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Eco-friendly piassava fiber reinforced composite for high performance coating application

Compósito eco-amigável reforçado com fibra de piassava para aplicação de revestimento de alto desempenho

Juliana Peixoto Rufino Gazem de Carvalho[1], Felipe Perissé Duarte Lopes[2], Noan Tonini Simonassi[2], Sérgio Neves Monteiro[3], Eduardo Atem de Carvalho[4], Carlos Maurício Fontes Vieira[4]

RESUMO

Os revestimentos de alto desempenho (RAD) podem ser utilizados como pisos, feitos a partir da mistura de substratos com resinas que hoje são aplicados por diversas indústrias brasileiras. A aplicação deste material está associada a alguns benefícios como rapidez de aplicação, alto desempenho mecânico e ausência de juntas de dilatação. A norma brasileira exige que a fabricação de RAD utilize resina epóxi e agregados minerais. Este trabalho, no entanto, teve como objetivo estudar o desempenho mecânico de um material semelhante, feito com a utilização de uma resina de poliuretano à base de óleo de mamona, ao invés de epóxi, misturada com fibras naturais de piaçava moída e determinar se é possível utilizá-lo como novo RAD. As fibras de piaçava foram obtidas como resíduo industrial de uma fábrica de vassouras localizada em Campos dos Goytacazes, Brasil. Foi realizada uma caracterização preliminar do resíduo fibroso para determinar sua densidade e as fibras foram submetidas a uma análise morfológica por meio de microscopia eletrônica de varredura (MEV). A absorção de água e a resistência à compressão do novo RAD foram determinadas e a superfície de fratura observada por MEV. Os resultados comprovaram a eficácia do uso de 20vol% de fibra, o que possibilitou a aplicação dessa composição como nova alternativa para RAD.

Palavras-chave: Óleo de mamona. Materiais Compósitos. Fibras Naturais. Compósitos Ecologicamente Corretos. Revestimento de alto desempenho.

ABSTRACT

High performance coatings (HPC) may be used as floors, made by mixing substrates with resin which are today applied in several types of floors by the Brazilian industries. The application of HPC floors is associated with some benefits such as speed of application, high mechanical performance and absence of expansion joints. The Brazilian standard requires that the manufacture of HPC uses epoxy resin and mineral aggregates. This work, however, aimed to study the mechanical performance of a similar material, made by using a castor oil based polyurethane resin, instead of epoxy, mixed with ground piassava natural fibers and determine if it is possible to use as a novel HCP. The piassava fibers were obtained as an industrial waste of a broom factory located in Campos dos Goytacazes, Brazil. A preliminarily characterization of the fibrous waste was carried out to determine its density and the fibers were subjected to a morphological analysis through scanning electron microscopy (SEM). The water absorption and compressive strength of the novel HPC were determined and the fracture surface was observed by SEM. The results proved the effectiveness of using 20% fiber, which made possible to apply this composition as HPC.

Keywords: Castor Oil Polyurethane, Composite Materials, Natural Fibers, Eco-friendly Composites, High performace coating.

1. INTRODUCTION

[1] Doutoranda. Engenharia e Ciências dos Materiais, Laboratório de Materiais Avançados (LAMAV), Universidade Estadual do Norte Fluminense (UENF), Campos dos Goytacazes, Rio de Janeiro, Brasil.

E-mail: julianarufino@pq.uenf.br

[2] Pós Doutorando. Engenharia e Ciências dos Materiais, Laboratório de Materiais Avançados (LAMAV), Universidade Estadual do Norte Fluminense (UENF), Campos dos Goytacazes, Rio de Janeiro, Brasil.

[3] Master e PhD em Ciência dos Materiais, Departamento de Materiais,Instituto Militar de Engenharia (IME), Rio de Janeiro, RJ, Brasil..

[4] Doutor. Docentes no curso de Engenharia e Ciências dos Materiais, Laboratório de Materiais Avançados (LAMAV), Universidade Estadual do Norte Fluminense (UENF), Campos dos Goytacazes, Rio de Janeiro, Brasil.

Natural fibers reinforced composites (NFRC) are today used worldwide in many consolidated industries such as automobile (MARTULLI et al., 2020; SIENGCHIN, 2017; WU et al., 2018), aerospace (KUMAR; HARIHARAN, 2019; LAU et al., 2018; MR et al., 2018). Recently, these materials are even suggested to be used as intermediate layer in multilayered ballistic armor systems (GARCIA FILHO et al., 2019; GARCIA FILHO; MONTEIRO, 2019; NEVES et al., 2019; PEREIRA et al., 2017). Moreover, the use of this type of material are becoming even more widespread as the mechanical, economic and ecological benefits are revealed (MADHU et al., 2020; ROBLEDO‐ORTÍZ et al., 2020; WU et al., 2018).

In the Brazilian construction sector, it is usual to use high performance coating (HPC) on floors when there is a need for improved and durable requirements but also easy to apply coating (MASSON et al., 2017). Indeed, The HPC can be easily applied in most surfaces, even if it presents some irregularities, with almost no previous preparation unlike traditional concrete floors or modular floor systems (slabs) (SANTOS et al., 2016; TEIXEIRA et al., 2019). Another advantage of HPC is that it is produced at the place of use which leads to greater practicality and absence of joints. In addition, since these joints on the floor can be a site for proliferation of bacteria, HPC presents less biohazard risks.

According to Brazilian standard, specifically the ABNT – NBR 14050 (NBR14050, 1998), “High performance coating systems based on epoxy resins and mineral aggregates - Design, execution and performance evaluation”, HPC are limited to a mineral aggregate reinforced epoxy resin systems. Furthermore, the standard requirements are a water absorption lower than 1% and a minimum compressive strength of 45 MPa. The the standard also indicates that the water absorption and the compressive strength are to be obtained according to ASTM C 413 (ASTMC413, 2013) and ASTM C 579 (ASTMC579, 2013), respectively.

The use of epoxy resin for a large scale production of HPC, in fact, represents a cheaper and easy alternative to conventional building methods. However, it is known that this type of synthetic matrix produces serious harmful effects both on the environment and on the people who handle it (BOSCH et al., 2016; HUANG et al., 2012; KUNDAKOVIC et al., 2013; REZG et al., 2014; VOM SAAL; MYERS, 2008). Therefore, the scientific community is constantly looking for solutions that are safer, and environmentally friendlier by using plant based resins (ABDEL-HAMID et al., 2019; ELLENBERGER et al., 2019; GIGANTE et al., 2017; MAZZANTI et al., 2019). In addition, the use of natural lignocellulosic fibers (NLFs) reinforcement might leads to a production cost reduction, as these fibers are often underused (ABDEL-HAMID et al., 2019; VINAY REDDY; BHARATHIRAJA; JAYAKUMAR, 2019; YADAV; GUPTA, 2019) and combine low cost and density with relatively good mechanical properties (ELLENBERGER et al., 2019; MADHU et al., 2020; ROBLEDO‐ORTÍZ et al., 2020; WU et al., 2018; YUVARAJ; JEYANTHI; BABU, 2018).

One interesting type of natural lignocellulosic fiber (NLF) is the piassava fiber. Originally from the Brazilian Atlantic forest region the piassava is a fiber with relatively high rigidity, elastic modulus around 5.5-6.3 GPa, and tensile strength higher than 100 MPa (FERREIRA; NASCIMENTO; MONTEIRO, 2018; NUNES et al., 2017) these natural fibers are capable to sustain its own weight without bend, even in fibers with long lengths (more than 30 cm). Indeed, the high rigidity alongside with high availability as well as low cost and easy production technology are some advantages responsible for the use of this material as brooms in Brazilian homes.

In the production of these brooms, the piassava fibers are cut in a standardized size. As consequence, a large amount of about 42% of these fibers become waste (CONAB, 2020; GARCIA FILHO et al., 2019; PIMENTEL; DEL MENEZZI, 2020) and are commonly discarded in landfills or burnt. Therefore, the objective of this work is to determine if these piassava fiber waste can be used as raw material in HCP systems using a castor oil based polyurethane resin as matrix. The use of a plant-based resin alongside a NLF reinforcement is a good sustainable alternative to replace traditional inorganic HPC systems. In the present investigated novel HPC both materials are renewable.

2. MATERIALS AND METHODSS

The materials used in this work were a polyurethane resin (PU) derived from castor oil, provided by the company Imperveg, Brazil, (Fig. 1a) and piassava fiber (Fig. 1b) acquired from a broom manufacturer in the city of Campos dos Goytacazes, Brazil, as industrial waste.

Initially, the collected residue was washed in running water and dried in an oven at 60ºC for 48h. In order to determine the dimensions of the fibers, a sample of one hundred randomly selected fibers were extracted from the batch and measured. The length was measured, on each fiber, with a 60 cm steel ruler and a profile projector Nikon model 6C was used for the diameter determination.

Figure 1. Castor oil based polyurethane resin (a) and the piassava Industrial waste fibers (b).

To calculate the density of the piassava residue, the fibers were idealized as a cylinder and the mass of each fiber was divided by its volume calculated after its dimensions determination. The density of piassava fibers was also obtained by the distilled water pycnometry method using two 50ml pycnometers in the Soil Laboratory at State University of Northern Rio de Janeiro (LSOL-CCTA). In this method, the density of the fiber is determined by dividing a mass of fibers by the amount of water dislocated by the volume of the same fibers when inserted inside the pycnometer.

To use the material as HPC, the piassava fibers after the cleaning process were shred in a knife mill. The maximum diameter of the fiber particles used in this work were 1.2mm, obtained by in a 16 mesh (approximately 1.2 mm of opening) sieve. Figure 2 shows the separation process of the piassava fibers after the shred process.

Figure 2. Piassava fiber particles after the shred process.

To simulate similar situations that common HCP materials are normally used, composites were made in open silicon mold by mixing the shred piassava fibers and the resin together. The shred piassava fibers were dried in a stove at 60°C for 24h to be later mixed with resin and left inside cylindrical silicone molds for another 24h. The proportion of piassava used was calculated based on the density value found by the pycnometer method described prior in section 1.1 of this work. Finally, samples of pure resin and composites reinforced by 10, 20 and 30% volume fraction of fibers were made separately for compression strength and water absorption tests.

Composites specimens were made for compressive strength tests according to the ASTM C579 standard. The specimens were made with pure resin and composites reinforced with 10, 20 and 30% volume fraction of shred piassava fibers. Compression tests were conducted in a Instron machine model 5582 at a 10 mm/min deformation rate in a controlled temperature of 25°C. Figure 3 (a) shows the cylindrical specimens used in this work for the compressive strength tests. The water absorption tests were carried out following the specifications of the ASTM C413 standard (ASTMC413, 2013). Initially, the specimens were dried in a stove and, subsequently, immersed in boiling water with the aid of a wire cage (Fig. 3b), in order to keep all the specimens fully submerged and boiled for 2 hours. Finally, the water absorption was calculated by dividing the amount of water absorbed on each specimen by its dry mass according to the standard.

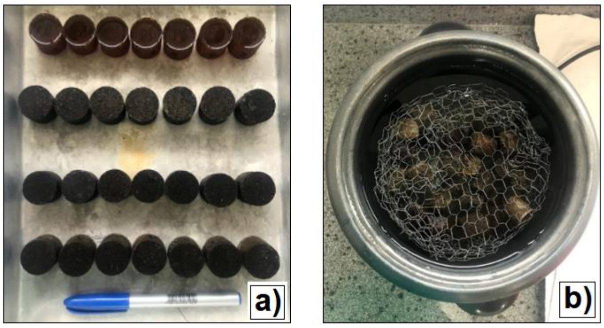

Figure 3. Composites specimens made for the compressive strength tests (a) and the boiling composites for the water absorption tests (b).

The morphology of the piassava fibers and the fracture surface of the compression tested composite specimen were observed by scanning electron microscopy (SEM) techniques using a microscope Shimadzu model SSX 550.

3. RESULTS AND DISCUSSION

3.1. FIBER RESIDUE SURFACE AND DIMENSIONS

Figure 4 shows the SEM images of the piassava fiber before it was shred and used as resin reinforcement. In this image it is possible to observe the characteristic irregularities of the piassava fibers. Indeed, the fiber surface presents spiny protusions previously identified as made of pure silica (GARCIA FILHO; MONTEIRO, 2019;

MIRANDA et al., 2015; NASCIMENTO et al., 2012), which are preserved even after all the handling and processing that these fibers went through during the manufacture of brooms at the factory. However, as seen in Figure 4 (b), some of these protusions are missing leaving concave holes that may serve as possible anchor capable of improving the fiber/resin interface. These piassava fiber surface irregularities are one of the factors responsible for a higher strength in piassava reinforced composites.

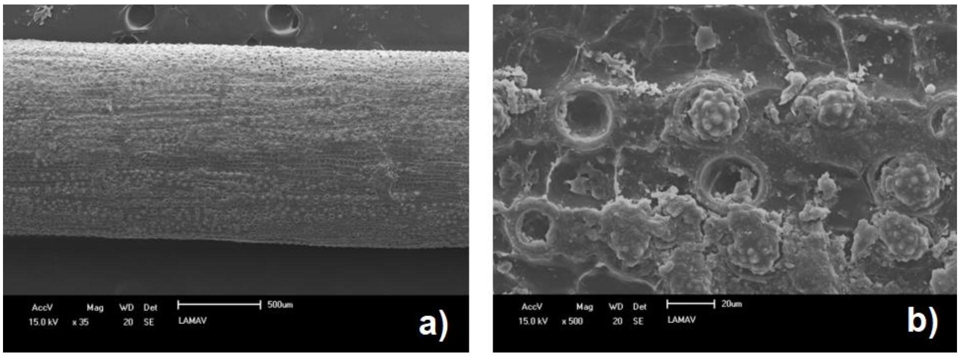

Figura 4. SEM Images of the piassava fiber for lower (a) and greater (b) magnifications.

Another important factor that influences the mechanical strength of the NLFs is the diameter distribution where the thinner fibers are usually the strongest (NASCIMENTO; LOPES; MONTEIRO, 2010; ROHEN et al., 2018). The collected piassava waste presented its diameter distribution mostly between 0.6-1.2 mm where more than 40% occurring between 0.8-1.0 mm. This fact is common because it is related to the heterogeneity of NLFs. Unlike synthetic fibers, NLFs have characteristics according to external factors such as climate, fiber collection position, source soil, cutting time among others. The measurement found in this work are similar to that found in the literature where reported ranges of main diameters vary between 0.40-0.88 mm (LOPES et al., 2012; MONTEIRO, 2009). Therefore, piassava is considered to be a coarse fiber, especially when compared to other NLFs as shown in Table 1. For the length of the residue, it was found that after the cutting process of the piassava in sufficient dimensions for the manufacture of the brooms, the residue varies significantly in length, thus not having a great regularity of measurement. Indeed, more than 85% of the waste piassava fiber length distribution occur between 20 to 32 cm and more than 25% of it occur between 24-26 cm. Figure 5 shows the diameter and length distribution of the batch studied.

Table 1. Diameter and density comparison for different NLFs according to the literature.

Natural Fiber	**Main diameter (mm)**	
Jute	0.015-0.025	(LIU et al., 2018; MOHANTY; MISRA, 1995)
Bamboo	0.025-0.162	(GUIMARÃES JUNIOR; NOVACK; BOTARO, 2010; PERREMANS et al., 2018)
Sisal	0.113-0.300	(GARAT et al., 2018; LI et al., 2015)
Curaua	0.092-0.114	(TEIXEIRA et al., 2019; TERASAKI; NODA; GODA, 2009)
Banana	0.131-0.167	(FERRANTE; SANTULLI; SUMMERSCALES, 2019; SINGH; MUKHOPADHYAY, 2020)
Piassava	0.400-0.880	(FERREIRA; NASCIMENTO; MONTEIRO, 2018; LOPES et al., 2012; MONTEIRO, 2009)
Piassava residue*	0.800-1.000	*This work

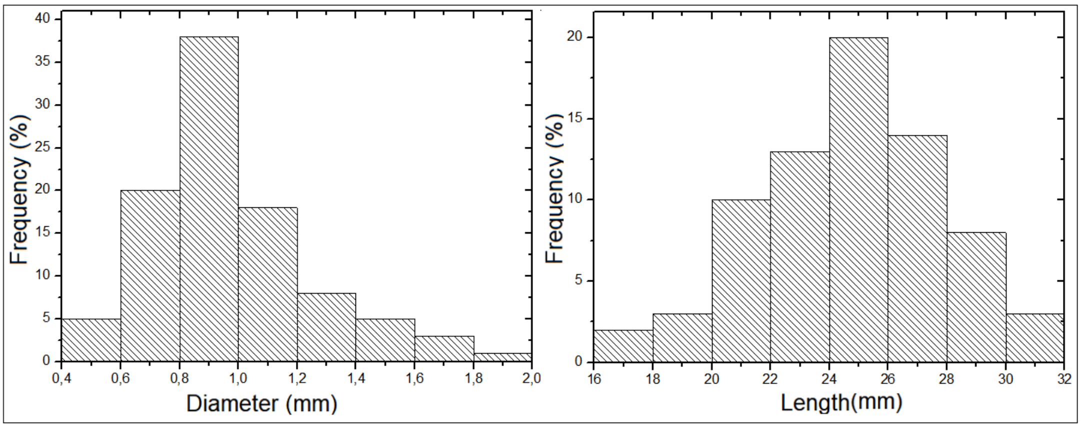

Figure 5. Diameter and length distribution of the piassava fiber residue.

3.2. FIBER RESIDUE DENSITY

The densities found in this study by dividing the weight by the volume for each fiber are presented in the Figure 6. As can be seen, the piassava fiber density distribution is concentrated mostly between 0.9-1.4 g/cm³ (around 85%) with almost half (47%) of the analyzed batch presenting a density range variating between 1.0-1.2 g/cm³, which is very similar to values found in the literature (ELZUBAIR et al., 2007; MIRANDA et al., 2015).

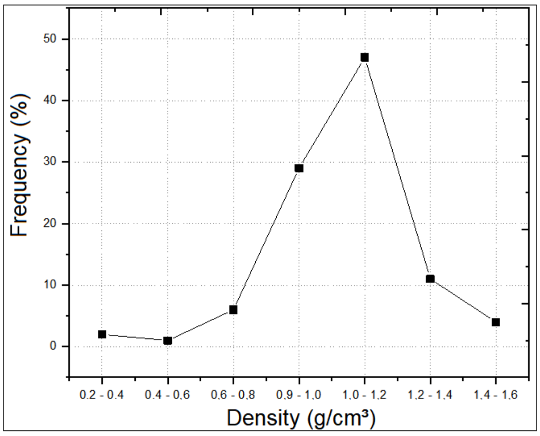

Figure 6. Density variation occurrence for the piassava fiber residue.

The pycnometer technique, however, revealed the real value of 1.42 g/cm³ for the waste fiber density. This approximately 15% difference between results can be explained by the fact that the pycnometer technique use a more precise volume measurement. In fact, it can be assumed that due to hollow spaces in the fiber, particularly the lumen, the measurement considering it as a cylinder is not a perfect approximation, although presented a significant close value for the density.

3.3. COMPOSITES WATER ABSORPTION

The composites water absorption (WA) values found in this study are presented in Table 2. In all composite cases studied, the addition of waste fiber residue powder led to an increase in the water absorption when compared to the pure resin. This behavior can be associated to a better water affinity of the piassava than the resin and also that the resin was not able to completely encapsulate the fiber powder.

Table 2. Water absorption variation for composites and pure resin.

Volume fraction of fiber (%)	Water Absorption (%)
0	0.61 ± 0.16
10	3.26 ± 0.48
20	0.81 ± 0.11
30	2.40 ± 0.56

The Brazilian standard NBR 14050 (NBR14050, 1998), requires that a HCP material should not present a WA value greater than 1%. This means that only the 20vol% piassava fiber reinforced composite formulation in Table 2 present acceptable WA value. Also the fact that the 10 and 30vol% reinforce composites present a weaker performance suggests that an optimum volume fraction of reinforcement is located between these intervals.

3.4. COMPOSITES COMPRESSIVE STRENGTH

The compressive test results are presented in Table 3. As can be seen, the addition of waste piassava powder reduces by almost half, in the best of cases, the compressive strength of the matrix. Another aspect is that the addition of fiber significantly increases the rigidity of the matrix as can be seen by the enhance of its elastic modulus, as shown in Table 3.

Table 3. Compressive mechanical properties for composites reinforced with piassava powder.

Volume fraction of fiber (%)	Compressive Strength (MPa)	Elastic Modulus (GPa)	Total Deformation (%)
0	90.14 ± 11.12	0.24 ± 0.09	6.465 ± 0.004
10	22.67 ± 4.98	0.38 ± 0.06	5.673 ± 0.003
20	50.13 ± 1.74	1.33 ± 0.17	5.983 ± 0.004
30	29.67 ± 2.65	1.11 ± 0.27	5.653 ± 0.004

In can be noticed in Table 3 the composites reinforced with 10 and 30% present no significant statistical variation between each other according to ANOVA followed by Tukey’s test statistical analysis. Moreover, in all cases, the results in Table 3 show that the composite reinforced with 20vol% is the one that presents the best compressive performance. Although the compressive strength is only half, as previously stated in comparison with the pure resin, the composites reinforce with 20vol% of piassava fibers is the only one that meet the standard NBR 14050 (NBR14050, 1998), which requires a minimum compressive strength of 45 MPa.

The success in meeting the standard NBR 14050 (NBR14050, 1998) requirements in both water absorption and compressive strength tests indicates that this 20vol% piassava fiber composite can replace epoxy reinforced resin based HPC floors. This would represent a greener and most likely a cheaper alternative solution since the resin is derived from a renewable source and the reinforcement is an industrial organic residue.

3.5. SURFACE OF FRACTURE

Figure 7 shows SEM micrographs from the fracture surface of samples reinforced with 0 (pure resin), 10, 20 and 30vol% of waste piassava powder, all with the same 45x magnification.

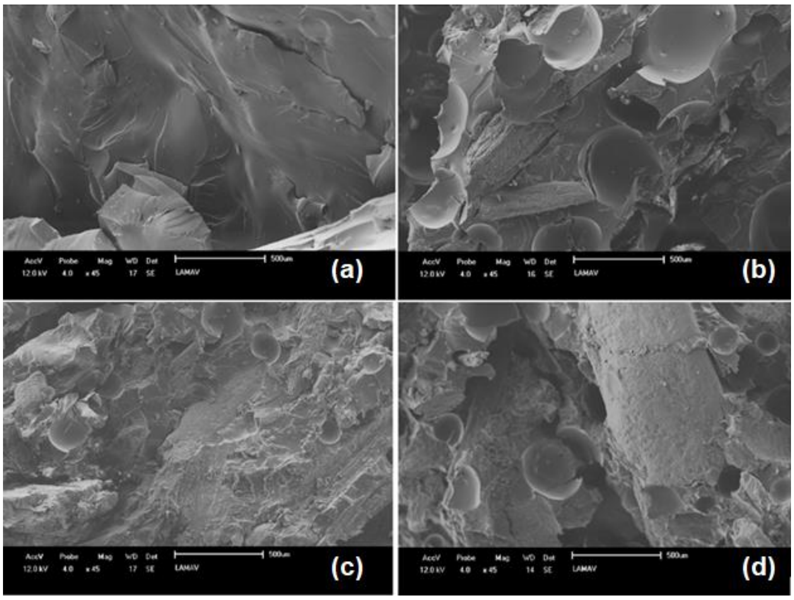

Figure 7. Surface of fracture at 45x magnifications for the pure resin (a), and composites reinforced by 10% (b), 20% (c) and 30% (d) volume fraction of piassava powder.

The evidence in the fractographs in Figure 7 suggests that the cracks were fee to propagate in the pure resin. Although the fiber powder added in the matrix acted as barrier to the crack propagation, the insertion of piassava fibers led to a significantly increase in large diameter pores. The increase in the total volume of pores is the most likely responsible for the high decrease of the compressive strength of the composite. Moreover, the presence of a great amount of porosity can also justify the increase in water absorption presented by the composites. In fact, the better performance shown by the 20vol% reinforced composites can be justified by, not only, by the lower amount, but also due to a lower porosity occurrence observed than those in 10 and 30vol% piassava powder reinforced composites.

4. CONCLUSIONS

- Piassava fibers supplied as waste still have silica pultrusions on their surface, even after industrial processing, which can be a benefit for incorporation into a polymeric matrix.
- The industrial waste does not have a length standardization, benefiting its incorporation in several types of composite materials.

- This fiber, despite being considerably thicker, when compared to other natural fibers, has low density, favoring the manufacture of advanced composites with high specific resistance when compared to other composites with synthetic loads.
- Samples with 10 and 30vol% fiber weakened the matrix, as they have a high amount of pores with a larger diameter.
- It was observed that the pore size and amount in the polymeric matrices can have a direct impact on the mechanical and water absorption properties of the composite, to a point that the composites would not meet the standard recommendations.
- The piassava fiber powder shown in the SEM analysis, allow cracks to easily cross the fiber / matrix interface, and offer low resistance to rupture.
- The eco-friendly composite of castor oil based polyurethane resin with an industrial residue addition of piassava fiber particles in a volume of 20vol%, meet the Brazilian standard for high performance coating, regarding water absorption and resistance to compression.

5. ACKNOWLEDGMENTS

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