2.7. Statistical Analysis: ANOVA and Tukey's Test

In some cases, the results obtained presented high statistical dispersion. In these cases, analysis of variance (ANOVA) was conducted with a 0.05 (5%) significance followed by Tukey's test if the results showed a *p*-value lower than the significance. Tukey's test is a complementary statistical analysis; the ANOVA results infer if there is difference between the analyzed groups (*p*-value < significance) while the Tukey's test shows which ones are different from each other.

2.2.8. Fracture Analysis

The fracture surfaces of the tested samples were analyzed by the scanning electron microscope (SEM) Shimadzu model SSX 550 (Shimadzu).

3. Results

3.1. Fiber Characterization

Well-known in the literature, piassava fibers, as seen in Figure 2, have oval-shaped cross-sections and a relatively high main diameter, as illustrated in Figure 2b. The surface morphology of the piassava fiber shows a rough surface and characteristic structures of spiny nodules made of pure silica (SiO_2) that occur in some spherical holes on the fiber surface [43,44]. These SiO_2 nodules are bonded on the fiber surface by weak hydrogen bridges. During the industrial processing steps, some of these nodules are lost, leaving a hollow cavity that provides good anchoring points for the polymeric resin [45]. This is an important feature since the hydrophilic characteristics of the piassava fiber, like those of many other NLFs, tend to form a week interface with hydrophobic polymer resins [25–36], thus creating defects that can accelerate the biocomposite degradation. All these structures were observed on the as-received fiber and are shown in Figure 2a. These structural morphologies were expected since there was no chemical treatment of the piassava fiber at any step of the broom production processes.

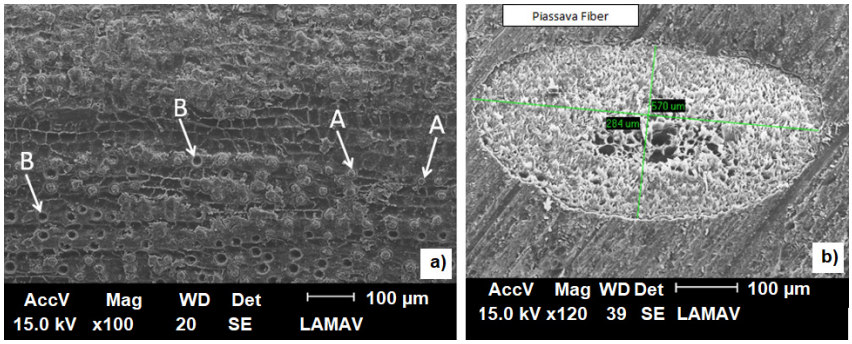

Figure 2. SEM photomicrography of the longitudinal surface of the piassava fiber (**a**) where the spiny silica spheres (indicated as "A") and some hollow holes (indicated as "B") and a cross-section of the piassava fiber (**b**) can be seen.

Regarding the mechanical behavior of the piassava fiber, the obtained tensile strength results of 87.9 ± 28.1 MPa and elastic modulus of 3.5 ± 1.2 GPa were similar to those reported in the literature [46], which corroborated the idea that, as expected, these fibers did not undergo significant changes during the broom manufacture process. Figure 3, obtained from SEM observations on the fracture surface, shows the characteristic rupture behavior of the piassava fibers. In this figure, the fiber cellulose microfibrils are ruptured in different regions, characterizing a non-uniform failure. Furthermore, Figure 3 displays a detailed image of the piassava fiber presenting columnar hollow lumen structures that justify its relatively low apparent density [39] and tensile strength with a great statistical dispersion.

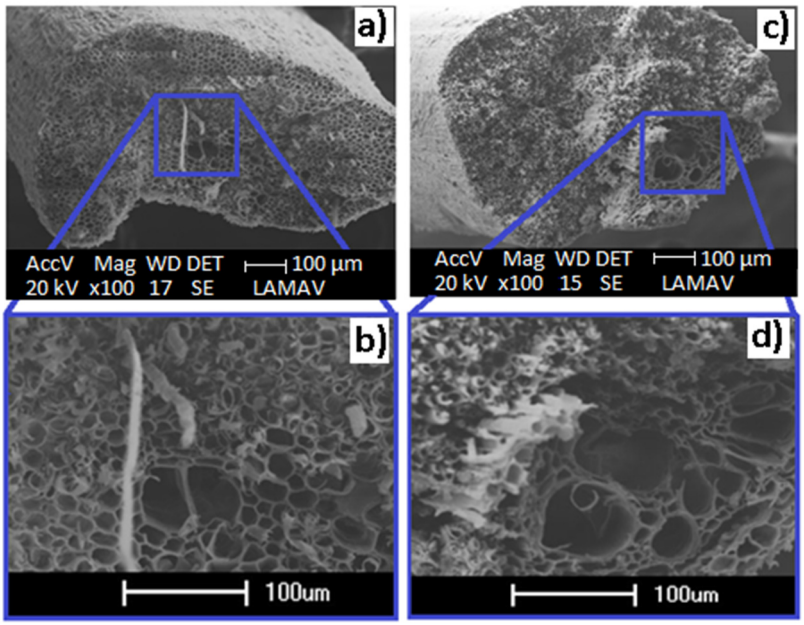

Figure 3. Surface of the fractures of piassava fibers at lower (**a**,**c**) and greater (**b**,**d**) magnifications.

Regarding the FTIR analysis of the piassava powder in Figure 4, the typical cellulose functional groups will appear around 3400 cm^{-1}—in this case, at 3317 cm^{-1}—and are related to OH groups that are linked in the main cellulose chain by a hydrogen bridge [47]. According to the literature [47,48], for CH aliphatic stretches of the methyl and methylene groups, the vibrations will be around 2936 and 2920 cm^{-1}, respectively, almost what was found for the piassava powder sample at the bands of 2930 and 2920 cm^{-1}. Furthermore, a band at 2116 cm^{-1} referred to a Si-H connection attributed to the spiny nodules on the fiber surface, already shown in Figure 2. This provided evidence that these structures

were present even after the broom manufacture processing. The bands at 1424, 1512 and 1608 cm^{-1} were attributed to the vibration and elongations in the O-C-O of the aromatic ring present in the lignin. Finally, it was possible to identify the three distinct units that formed lignin molecules: guaiacyl (1278 cm^{-1}), syringyl (1332 cm^{-1}) and *p*-hydroxyphenyl (875 cm^{-1}).

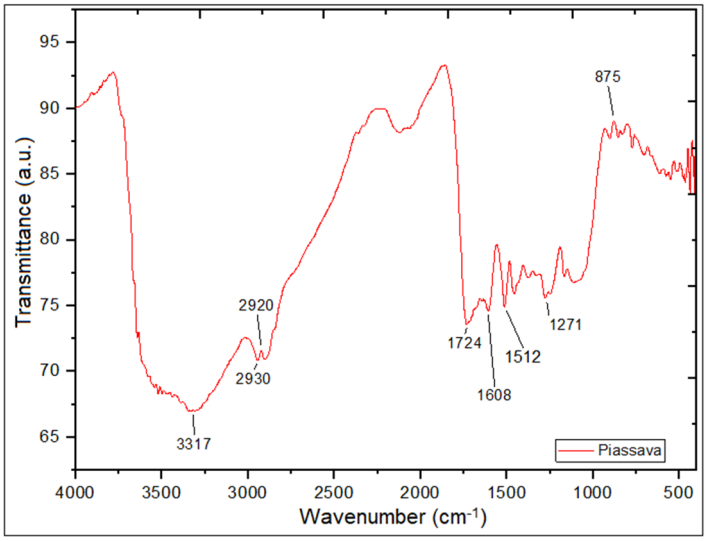

Figure 4. FTIR spectra of the piassava powder.

3.2. FTIR Analysis of the COPU Resin and Its Biocomposites

Figure 5 shows the FTIR spectra of plain COPU along with its piassava powder-incorporated biocomposites. As can be seen, the spectra obtained for the COPU biocomposites presented almost the same bands and were very similar to the COPU resin.

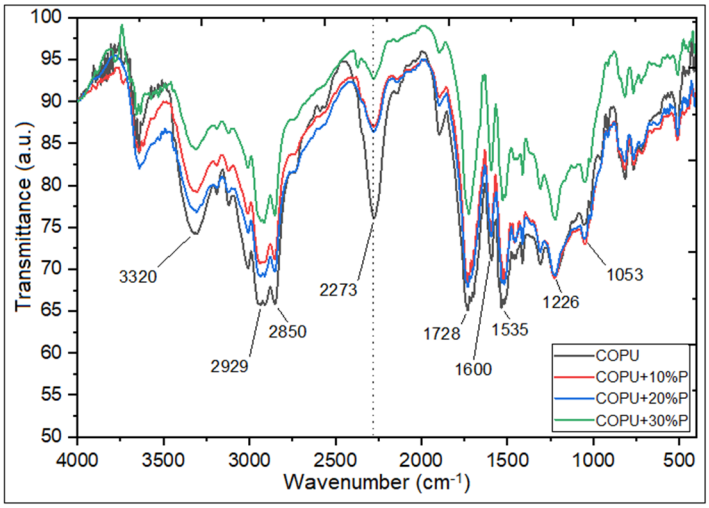

Figure 5. FTIR spectra for COPU and its composites reinforced by 10% (COPU + 10%P), 20% (COPU + 20%P) and 30% (COPU + 30%P) volume fraction of piassava powder.

It should be noticed in Figure 5 that the characteristic groups of the COPU resin were found, as reported by [49,50]. The bands at 3320, 2929 and 2850 cm^{-1} corresponded, respectively, to amine (NH), methyl (CH3) and methylene (CH2). The 1728 cm^{-1} band corresponded to the stretching of the pre-polymer carbonyl and, finally, the 1226 and 1053 bands corresponded to ether groups. The 2273 cm^{-1} band was attributed to groups of free isocyanates (NCO) in the COPU resin. Its presence indicated the excess of the NCO group in the polymeric structure. Moreover, as the amount of piassava powder increased

in volume, the 3317 cm^{-1} band (OH cellulose group) on the composites had its intensity diminished along with the 2273 cm^{-1} band (free isocyanates in the COPU resin). Indeed, at 30% volume fraction of piassava powder, the 3317 cm^{-1} band almost disappeared and the 2273 cm^{-1} band had its intensity drastically lowered.

The interaction between the cellulose and the free isocyanates was expected [50,51]. The FTIR results in Figures 4 and 5 suggested that, not only was the interaction occurring, but the level of interaction was also greater with higher amounts of piassava powder on the biocomposites, compared to lower volume fractions.

3.3. Flexural Strength

Figure 6 shows the flexural strength and flexural elastic modulus obtained for the COPU resin (0%), and the 10, 20 and 30 vol% piassava powder-reinforced biocomposites along with a statistical analysis of the data. It was noticed that, in all cases, none of the biocomposite materials was able to meet the standard requirements presented in Table 1. However, it was evident that the use of piassava powder significantly enhanced both the flexural strength and elastic modulus of the COPU matrix. Indeed, the 30 vol% reinforced composite presented a resistance more than four times and stiffness more than seven times greater than the plain COPU. Moreover, the results showed almost irrelevant data dispersion, which is not a common behavior for composites reinforced by NLFs.

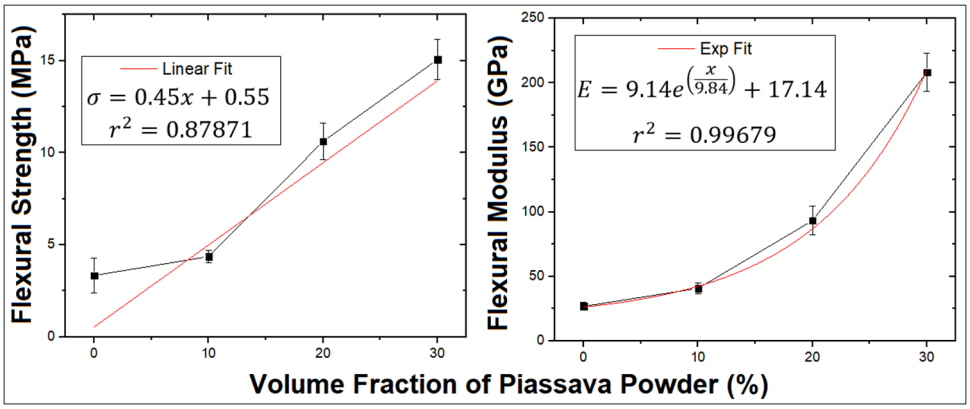

Figure 6. Flexural strength and elastic modulus for COPU resin and its composites along with linear fit of the results.

In fact, the COPU resin tended to present elastomeric characteristics, and the addition of reinforcement was enough, at least partially, to change this behavior [52]. Moreover, both good approximated linear fit (r^2 = 0.87871) and exponential fit (r^2 = 0.99679) indicated that the flexural strength and the stiffness, respectively, of the biocomposites could be further increased with higher amounts of piassava powder, enough to meet the standard criteria. In addition, the discussion of the FTIR results for the biocomposites indicated that not all the free NCO groups were completely bonded with the piassava cellulose OH, which indicated that more reinforcement could be added to the matrix without loss of strength of the interface between reinforcement and matrix. In contrast to what was observed in this work, piassava powder was reported to present a decrease of around 30% flexural resistance when incorporated with up to 30 vol% in other polymer matrixes [38], reaching around 30–35 MPa. This also suggested that the flexural strength of the composites can be enhanced, since the curves presented in Figure 6 showed a tendency to growth.

Figure 7 shows the fracture surface of the biocomposites. In this figure, we noticed the presence of bubbles on the matrix that were associated with existing retained gases during the polymer curing. On one hand, the use of the open mold tended to mimic the application of this composite as an HPCF. On the other hand, this also facilitated the appearance of defects such as the bubbles in Figure 7, which further explained the lower flexural strength than that required by the standard [10].

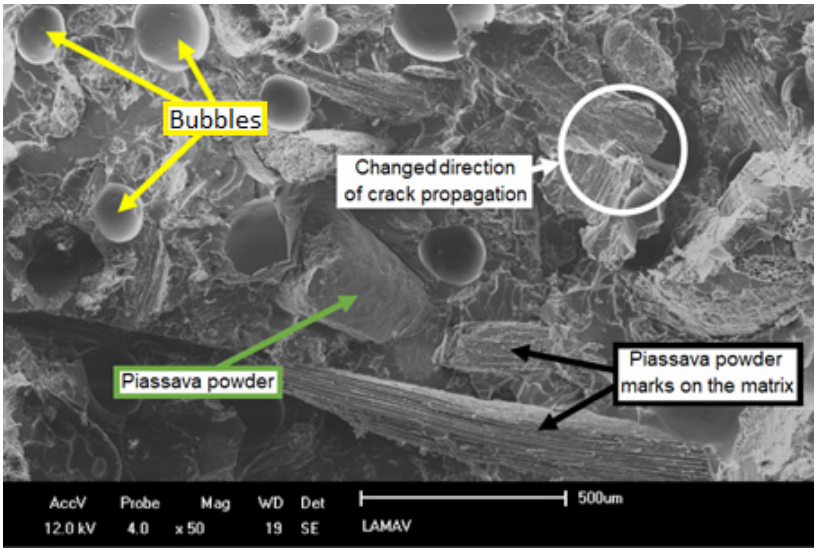

Figure 7. Surface of fracture for a 30% volume fraction reinforced by piassava powder COPU resin composites.

Regarding the crack propagation, also evidenced in Figure 7, it occurred on the matrix, as expected, by the change of direction when in contact with the reinforcement. The fiber powder marks presented on the matrix indicated a relatively stronger interface between reinforcement and matrix, which is not common on this kind of material, as already discussed.

3.4. Impact Resistance

As seen in Table 2, the addition of piassava powder to the COPU matrix tended to decrease the Izod impact resistance of the biocomposites. However, one may notice that, owing to greater data dispersion, almost all the conditions studied were statistically equal. Actually, with ANOVA tests, *p*-values of 0.0321 and 0.210 were obtained for notch resistance and impact resistance, respectively, which indicated that there was a statistical difference in at least one of the analyzed conditions for notch resistance and none for the impact resistance. In fact, the honest significant difference (HSD) of 14.59 was obtained on the Tukey's test for the notch resistance. This meant that only the 30 vol% reinforced COPU resin presented a significant HSD compared to the plain resin.

Table 2. COPU resin (0%) and its biocomposites' notch resistance and impact resistance obtained by Izod tests.

Volume Fraction of Piassava Powder	Notch Resistance (J/m)	Impact Resistance (kJ/m^2)
0%	69.0 ± 19.5	7.5 ± 2.7
10%	56.9 ± 7.1	5.6 ± 0.6
20%	52.8 ± 8.9	5.4 ± 0.9
30%	43.8 ± 4.6	4.0 ± 0.5

3.5. Abrasive Wear Resistance

Perhaps more important than the floor's ability to resist impact is its ability to withstand abrasion for long periods without wear loss. In this particular case, the biocomposites made with piassava powder reinforcing the COPU resin presented satisfactory results, since in all the cases studied the total material loss due to wear was lower than the standard requirements. The results in Table 3 show the amounts of material loss in wear tests after 500 and 1000 m on the abrasive track.

Table 3. Loss of material in the abrasive wear test for COPU resin (0%) and its piassava powder biocomposites after 500 and 1000 m on the abrasive track.

	Wear (mm) after Distance on the Track	
Volume Fraction of Piassava Powder	**500 m Distance (mm)**	**1000 m Distance (mm)**
0%	0.10 ± 0.06	0.28 ± 0.13
10%	0.47 ± 0.23	0.82 ± 0.30
20%	0.52 ± 0.05	0.97 ± 0.05
30%	0.59 ± 0.02	1.06 ± 0.11

The results in Table 3 show that the addition of piassava powder up to 30 vol% decreased by more than three times the wear resistance compared to the pure resin. This was somewhat expected for this kind of material since the interface between the two was relatively weak because of bubbles (Figure 7). Actually, by adding a material that creates a weak bond with the resin, the reinforcement should easily be pulled out from the matrix, leaving a hollow behind. In this scenario, the interface between the two phases should provide a weaker material. The fact that the biocomposites presented a total wear lower than half of the standard requirement from Table 1 revealed an interface that was moderately strong.

4. Discussions

From the results shown in this work the great potential of using piassava powder as a reinforcement in the COPU matrix for HPCF application was evident. Along with the results of a previous work [39], almost all standard requirements were attained. By comparing the results obtained for impact, abrasive wear and flexural strength with the results from FTIR analysis, there was space to improve the flexural strength of the material by further addition of piassava powder without greater loss of impact resistance and yet maintain the wear resistance at acceptable levels.

Finally, the use of the polyurethane material with approximately 60% volume fraction derived from castor oil (mass proportion use converted to the volume fractions) with a 30 vol% of piassava powder obtained as an industrial waste represented a biocomposite made almost 80% in volume from a renewable source. This alone represented a much greener solution compared to composites made with matrices or reinforcements from the non-renewable sources commonly applied in high-performance floors. Furthermore, the fact that the COPU resin used in this study was biodegradable, as well as the piassava powder, meant an environmentally friendly end-of-cycle alternative for natural materials.

To be used as HPCFs, according to the standard [10], the biocomposites are required to withstand a 10-year-long period. This can be a problem owing to the biodegradable characteristics of this biocomposite. However, the castor oil-derived polyol is reported to be antimicrobial, and the biocomposite itself can be designed to present a good resistance to biodegradability until its end of cycle [19]. Further studies should determine the life cycle times of these materials.

5. Conclusions

Novel sustainable castor oil-based polyurethane (COPU) biocomposites reinforced with piassava fiber powder waste were characterized for possible application as a high-performance coating floor (HPCF). The following conclusions were drawn:

FTIR results suggested interaction occurring between the piassava powder and COPU matrix.

Both flexural strength and modulus were substantially improved for the 30 vol% piassava powder biocomposite, with values reaching more than 500% the strength and more than 800% the stiffness of the plain COPU.

Izod notch impact resistance and absorbed energy displayed a tendency to decrease with the amount of piassava powder incorporated into the biocomposite. However, within

the statistical precision, the values might be considered unchanged up to 20 vol% of incorporated piassava powder.

The loss of material in wear tests was accentuated in biocomposites with the incorporation of piassava powder. However, the maximum attained value of 1.06 mm/km for the 30 vol% biocomposite was significantly lower than the maximum abrasion of 2.30 mm/km specified by the standard.

Preliminary results from greener biocomposites made of a castor oil-based polyurethane matrix added with a natural piassava industrial waste revealed a promising material for high-performance coating floors. Ongoing research is being conducted aiming to improve the mechanical resistance of the biocomposites by enhancing the adhesion between the piassava and polyurethane matrix.

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