Effect of Accelerated Weathering and *Phanerochaete chrysosporium* on the Mechanical Properties of a Plastic Composite Prepared with Discarded Coir and Recycled HDPE

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Solid urban wastes are a primary source of local and global contamination. One approach to slow their accumulation is by using them to obtain added-value products. One common example of these waste materials is the fiber from the husks of coconuts, *i.e.* coir. However, it is also known that microorganisms such as fungi can attack products containing natural fibers. In this respect, this study aimed to evaluate how the mechanical properties of an extruded composite made of 60% recycled HDPE and 40% discarded coir were affected due to accelerated weathering and *Phanerochaete chrysosporium* attack. The effect of *P. chrysosporium* on the materials' mechanical properties before and after weathering, using an accelerated weathering (AW) test device, was evaluated by means of tensile and flexural analysis following ASTM standards. Samples were also characterized using Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). FTIR spectroscopy and SEM showed that both types of treatment degraded the surfaces of the tested samples. However, the mechanical performance was not seriously affected, which means that other fungal species would affect the composites to a lesser extent.

Keywords: Coir; Degradation; Fungi; Recycling; Plastic composites

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INTRODUCTION

Plastics have become an inseparable and integral part of human life. The amount of plastics consumed annually around the world has been growing steadily, increasing from around 5 million tons in the 1950s to nearly 100 million tons in 2001 (Siddique 2008). Considering all of the various applications of plastic materials, it is clear how significantly they contribute to the ever-increasing volume of the solid waste stream. In addition to the accumulation of synthetic residues, a great amount of cellulolytic residues are also generated around the world every year. A clear example of this is the by-products that originate from the coconut industry in Mexico. Coconuts grow abundantly in coastal areas of Mexico, and its husk is available in large quantities as residue in many areas (Sagarpa 2005).

One way to solve the problems related to the excessive accumulation of solid wastes is to transform them into useful products. A way to do so is to produce natural fiber/plastic-based composite materials with applications in the construction and furniture markets. Specific applications for this kind of material are found in gardening, indoor and outdoor furniture production, ornamentation, and many others (Morton *et al.* 2003). Natural fibers have become attractive as an alternative reinforcement for fiber-reinforced polymer composites due to their low cost, fairly good mechanical properties, as well as eco-friendly and bio-degradability characteristics (Ku *et al.* 2011). However, despite these advantages, it is also known that natural fibers have a tendency to absorb moisture from the air or from direct contact with water or other liquids due to their hydrophilic nature. Studies have proven that absorbed moisture on natural fiber composites weakens fibers and the bonding between fiber and matrix, resulting in an overall reduction in mechanical properties (Fotouh *et al.* 2014). Additionally, they are susceptible to biological degradation by a wide variety of agents, including fungi. Evidence for the fungal decay and discoloration of fiber/plastic-based composite materials was first presented by Morris and Cooper (Schirp 2008), who isolated and identified white and brown rot fungi growing on a wood-plastic composite (WPC) boardwalk in Florida that had only been in service for four years. Other natural fiber-based composites may be affected when fungi-supporting conditions are met. The most important conditions to fungal growth are moisture and temperature (Stark and Gardner 2008). For this reason, the properties of plastic-based products reinforced with natural fibers can be affected when they are intended for outdoor use. In this kind of application, weather promotes the microbial deterioration of these materials, affecting their performance (for example, their aesthetics and mechanical properties). In this respect, it is important to investigate the effects of such attack on weathered and non-weathered fiber-based composites intended for outdoor applications.

In this work, coir was chosen as reinforcement material due to its low thermal conductivity and bulk density, which reduces the thermal conductivity of the composite specimens and yields lightweight products. Coir, a lignocellulosic natural fiber, is obtained from the outer shell, or husk, of the coconut, the fruit of *Cocos nucifera*, a tropical plant of the Arecaceae (Palmae) family. The husk comprises *ca.* 30 wt% coir fibers and 70 wt% pith. Both fiber and pith are extremely high in lignin and phenolic content (Asasutjarit *et al.* 2009). Accordingly, this study pertains to the preparation of composites using discarded coir fibers and recycled high-density polyethylene (HDPE), their surface characteristics, and their mechanical performance after exposure to accelerated weathering and fungal attack. White-rot fungus, *Phanerochaete chrysosporium*, was selected as the biotic degradation agent since it is known to thoroughly degrade coir fibers. Kanmani *et al.* (2009) reported that of the six fungal strains tested in their work, only two (*P. chrysosporium* and *R. stolonifer*) were able to degrade coir waste. Among those, the white rot fungus *P. chrysosporium* exhibited faster linear growth and mycelial proliferation (Kanmani *et al.* 2009). Additionally, *P. chrysosporium* has been found to be one of the most efficient lignin-degrading microorganisms (Dashtban *et al.* 2009), which is a very important feature since coir possesses a high lignin content (approximately 40 to 45 wt.%) compared to other waste fibers (Faruk *et al.* 2012). This means that *P. chrysosporium* will likely affect the performance of a plastic composite prepared with this type of fiber. Thus, the aim of this research was to investigate the effects of *P. chrysosporium* on the mechanical properties of weathered and non-weathered, discarded coir/recycled HDPE composites. Scanning electron microscopy (SEM) was undertaken to characterize the composite surface topology. Fourier transform infrared spectroscopy (FTIR) was used to study the surface chemical modifications after accelerated weathering and fungal attack.

EXPERIMENTAL

Raw Materials

Coir fiber from coconut palm trees of ecotype MXPT2 (Mexican Pacific Tall 2) provided by Coirtech (Tecomán, Colima, Mexico) was used as filler, and injection-grade recycled HDPE flakes (from Recuperadora de Plásticos Hernández, Merida, Mexico) with a melt flow index of 4.56 g/10 min served as the thermoplastic matrix material. Two processing additives were used in the formulation of the tested composite. These were HDPE grafted with maleic anhydride (Polybond 3009 from Brenntag México S.A. de C.V.) as coupling agent (CA) and Struktol TPW113 (Struktol Company of America) as a processing aid (PA).

Fungi

Of all ligninolytic microorganisms, white-rot basidiomycete fungi are the only known natural microorganisms that are capable of completely degrading lignin (Oliveira *et al.* 2010). Among them, *Phanerochaete chrysosporium* (Pc) is considered one of the most efficient at depolymerizing the complex structure of lignin (Dashtban *et al*. 2009). Thus, a strain of *P. chrysosporium*, cultivated at the Biotechnology Unit of Centro de Investigación Científica de Yucatán (UBT-CICY), was used as the biotic degradation agent in this study. The reactive substances used to inoculate the composites with *P. chrysosporium* are described in ASTM G21-96 standard test method (Materials 2003a).

Composite Preparation

Coir fibers were dried for 24 h at 80 ºC with a convection oven (Fisher Scientific) to remove moisture. Afterwards, the fibers were milled (using a Pagani mill machine, model 1520) and screened in a Tyler nest of sieves using a W. S. Tyler RO-TAP sieve shaker (model RX-29). Only those particles retained by a 40-mesh screen were used (size ranging from approximately 0.297 to 0.420 mm). HDPE, CA, and PA were milled with a Brabender granulating machine (model TI 880804) fitted with a screen plate with 1-mm-diameter holes. Afterwards, a blend containing 60 wt.% HDPE, 40 wt.% coir, and 5 and 3 wt.% CA and PA, respectively, was pre-mixed using a horizontal mixer with a helical agitator (Intertécnica Co., model ML-5), and dried in a convection oven (Fisher Scientific) at 80 ºC for 24 h before extrusion. Compounding was carried out in a laboratory-scale conical twin-screw extruder (Brabender EP1-V5501) using a 4-cm-long extrusion die, of 2-mm internal diameter, fitted to the extruder. The extrusion die allowed for rods of approximately 3 mm in diameter to be obtained. The rods were pelleted using a Brabender laboratory pelletizer machine (type 12-72-000). During extrusion, the screw speed was 50 rpm and the barrel and die temperatures were set at 140 ºC.

Tensile Samples Preparation

Test specimens were prepared using the pellets obtained by the twin-extrusion procedure detailed above. Pellets were hot-pressed using a Carver automatic hydraulic press (model 3819) at 145 ºC for 15 min with a compression force of approximately 44,482 N (10,000 lb_f) to obtain 3-mm-thick, dumbbell-shaped test specimens. A type V mold was used in order to fulfill the conditions for specimens' dimensions detailed in standard test method ASTM D 638 (Materials 2003b).

Flexural Samples Preparation

Test specimens were obtained by means of compression molding. Pellets were hot-pressed using the same hydraulic press previously mentioned at 145 ºC for 15 min, with a compression force of approximately 26,690 N (6,000 lb_f) to obtain 3-mm-thick, flat plaques, from which the samples were cut. The test specimens' dimensions are those specified in standard test method ASTM D 790 (3.2 x 12.7 x 127 mm) (Materials 2003c).

Accelerated Weathering Tests

Experiments were performed using an ATLAS UVCON tester. Samples were exposed to UV condensation cycles consisting of 4 h of UV light irradiation at 60 ºC with UVA-340-type fluorescent lamps followed by 4 h of condensation at 50 ºC, using ASTM D 4329 as a reference (Materials 2003d). Prior to exposure, samples (10 replicates per material) were conditioned according to ASTM D 618 (105 ºC for 24 h) (Materials 2003e). Samples were subjected to a total of 1000 h of accelerated weathering (AW).

Samples Inoculation and Incubation

A general sterilization process was carried out at 120 ºC and approximately 103 kPa (15 psi) for 15 min with an automatic autoclave (Felissa model FE-399) before inoculation to ensure that no other biological agent was present before the tests began. The spore production, suspension, preparation, and inoculation of the test samples with *P. chrysosporium* were performed according to the test method detailed in ASTM G21-96 (Materials 2003a). Incubation was performed for 28 and 56 days at room temperature (30 to 32 ºC). After incubation, samples were disinfected with a 10% v/v chlorine/ethanol solution and stored until analysis. Non-inoculated and inoculated samples are referred to throughout the text as 0I, 28I, and 56I, respectively.

Characterization Experiments

Weight loss

This experiment was performed in order to determine the sample weight loss associated with biodegradation of coir by fungi. The polymer matrix is not supposed to rot. Before inoculation, the samples were conditioned using a conventional oven at 60 ºC to reach a constant weight (P_o). Once the experiments concluded, samples were disinfected and conditioned again. Once a constant weight was reached it was denoted P_f. The quantities P_o and P_f were used to calculate the weight loss (%wl) according to Eq. 1:

$$\%wl = [(P_o - P_f)/P_o] \times 100 \qquad (1)$$

Fourier transform infrared spectroscopy

Fourier transform infrared (FTIR) spectroscopy was conducted with a Nicolet Protégé 460 spectrophotometer in order to identify the functional groups present at the surface of the samples with a photo-acoustic detector. Scans were run at a resolution of 8 cm^{-1}. For each sample, 100 scans were recorded from 4000 to 400 cm^{-1}. The peaks' intensities were normalized using the peak at 2912 cm^{-1}, corresponding to the alkane C-H stretching vibrations of methylene groups. This peak was chosen as a reference because it changed the least during weathering (Stark and Matuana 2004). Samples, both those exposed and not exposed to accelerated weathering and fungal attack, were analyzed to understand the effects of each degradation agent on the surfaces of the composites.

Scanning electron microscopy

Morphological analysis was performed on the samples surfaces with SEM. Samples were cut into small sections with a razor blade and were mounted onto stubs and gold-coated with a sputter coater (Denton Vacuum Desk II). The samples were examined with a JEOL JSM-6360 LV electron microscope at a working distance of approximately 10 mm and a voltage of 20 kV.

Tensile characterization

Tensile tests were performed using an Instron 5500R (1125) universal testing machine following standard ASTM D 638 (Materials 2003b) with a 500-kg load cell and a crosshead speed of 1 mm/min. At least 10 specimens corresponding to each treatment were tested to obtain values for the modulus of elasticity and tensile strength. Samples were oven-dried at 105 ºC for 24 h before testing to ensure the same conditioning before and after weathering. All samples were conditioned at 23 ± 2 ºC and 50 ± 5% relative humidity for at least 40 h before testing, in accordance with ASTM D 618 (Materials 2003e). Tensile characterization was performed on inoculated (28 and 56 days) and non-inoculated samples exposed to 0 and 1000 h of accelerated weathering. Non-weathered and non-inoculated samples are referred to throughout the text as the control samples.

Flexural characterization

Flexural tests were carried out using the Instron machine previously mentioned, in accordance with test method ASTM D 790 (Materials 2003c). The three-point loading system was used with a crosshead speed of 10 mm/min and a 500-kg load cell. Aged samples were oven-dried at 105 ºC for 24 h before testing to ensure the same conditioning before and after accelerated weathering. All samples were conditioned following the procedure previously mentioned for the tensile testing. In each case, 10 specimens were tested to obtain average values of flexural strength and flexural modulus. Tests were performed on previously-aged and non-aged samples incubated for 28 and 56 days, as well as on non-inoculated samples.

Statistics

The collected data were analyzed with statistical software (Graphpad Software, Inc., San Diego, CA, USA). An unpaired *t*-test with Welch's correction was performed considering the mechanical property results as the variables. Statistical significance was defined as $P < 0.05$.

RESULTS AND DISCUSSION

Weight Loss

The weight loss values of the tensile and flexural specimens are shown in Table 1. After 28 days of fungal attack, drops of 1.2 and 1.6% in the non-aged tensile and flexural specimens, respectively, were registered. After a total of 56 days of exposure, the mentioned loss increased to 1.6 and 1.9%, which makes it evident that the most important loss occurred during the first 28 days of fungal exposure. The combined effect of accelerated weathering and fungal attack gave place to a significant increase in the weight loss percentage with respect to the non-weathered samples, as can also be observed in Table 1. This means that accelerated weathering enhanced the effect of *P. chrysosporium*.

Table 1. Weight Losses (%) of Aged and Non-aged Samples Inoculated with Pc

Exposure to AW (h)	28I Tensile Samples	56I Tensile Samples	28I Flexural Samples	56I Flexural Samples
0	1.2 (0.080)	1.6 (0.121)	1.6 (0.104)	1.9 (0.046)
1000	2.1 (0.120)	2.0 (0.043)	2.4 (0.110)	2.3 (0.073)
Standard deviation is indicated in parentheses				

Fourier Transform Infrared Spectroscopy

The effects of the exposure of the HDPE-coir based samples to *P. chrysosporium* are shown in Fig. 1 (FTIR spectra) and in Table 2 in terms of degree of degradation (D_d) calculated according to Eq. 2,

$$D_d = (I_f - I_i)/I_i \tag{2}$$

where I_f corresponds to the final intensity (degraded samples) and I_i represents the initial intensity (control samples) of the identified peaks.

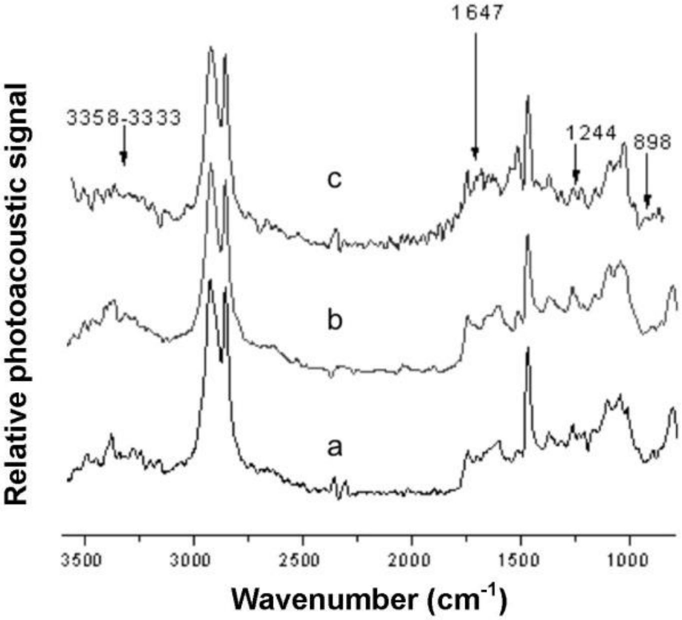

Fig. 1. FTIR spectra showing the effects of the exposure of non-aged HDPE-coir based samples to *P. chrysosporium*: (a) 0I, (b) 28I, and (c) 56I

The intensities of the peaks at 1244 cm^{-1} (representing aliphatic and aromatic C-O) and 898 cm^{-1} (representing aromatic C-H), corresponding to the components of the coir fibers (cellulose, hemicelluloses, and lignin), decreased as the exposure to fungi increased, which makes clear the ability of *P. chrysosporium* to degrade the natural fiber fraction of the composites' surface. In contrast, the intensity of the peak at 1647 cm^{-1}, corresponding to alkenyl C=C stretching, increased as exposure time increased. Further, both increments in the size of certain peaks and the appearance of new peaks (particularly after 28 days of fungal exposure) were observed. These phenomena are related to the presence of -OH groups (3358 to 3333 cm^{-1}) originating from the biodegradation of lignin.

Table 2. D_d of Non-aged HDPE-coir based Samples due to the Exposure to *P. chrysosporium*

Samples	898 cm^{-1}	1244 cm^{-1}	1647 cm^{-1}	3358-3333 cm^{-1}
28I	-0.01	-0.01	0.03	0.06
56I	-0.01	-0.02	0.04	0.06

The FTIR spectra of samples exposed and not exposed to accelerated weathering are presented in Fig. 2. Additionally, the D_d value of samples exposed to accelerated weathering was 0.02, evaluated at 1714 cm^{-1}. Comparing the spectra of non-fungi exposed samples before and after weathering, FTIR show that in the carbonyl region (1750 to 1700 cm^{-1}), a sharp peak formed at 1714 cm^{-1}, corresponding to carboxylic acid groups. These -COOH groups originated due to ultraviolet radiation.

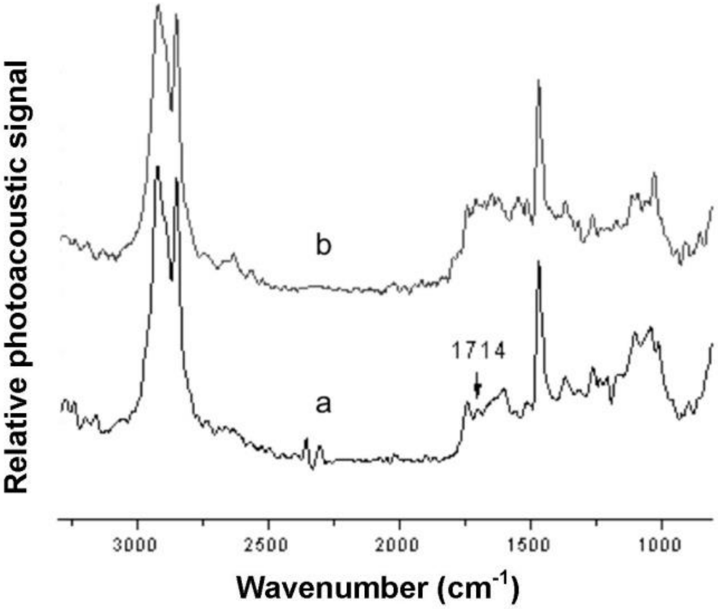

Fig. 2. FTIR spectra of HDPE-coir based samples exposed to accelerated weathering: (a) aged, and (b) non-aged

The FTIR spectra showing the combined effect of fungi and AW exposure appear in Fig. 3, while Table 3 indicates the D_d. A decrement in the intensity of the peak at 1428 cm^{-1} (olefinic C-H), corresponding to lignin, was observed. Decreases in the intensities of the peaks at 1368 (O-H bonds) and 898 cm^{-1} (corresponding to aromatic C-H), associated to holocellulose, which represents approximately 70% of the total composition of coconut coir fiber (Asasutjarit *et al.* 2009; Ezekiel *et al.* 2011), were also observed, indicating the degradation of natural fibers by *P. chrysosporium*. Similarly to what was observed in Fig. 1, increments in the intensity of the peak at 1647 cm^{-1} and the region corresponding to the -OH groups (3358 to 3333 cm^{-1}) were observed.

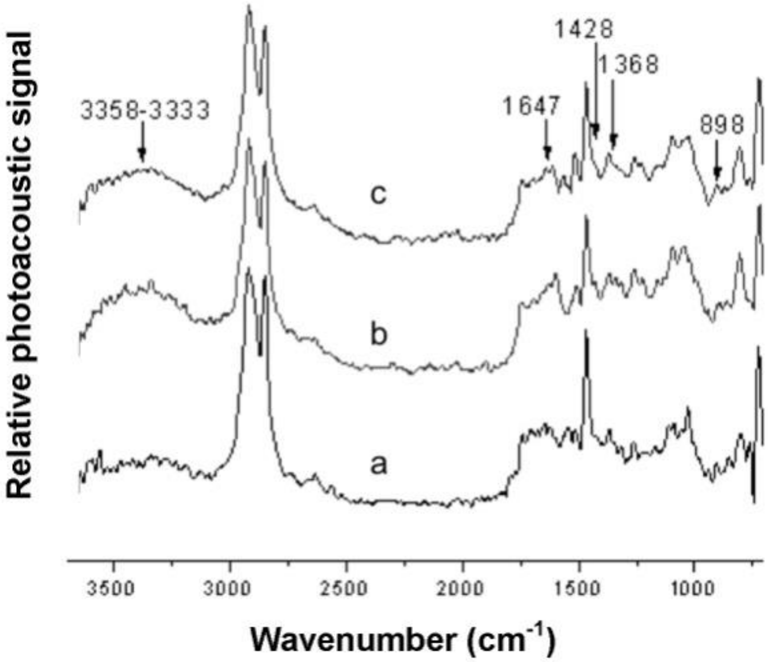

Fig. 3. FTIR spectra showing the effect of Pc on aged HDPE-coir based samples: (a) 0I, (b) 28I, and (c) 56I

Table 3. D_d of Aged HDPE-coir based Samples due to the Exposure to *P. chrysosporium*

Samples	898 cm^{-1}	1368 cm^{-1}	1428 cm^{-1}	1647 cm^{-1}	3358-3333 cm^{-1}
28I	-0.02	-0.01	-0.02	0.04	0.08
56I	-0.03	-0.02	-0.03	0.04	0.08

Scanning Electron Microscopy

Selected micrographs of control, aged, and biotically-attacked samples are presented in Fig. 4. The control sample surface (Fig. 4a) appeared relatively smooth and free of cracks. After 28 and 56 days of exposure to fungal attack (Figs. 4b, c, respectively), holes appeared across the surfaces of the samples, leaving the coir fibers exposed to the environment.

After exposure to accelerated weathering, the number of cracks on the materials' surfaces increased, increasing the number of unprotected, exposed coir particles (Fig. 4d) due to the degradation of the polymer matrix. Finally, when aged samples were exposed to fungal attack, even more significant damage was observed because *P. chrysosporium* was more able to access coir particles. Thus, more damage to the coir particles was observed (Figs. 4e, f), making it possible to identify filament-like features within the surface cavities. These filaments, known as hyphae, constitute the fungi mycelium (Fig. 5) and have been observed by other researchers (Schirp and Wolcott 2006).

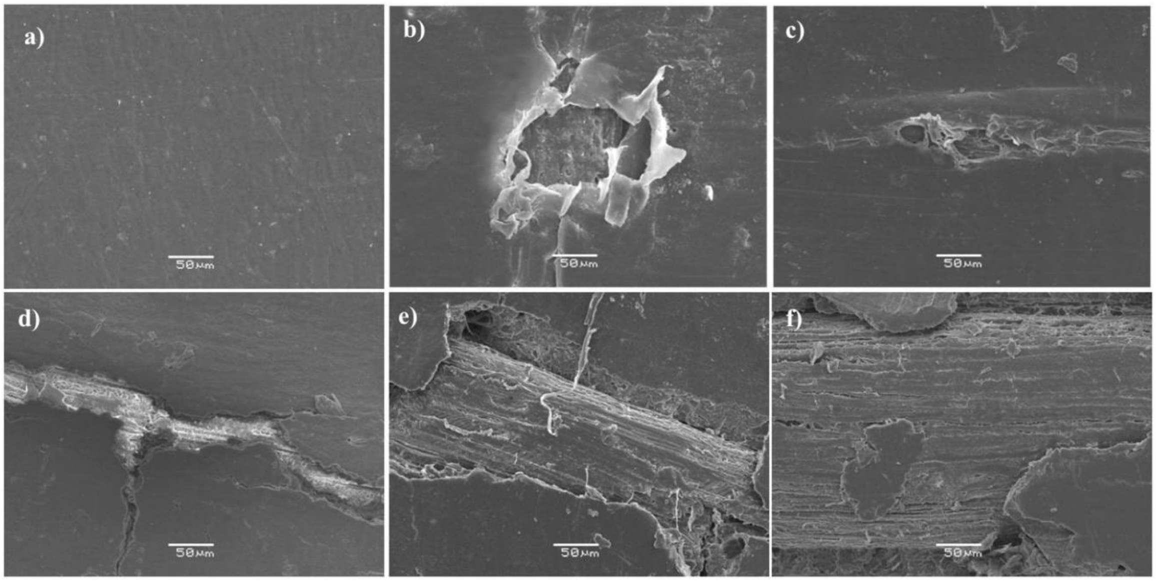

Fig. 4. SEM micrographs showing the effects of Pc and AW on tested samples: (a) Control, (b) 28I non-aged, (c) 56I non-aged, (d) aged, (e) 28I aged, and (f) 56I aged

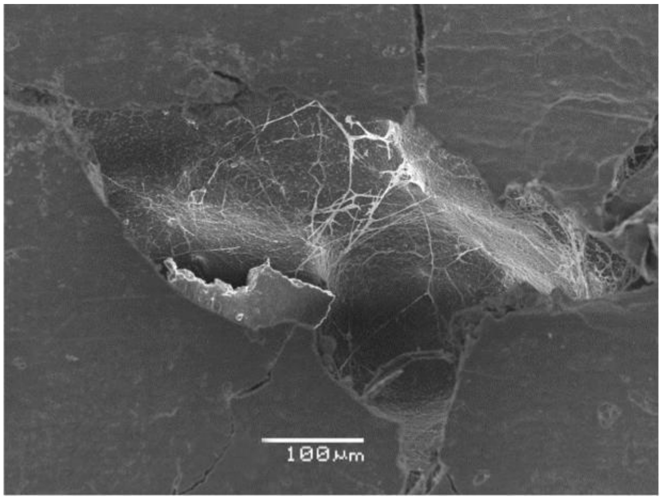

Fig. 5. SEM micrograph showing fungi hyphae

Tensile Properties

The tensile strengths of the composites subjected to the various different treatments are shown in Fig. 6. The initial tensile strength of the tested composite was 14.83 MPa (control), but after 28 days of biotic attack a reduction to 13.31 MPa (10.3%) was observed. After 56 days of exposure, the final strength was 12.17 MPa, a decrease of 18.0% with respect to the original value. Thus, fungal attack decreased the tensile strength of the composites by 18.0%.

On the other hand, AW caused a 20.0% loss of tensile strength in the tested composite. As expected, the combined effect of AW and fungal attack produced greater drops in the tensile strength of the tested samples than either did individually. 1000 h of AW with 28 days of fungal attack caused a drop of 26.0% with respect to the control samples, while a drop of a 28.0% occurred when samples were exposed to 1000 h of AW and 56 days of fungal attack.

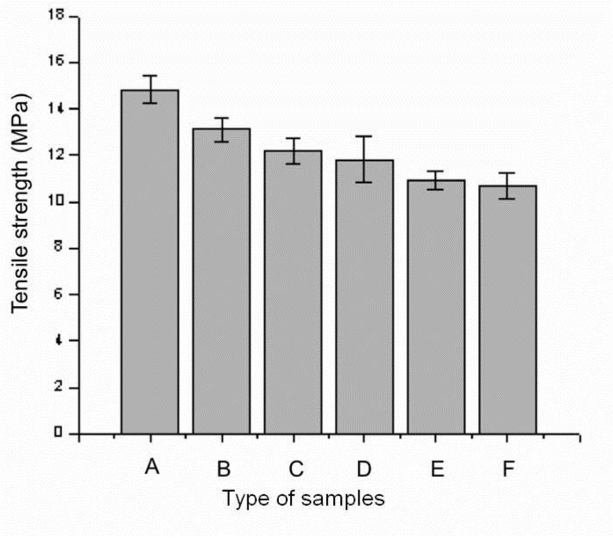

Fig. 6. Tensile strength of samples exposed to Pc and AW: (A) Control, (B) 28I non-aged, (C) 56I non-aged, (D) aged, (E) 28I aged, and (F) 56I aged

With respect to the tensile modulus, a similar behavior was observed as the time of exposure to *P. chrysosporium* (Fig. 7) increased. In the case of the non-aged samples, a maximum drop of 25.0% was observed after 56 days of fungal attack.

In the case of the aged samples, a maximum drop of 22.2% occurred. On the other hand, the combined effect of AW and fungal attack decreased the tensile modulus by 34.4%.

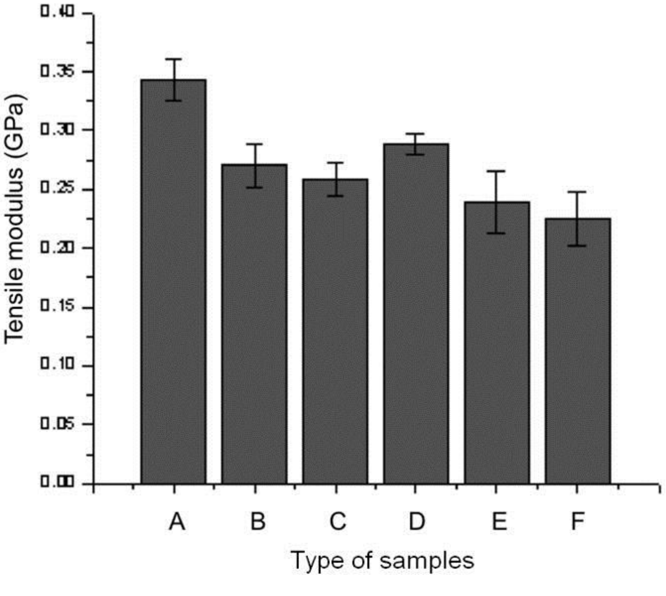

Fig. 7. Tensile modulus of samples exposed to Pc and AW: (A) Control, (B) 28I non-aged, (C) 56I non-aged, (D) aged, (E) 28I aged, and (F) 56I aged

Flexural Properties

The results of the flexural essays are presented in Figs. 8 and 9.

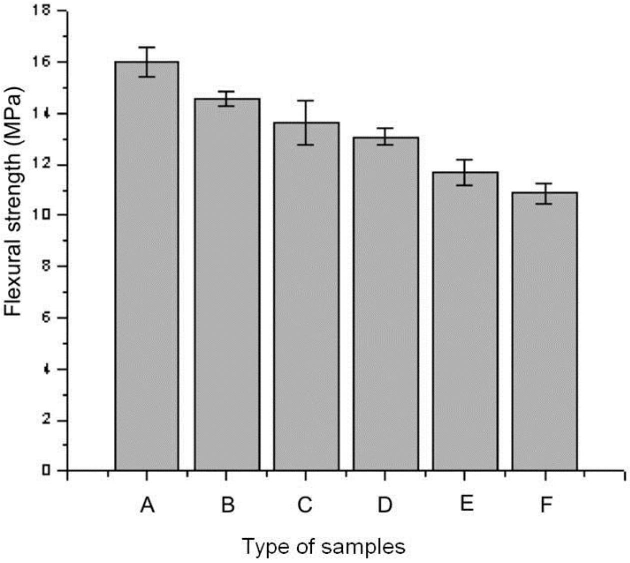

Fig. 8. Flexural strength of samples exposed to Pc and AW: (A) Control, (B) 28I non-aged, (C) 56I non-aged, (D) aged, (E) 28I aged, and (F) 56I aged

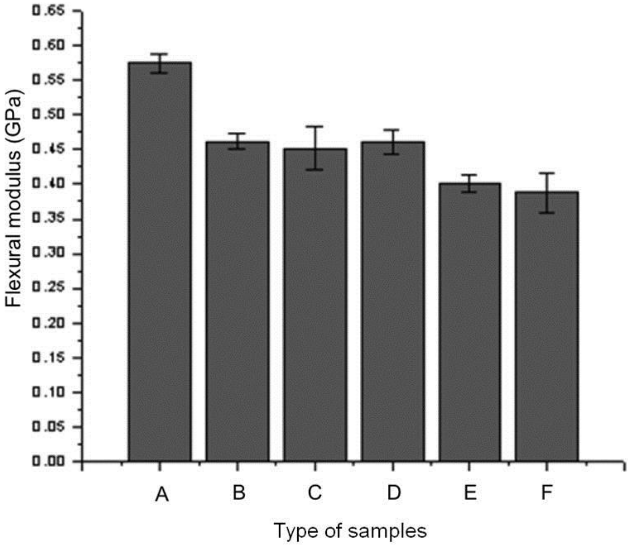

Fig. 9. Flexural modulus of samples exposed to Pc and AW: (A) Control, (B) 28I non-aged, (C) 56I non-aged, (D) aged, (E) 28I aged, and (F) 56I aged

As shown in Fig. 8, the flexural strength of non-aged samples was decreased by approximately 9.0% after 28 days of exposure and by 14.9% after 56 days of fungal attack. Accelerated weathering reduced it by approximately 18.5%, while the combined effect of both degradation agents yielded a decrease of about 32.0% after 1000 h of AW and 56 days of fungal attack.

Regarding the flexural modulus (Fig. 9), a maximum drop of approximately 21.4% was observed in non-aged samples exposed to 56 days of fungal attack, while AW produced a decrement of 19.8% after 1000 h of exposure.

Effect of *P. chrysosporium* on the Properties of the Recycled HDPE-Discarded Coir Composite

According to Fig. 4a, before the materials were exposed to the degradation agents, no cracks were present on their surfaces. After exposing non-aged samples to *P. chrysosporium*, weight losses were registered, confirming that biotic degradation took place, even on that type of sample. Previous studies report different weight-loss percentages caused by fungi. For example, Clemons and Ibach (2002) report a maximum drop of 3.0% in materials made with pinewood and HDPE using *Gloeophyllum trabeum* fungi. Other works report drops of 6.8 and 3.0% for pinewood-plastic composites exposed to 12 weeks of *G. trabeum* and *P. chrysosporium* attack, respectively (Lomelí *et al.* 2009). Differences between the results of this study and those in other literature are attributable to differences in the type of fungi, the origin of the strain used, variations in the types and ratios of lignocellulosic fillers and the plastic matrix, and the processing methods used to obtain and moisten the samples for testing.

As a consequence of the observed weight loss, holes originated on the surfaces of tested samples, as shown in Figs. 4b and 4c. Similar results have previously been reported in the literature, suggesting that these holes indicate that the microorganisms degraded the lignocellulosic component of the composite (Clemons and Ibach 2004; Fabiyi *et al*. 2011). Results of FTIR analyses confirmed the degradation of the lignocellulosic component, since the intensities of peaks corresponding to coir fiber components (cellulose, hemicelluloses, and lignin) decreased as exposure time to fungi increased. Additionally, some authors hold that the increase in intensity observed in the peak at 1647 cm^{-1} (corresponding to alkenyl C=C bonds; Fig. 1) could be related to a proportional intensity increase in the plastic content as the wood is degraded (Fabiyi *et al.* 2011), since HDPE is unlikely to be affected by fungi.

With regards to the mechanical properties of the composites, results demonstrated that drops caused by *P. chrysosporium* in non-aged samples were statistically significant for both the flexural and tensile strength and modulus. Although *P. chrysosporium* caused significant reductions in the mechanical properties of the composites, such decreases do not seriously affect the mechanical performance of the tested material. Therefore, it can be inferred that other fungi species would affect the mechanical properties of the composites to a lesser extent because, as mentioned before, *P. chrysosporium* is considered one of the most efficient white rot fungi, specialized in depolymerizing the complex structure of lignin.

Effect of Accelerated Weathering

The exposure of samples to AW caused more deep cracks on the surface of the composites as shown in Fig. 4d. This increased the number of access routes by which *P. chrysosporium* could reach coir particles. These cracks originated due to chain scission reactions within the polyethylene matrix as a consequence of their exposure to ultraviolet light, as evidenced by the FTIR peak appearing at 1714 cm^{-1} (Fig. 2), and due to fiber swelling *via* moisture absorption (Stark and Matuana 2004).

Accelerated weathering also significantly decreased the mechanical properties tested in this work because the combined effect of ultraviolet light and condensation cycles damaged the polymer matrix, the lignocellulosic filler, and the interface of the composite, affecting its mechanical performance. Other researchers have also studied this phenomenon (Gulmine *et al.* 2003).

Combined Effect of Exposure to Accelerated Weathering and *P. chrysosporium*

When samples were exposed to AW, more cracks were produced on their surface, allowing fungi easier access to the natural fibers that were originally protected by the polymer matrix. This caused higher weight losses, as indicated in Table 1.

The combined effect of *P. chrysosporium* and AW exposure is shown in Fig. 3. Drops in the intensities of the peaks corresponding to natural fiber content can be observed. Increases of the intensities of the peaks in the carbonyl region (1750 to 1700 cm^{-1}), commonly related to the degradation of HDPE, were also observed. This is evidence that both components of the composite were damaged. Similar results have been reported in other literature (Fabiyi *et al*. 2009; Stark and Matuana 2004).

SEM results agreed with those reported in previous works regarding aged wood-plastic composites exposed to white- and brown-rot fungi. Filaments known as hyphae (Fig. 5), which constitute the fungi mycelium, have been previously observed in the zone of the composites directly exposed to fungi (Mankowski and Morrell 2000; Schirp and Wolcott 2006).

The results of mechanical property tests indicated significant drops in all experiments, except in the case of the tensile strength of the aged samples exposed to 28 and 56 days of fungal attack, whose results were not statistically significant. This behavior is clearly shown in Fig. 6 (columns D, E, and F). In this particular case, the wide variation of the data collected regarding aged samples (column D) prevented the results shown in columns E and F from being statistically significant.

Future Work

Additional research can be carried out at a later stage to investigate the effect of *P. chrysosporium* and accelerated weathering on the materials' impact strength by following ASTM D256 standard test method to perform notched Izod Impact experiments. These experiments will surely provide information on how the treatments above mentioned can affect, for example, the amount of energy absorption and the fracture mechanics of the composites studied. Now, the effect on the viscoelastic behavior of the composites can be investigated using a TA Instruments Q800 series dynamic mechanical analyzer (DMA) under the 3-point bending mode. DMA testing can be carried out to study the storage modulus (E'), loss modulus (E''), and damping coefficient (δ). The value of storage modulus indicates a material's ability to store the energy of external forces without permanent strain deformation. Therefore, higher storage modulus would be associated with a higher elastic property of the composites. The loss modulus value would be a good indicator of the viscous behavior of the composites, and very sensitive to the molecular motions. Therefore, a high loss modulus value would indicate, for example, high energy dissipating at the interface, which suggests poor interface bonding. The damping coefficient of a material is expressed as tan delta (tan δ), which shows the energy dissipation of that material under cyclic load. The tan δ is used to predict how well a material would perform at absorbing and dissipating energy.

CONCLUSIONS

1. Although *P. chrysosporium* caused significant decreases in the mechanical properties of the composites, such decreases did not seriously affect the mechanical performance of the tested materials. Therefore, it can be inferred that other less effective lignin-degrading fungi species would affect the mechanical properties to a lesser extent, considering that *P. chrysosporium* has been found to be one of the most efficient lignin-degrading microorganisms.
2. Results of the FTIR analyses suggest that oxidative species were generated during exposure to accelerated weathering and *P. chrysosporium*. It is clear that more weight loss occurred in the aged samples, which is logical because in those samples *P. chrysosporium* had better access to coir fibers, which may be attributed to damage caused on their surface after exposure to accelerated weathering.
3. The mechanical assay results and the weight loss are directly proportional, according to the results of the present study, as a low weight loss is associated with a small decrease in mechanical properties.
4. SEM micrographs showed that *P. chrysosporium* superficially affected the tested composites most dramatically in the samples previously exposed to accelerated weathering. This is also attributed to the hydrophilic nature of the natural fibers, which results in a reduction of interfacial and fiber strength.

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