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# Effect of Biological Degradation by Termites on the Flexural Properties of Pinewood Residue/Recycled High-Density Polyethylene Composites

**Edgar J. López-Naranjo,[1] Liliana M. Alzate-Gaviria,[2] Galdy Hernández-Zárate,[3] Javier Reyes-Trujeque,[4] Carlos V. Cupul-Manzano,[1] Ricardo H. Cruz-Estrada[1]**

[1]Centro de Investigación Científica de Yucatán, Unidad de Materiales, Calle 43 Número 130, Colonia Chuburná de Hidalgo, CP 97200, Mérida, Yucatán, México

[2]Centro de Investigación Científica de Yucatán, Unidad de Energía Renovable, Calle 43 Número 130, Colonia Chuburná de Hidalgo, CP 97200, Mérida, Yucatán, México

[3]Instituto Tecnológico de Boca del Río, Área de Biología Molecular, Km 12 Carretera Veracruz-Córdoba, CP 94290, Boca del Río, Veracruz, México

[4]Universidad Autónoma de Campeche, Centro de Investigación en Corrosión, Avenida Agustín Melgar S/N entre Calle 20 y Juan de la Barrera, Colonia Buenavista, CP 24039, Campeche, Campeche, México

Correspondence to: R. H. Cruz-Estrada (E-mail: rhcruze@cicy.mx)

**ABSTRACT:** Wood–plastic composites (WPCs) are considered to be highly durable materials and immune to any type of biological attack. However, when one of these composites is exposed to accelerated weathering, its surface is affected by the appearance of cracks, which constitute an ideal access route for biotic agents. Although the destruction of wood caused by termites is recognized worldwide, information on their effects on WPC-based products is scarce. Thus, in this study, we aimed to examine the effects of termite attacks on weathered and nonweathered pinewood residue/recycled high-density polyethylene composites. In this study, WPCs with 40 wt % wood were prepared. Test samples obtained by compression molding and profile extrusion were subjected to weathering cycles for 1000 and 2000 h with a UV-type accelerated tester equipped with UVA-340 fluorescent lamps. Afterward, specimens were exposed to the attack of higher termites (*Nasutitermes nigriceps*) native to the Yucatan Peninsula. Subsequently, flexural mechanical essays, Fourier transform infrared (FTIR) spectroscopy, differential scanning calorimetry (DSC), and scanning electron microscopy (SEM) analyses were performed. FTIR spectroscopy and DSC showed that the surfaces of the compression-molded specimens were degraded to a higher extent because of the accelerated weathering. The microscopy results revealed that severe damage was caused by the termites on the surface of the compression-molded samples. Statistical analysis of the mechanical test results showed that biotic attack produced significant changes in the samples previously exposed to accelerated weathering. The results show that the processing method directly affected the sample performance because of differences in the surface composition. The profile-extruded composites seemed to better resist termite attack. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

**KEYWORDS:** ageing; composites; degradation; mechanical properties; recycling

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## INTRODUCTION

Although wood–plastic composites (WPCs) have been used to fabricate low-maintenance and highly durable products, their use in the construction industry is still subordinate to their performance, especially when they are used for outdoor applications. It has been demonstrated that WPCs that are exposed to accelerated weathering may experience color changes and crack formation; this leaves the wood uncovered and affects the aesthetic appeal and mechanical properties of the products.[1–3] It is also known that manufacturing methods play an important role in determining the properties of WPCs. For instance, parameters such as temperature, pressure, and flow rate, among many others, may cause differences in the surface composition and promote different moisture absorption rates.[4,5] Additionally, it is widely known that unprotected wood can be attacked by a wide variety of biotic agents.[3] In general, this action occurs as an extracellular process and is catalyzed by three major types of enzymes involved in the hydrolysis of cellulose (i.e., endo-$\beta$-1,4-glucanases, $\beta$-glucosidases, and cellobiohydrolases).[6,7] Although insects never appear to be capable of forming cellobiohydrolases, some of them, such as termites, are said to digest a significant proportion of the cellulose (74–99%) and hemicellulose (65–87%) components of the lignocellulose they ingest.[8] As termites search for food, they may penetrate and damage many noncellulose materials as well, including plastics, even when these do not serve as a food source and cannot be digested. It is, therefore, not surprising that most plastics fail in tests for resistance to this kind of insect. In this respect, not only the mechanical hardness of plastics but also the surface structure of the material characterizes their durability against termite attack. Smooth and even rough surfaces are more likely to prevent it, but even the smallest cracks and crevices or ruffled surfaces and edges provide immediate access for their mandibles.[9] Hence, we believed it would be interesting to investigate the effects of this type of biotic attack on weathered and nonweathered WPCs, especially those intended for outdoor applications. Consequently, as part of a broad research project, we studied the availability of wood and plastic wastes generated in the Yucatan state (southeastern Mexico) to be used in the preparation of WPCs with potential applications as structural materials. The main aim of the whole research project is to scale up the experimentation in the laboratory to a pilot level to fully evaluate the feasibility for the use of these materials in construction. Potential applications include constructive elements for housing, such as frames for windows and doors, the windows and doors themselves, dividing panels, fencing, decking, and eaves for protection against sunlight and rain, among many others. Thus, we preliminarily evaluated how the flexural performance of pinewood residue/recycled high-density polyethylene (HDPE) composites was affected when they were exposed to accelerated weathering and the attack of higher termites (*Nasutitermes nigriceps*) native to the Yucatan Peninsula. These insects were selected because of their importance as native degradation agents in the area where our materials could be used in real applications. Therefore, compression-molded and profile-extruded samples previously exposed to accelerated weathering for 0, 1000, and 2000 h were subjected to 0, 15, and 30 days of termite attack. Our results show that the profile-extruded samples were less degraded by the action of accelerated weathering and termite attack. Fourier transform infrared (FTIR) spectroscopy showed that the samples obtained by compression molding were more affected by accelerated weathering than those obtained by extrusion (i.e., wood was lost to a higher extent, and HDPE experienced higher chain scissions). Showing a similar trend, differential scanning calorimetry (DSC) confirmed that the polymer matrix was less affected when the samples were obtained by extrusion. Contrary to what was observed on such samples, in the compression-molded ones, new thermal energy absorption peaks were identified; this provided evidence that the secondary recrystallization of short polymer segments produced by chain-breaking reactions on the polyethylene matrix exposed to accelerated weathering occurred. Scanning electron microscopy (SEM) micrographs showed severe damage caused by biotic attack on the surface of the compression-molded samples, whereas the extruded ones seemed to have resisted it better. Finally, the flexural characterization demonstrated that significant drops in such properties occurred mostly in the compression-molded materials. These results will contribute to a better understanding of the effects of termite attack on WPC performance.

## EXPERIMENTAL

### Raw Materials

Pinewood residues were collected from Maderas Bajce (Merida, Mexico) and screened in a Tyler nest of sieves with a W. S. Tyler RO-TAP sieve shaker (model RX-29) (Mentor, OH). Residues retained on mesh 40 were used (particle size $>$ 0.43 mm). Injection-grade recycled HDPE with a melt flow index (MFI) of 4.56 g/10 min from Recuperadora de Plásticos Hernández (Merida, Mexico) was used as the polymer matrix. The as-received flake-shaped material was ground with a Brabender granulating machine (model TI 880804) fitted with a screen plate drilled with holes 1 mm in diameter. Maleic anhydride grafted HDPE (Polybond 3009), supplied by Brenntag México, S. A de C. V., was used as the coupling agent (CA). Its physical properties were as follows: MFI = 0.5 g/min at 190°C, density = 950 kg/$m^3$ at 23°C, and melting point = 127°C. The maleic anhydride level was 1 wt %. A blend of modified fatty acid esters (Struktol TPW 113, dropping point = 67–77°C, specific gravity = 1.005) from Struktol Co. of America was used as a processing aid (PA). Both the CA and PA were ground with the instrument previously described.

### Termites

Higher termites (species *N. nigriceps*) collected from nests situated in the mangrove forest of Ría Celestún in Yucatan, Mexico (20°51′52.1″ N; 90°22′58.7″ W) were used as the biotic agent. These insects were chosen because of their feeding behavior, which is not limited to xylophagy.[8]

### WPC Preparation

The HDPE, pinewood, and additives were premixed with a horizontal mixer with a helical agitator (Intertécnica Co., model ML-5) (Mexico City, Mexico) and dried in a convection oven (Fisher Scientific, Pittsburgh, PA) at 105°C for 24 h before extrusion. Two different pinewood–HDPE formulations with 40 wt % wood were prepared. Their details are shown in Table I. Compounding was carried out in a conical twin-screw extruder (Brabender EPl-V5501). Formulation 1 was extruded with a 4 cm long extrusion die 2 mm in internal diameter fitted to the extruder to obtain rods approximately 3 mm in diameter that were pelleted with a Brabender laboratory pelletizer machine (type 12-72-000). Formulation 2 was processed with both a slot die ($\sim$ 100 mm wide) with a 3 mm maximum allowed lip opening to produce flat WPCs sheets and the die previously described. During extrusion, the screw speed was 50 rpm, and the barrel and die temperatures were set at 140°C.

### Preparation of the Flexural Test Specimens

Test specimens were obtained by means of two different methods, namely, profile extrusion and compression molding. The profile-extruded samples were cut directly from the extrudates obtained with the extruder, the slot die, and the processing conditions previously described. On the other hand, the pellets were hot-pressed with a Carver automatic hydraulic press (model 3819) (Wabash, IN) at 140°C for 5 min with a compression force of about 26,690 N (6000 lbf) to obtain flat plaques 3 mm in thickness from which the compression-molded samples were cut. In all cases, the test

**Table I.** Formulations of the WPCs Based on Pinewood Residues and Recycled HDPE

| Formulation | Composite | Wood (wt %) | HDPE (wt %) | CA (wt %)[a] | PA (wt %)[a] | Method[b] |
|---|---|---|---|---|---|---|
| 1 | A | 40 | 60 | 0 | 3 | Compression molding |
| 2 | B | 40 | 60 | 5 | 3 | Compression molding |
| 2 | C | 40 | 60 | 5 | 3 | Profile extrusion |

[a]Weight percentage with respect to the wood content, [b]Processing method used to obtain the test samples.

specimens' dimensions were specified in the ASTM D 790 standard test method (i.e., 3.2 × 12.7 × 127 $mm^3$).[10]

### Accelerated Weathering

Experiments were performed with an Atlas ultraviolet-condensation (UVCON) tester (Moussy Le Neuf, France). The samples were exposed to UV condensation cycles with 4 h of UV light irradiation at 60°C with UVA-340 type fluorescent lamps followed by 4 h of condensation at 50°C with the ASTM D 4329 method as a reference.[11] Before exposure, the samples (10 replicates per material) were conditioned according to ASTM D 618 (at 105°C for 24 h).[10] These samples were subjected to accelerated weathering for 0, 1000, and 2000 h and are referred to throughout the text as 0AW, 1000AW, and 2000AW, respectively.

### Biodegradation Tests

The weathered and nonweathered samples were exposed to termite attack with the ASTM D 3345 standard test method as a reference.[12] Composite specimens were exposed to termites for a maximum period of 30 days. Glass containers (40 × 20 × 30 $cm^3$) sealed with 3-cm adhesive tape were used to carry out the experiments. The containers were kept at 25.5–27.7°C for 30 days. Test specimens were placed on a sand layer around a termites' nest. Sand was previously added with distilled water to supply it to the insects. The percentage of water added was calculated according to the reference method. Once the tests were finished, the nests were destroyed, and the termites were collected and weighed. An average of 25 g of termites was collected from each glass container. Five additional containers with sand and water but without samples were used as controls to evaluate the termites' vigor. The samples were subjected to attack for 0, 15, and 30 days. These samples are referred to throughout the text as 0TA, 15TA, and 30TA, respectively.

### Material Characterization

**FTIR Spectroscopy.** FTIR spectroscopy was conducted on a Nicolet Protégé 460 spectrophotometer (Madison, WI) to identify the evolution of the functional groups present at the surface of the samples as a result of their exposure to weathering. A photoacoustic detector was used for the experiments. The scans were run at a resolution of 8 $cm^{-1}$. For each sample, 100 scans were recorded from 4000 to 400 $cm^{-1}$. The peak intensities were normalized with the peak at 2912 $cm^{-1}$, which corresponded to the alkane CH stretching vibrations of the methylene groups. This peak was chosen as a reference because it changed the least because of weathering.[13] Three replicate specimens were analyzed for materials A, B, and C exposed to 0, 1000, and 2000 h of accelerated weathering. The samples were analyzed on the exposed side of all of the specimens. Special interest was focused on the carbonyl region and hydroxyl region.

**DSC.** A PerkinElmer DSC-7 (Waltham, MA) was used to monitor the thermal behavior of the composites exposed to accelerated weathering and termite attack. The samples were analyzed with a temperature profile after an initial equilibration at 50°C; they were ramped to 140°C at a rate of 10°C/min, held isothermally for 10 min, and finally cooled to 50°C at −10°C/min. All of the experiments were performed under nitrogen flow to prevent thermal degradation. In all cases, the analyzed samples were obtained from the surface of the composite.

**SEM.** Morphological analysis was performed on the sample surfaces by SEM. The WPC specimens were cut into small sections (6 × 6 $mm^2$) with a razor blade and were then mounted onto stubs and gold-coated with a sputter coater (Denton Vacuum Desk II). The samples were examined with a JEOL JSM-6360 low vacuum (LV) electron microscope (Tokyo, Japan) at a working distance of approximately 10 mm, a voltage of 10 kV, and a magnification of 100×. Sections of the previously weathered and nonweathered samples exposed to 0, 15, and 30 days of termite attack were analyzed.

**Mechanical Characterization.** Flexural tests were carried out with an Instron 5500R (1125) universal tester machine (Norwood, MA) according to ASTM D 790.[10] The three-point loading system was used with a crosshead speed of 10 mm/min and a 500-kg load cell. In each case, 10 specimens were tested to obtain the modulus of elasticity and flexural strength. The weathered samples were oven-dried at 105°C for 24 h before testing to ensure the same conditioning for samples before and after weathering. All samples were conditioned at 23 ± 2°C and 50 ± 5% relative humidity for at least 40 h before testing according to ASTM D 618.[10] Flexural characterization was performed on samples exposed to 0, 15, and 30 days of termite attack and previously subjected to 0, 1000, and 2000 h of accelerated weathering.

### Statistics

The collected data were analyzed with statistical software (Graphpad Software, Inc., San Diego, CA). The normally distributed data are shown as the mean plus or minus the standard deviation. Analysis of variance for repeated measures was performed with the mechanical properties results considered to be the variables. Dunnett's posttest was used for the determination of statistical significance, which was defined as a value of $p$ of less than 0.05.

## RESULTS AND DISCUSSION

### FTIR Spectroscopy

The FTIR results are presented in Figure 1, which shows the shape and location of the carbonyl and hydroxyl bands for the WPC samples after various times of exposure to accelerated

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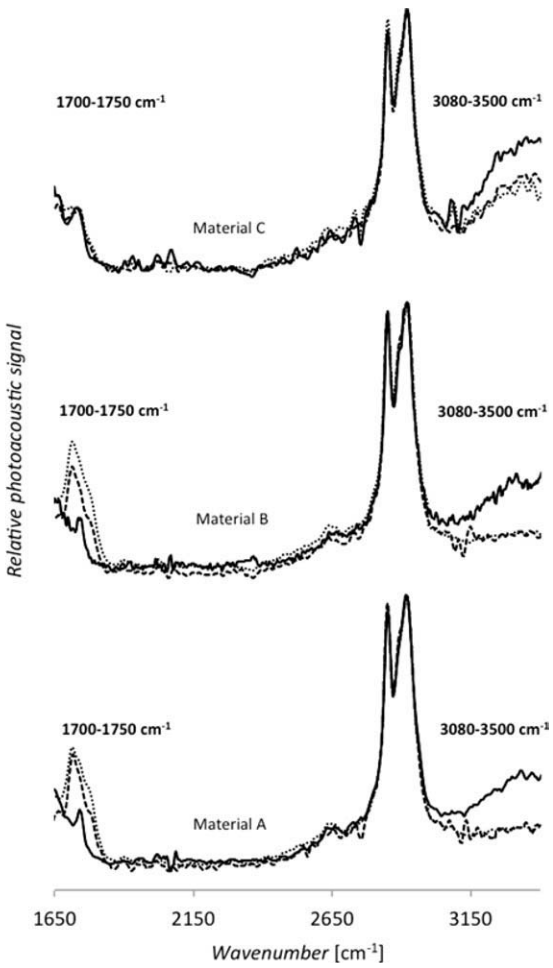


**Figure 1.** FTIR spectra of materials A, B, and C exposed to various accelerated weathering times: (—) 0, (- - -) 1000, and (· · ·) 2000 h.

weathering. Special interest was focused on the carbonyl region and hydroxyl region, which are indicators of WPC oxidation and wood content, respectively.[14]

In the carbonyl region (1750–1700 $cm^{-1}$), a sharp peak formed at 1715 $cm^{-1}$, and a shoulder peak at 1735 $cm^{-1}$, corresponding to carboxylic acid and ester groups, respectively, could be observed for materials A and B. The increase in the carbonyl group concentration due to weathering is known to be proportional to the number of chain scissions that occur in the polyethylene matrix. Then, our results indicated that chain scission increased as the exposure time to accelerated weathering also increased. Similar results were reported previously by Stark and Matuana.[13] On the other hand, the hydroxyl region (3080–3500 $cm^{-1}$), assigned to the presence of wood components, clearly showed a decrement in its concentration upon exposure of the samples to accelerated weathering; this meant that wood was lost in all of the composites. We also observed that composites A and B showed a similar decrement in wood content. Fabiyi and coworkers[14,15] reported similar behavior for weathered HDPE-based WPCs. Therefore, according to these results, it was evident that materials A and B showed a similar degree of degradation due to accelerated weathering.

When we compared the spectra of materials A and B with those of material C, we observed that the latter was not affected to the same extent. The carbonyl concentration on the surface of composite C remained practically constant during the analysis, contrary to what was noticed on samples obtained by compression molding, where a considerable increment was observed. From these results, we inferred that a higher number of polymer chains were broken in composites A and B. In addition, the hydroxyl index decreased the least on material C; this indicated that this composite lost less wood than its counterparts. Thus, accelerated weathering seemed to have affected material C to a lesser extent. This was attributed to the method by which this material was obtained. In this respect, it has been reported that the manufacturing method can actually affect the performance of WPCs when they are exposed to accelerated weathering. For instance, Clemons and Ibach[5] and Stark and Matuana[16] reported that different levels of temperature, pressure, and flow directly influenced the surface characteristics of WPCs and their response to weathering. They indicated that extruded and planed composite surfaces were more degraded by weathering than injection-molded ones because of the presence of a HDPE-rich layer on the surface of the injection-molded composites. In their work, they used a polymer matrix with MFIs of 0.70 and 0.72 g/10 min, respectively.

Like the previous researchers, we believe that our results indicate that the different processing methods we used produced samples with differences in their surface composition. Although the profile extrudates and pellets had a similar surface composition, the latter were arranged randomly within the press molds to obtain test samples. This means that it was likely that their surface composition was less homogeneous than that of the profile extrudates, which had surfaces slightly richer in HDPE. On the other hand, the higher MFI of our polymer matrix (4.56 g/10 min) in comparison with the values of the polymers used by the aforementioned authors[5,16] could have created a better protection for wood during extrusion because of a more efficient flow. As a result, composite C was expected to better resist the effects of accelerated weathering.

## DSC

DSC results are shown in Figure 2. The calorimetric curves for the melting regions of materials A, B, and C are presented for the weathered and nonweathered materials. We observed that because of accelerated weathering, new thermal energy absorption peaks (shoulders at about 110°C) appeared on materials A and B. Also, a broadening of the endotherm peak was observed but only on material A. Gulmine et al.[17] and Valadez-Gonzalez et al.[18] reported that the appearance of similar shoulders was due to the secondary recrystallization of short polymer segments produced by chain-breaking reactions on polyethylene samples exposed to accelerated weathering. On the other hand and supported by an additional literature survey related to this matter;[15] we inferred that the broadening of the endotherm observed only on composite A could have been caused by the lack of CA on its formulation. Thus, the HDPE in this composite could have experienced a higher increase in its crystallinity during weathering because of a reduction in the density of entanglements in the amorphous phase; this allowed the lower

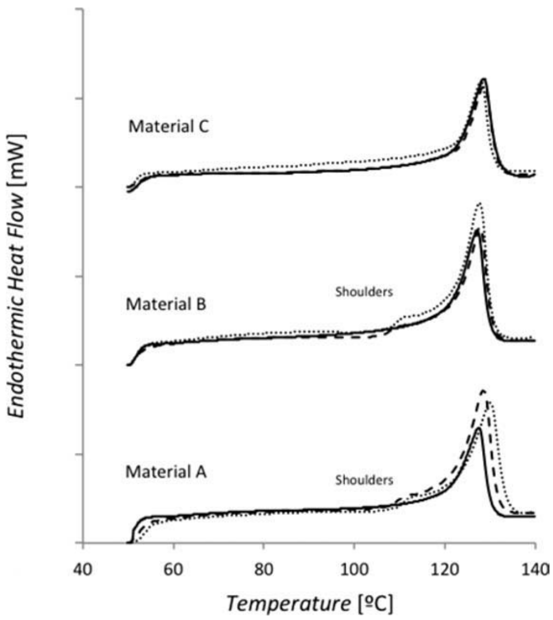


**Figure 2.** DSC thermograms of materials A, B, and C exposed to different accelerated weathering cycles: (—) 0, (- - -) 1000, and (· · ·) 2000 h of exposure.

molecular weight HDPE molecules to crystallize because of their higher mobility. It should be also mentioned that even after 2000 h of accelerated weathering, the melting temperature values of HDPE remained practically constant (i.e., 127.5 ± 2.5°C for material A and 127.2 ± 0.5°C for materials B and C).

With respect to the DSC thermograms of specimens subjected to both weathering and termite attack, the effects of UV degradation (secondary peaks and broadening of the endotherm) were not observed anymore because, we presumed, that once termites attacked test samples, they removed the superficial plastic layer to access wood. As UV light penetrated surfaces no deeper than 75 $\mu$m, as reported in the literature,[3] this explained the results presented. To exemplify this phenomenon, only thermograms corresponding to samples of composite A exposed to 30 days of biotic attack after 0, 1000, and 2000 h of weathering are presented for simplicity (Figure 3). These samples were the most affected by accelerated weathering.

According to our results, material C seemed to be less affected by the accelerated weathering process, whereas materials A and B presented a similar level of degradation. Once again, it is important to remark that whereas composites A and B were compression-molded, material C was obtained directly from a profile extrudate. As mentioned before, differences in processing methods produced surfaces with different compositions. Therefore, a richer polymer layer on the surface of composite C made it more resistant to accelerated weathering than the compression-molded ones. The DSC results were consistent with the trends observed by FTIR spectroscopy.

## SEM

The micrographs in Figure 4(a–i) show the surface of nonweathered materials exposed to different periods of termite attack. We observed that in all cases, the sample surface was relatively smooth and the polymer apparently encapsulated the wood particles. Therefore, when they were attacked [Figure 4(d–i)], no apparent damage was caused because seemingly no access route was provided for the termites' mandibles. Once composites were exposed to 1000 and 2000 h of accelerated weathering [Figures 5(a–c) and 6(a–c), respectively], cracks and holes appeared all over the surface; this exposed wood to the environment and, thus, provided access routes to termite attack. Fabiyi et al.[19] had similar results on HDPE-based WPCs exposed to accelerated weathering. They reported that the crazing of WPCs might have been caused by polymer chain scission reactions, which caused highly crystallized polymer zones under the surface that cracked during weathering.

The effect of termite attack on the surface of materials A, B, and C previously exposed to accelerated weathering is shown in Figures 5(d–i) and 6(d–i). We noticed that fibers were clearly degraded by the termites, especially in materials A and B. The wood fiber bundles looked broken and disordered after this biotic degradation process. We also observed that the termites removed the polymer matrix sections while degrading the wood. These results indicate that material C seemed to be the least affected. It seemed that in this case, the termites did not degrade the fibers as they did with materials A and B. As was previously shown by the FTIR and DSC results, a richer polymer layer on the surface of material C made it more resistant to accelerated weathering and, hence, enhanced its resistance to biotic attack.

Information on the damage caused by termites on WPCs is scarce.[3,20] However, research articles reporting the effects of other biotic agents on the aesthetic appeal of this kind of composites are available, for instance, the works of Schirp et al.[21] and Clemons and Ibach.[5] They observed that after fungal attack with white and brown rot fungi, the micrographs of the surfaces showed partially degraded wood particles as well as holes, where the wood particles were fully degraded. It was, therefore, remarkable that our results not only show that the termites affected the surface quality of the tested samples, as occurred in the presence of fungi, but it also seemed to be that they were more aggressive because they degraded both wood and plastic, removing the latter in their search for food.

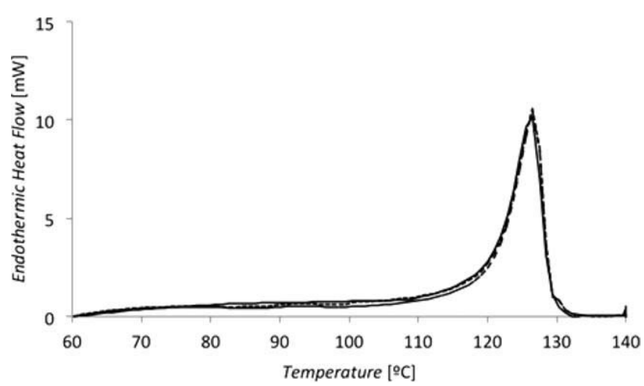


**Figure 3.** DSC thermograms of material A exposed to 30 days of termite attack after (—) 0, (- - -) 1000, and (· · ·) 2000 h of accelerated weathering cycles.

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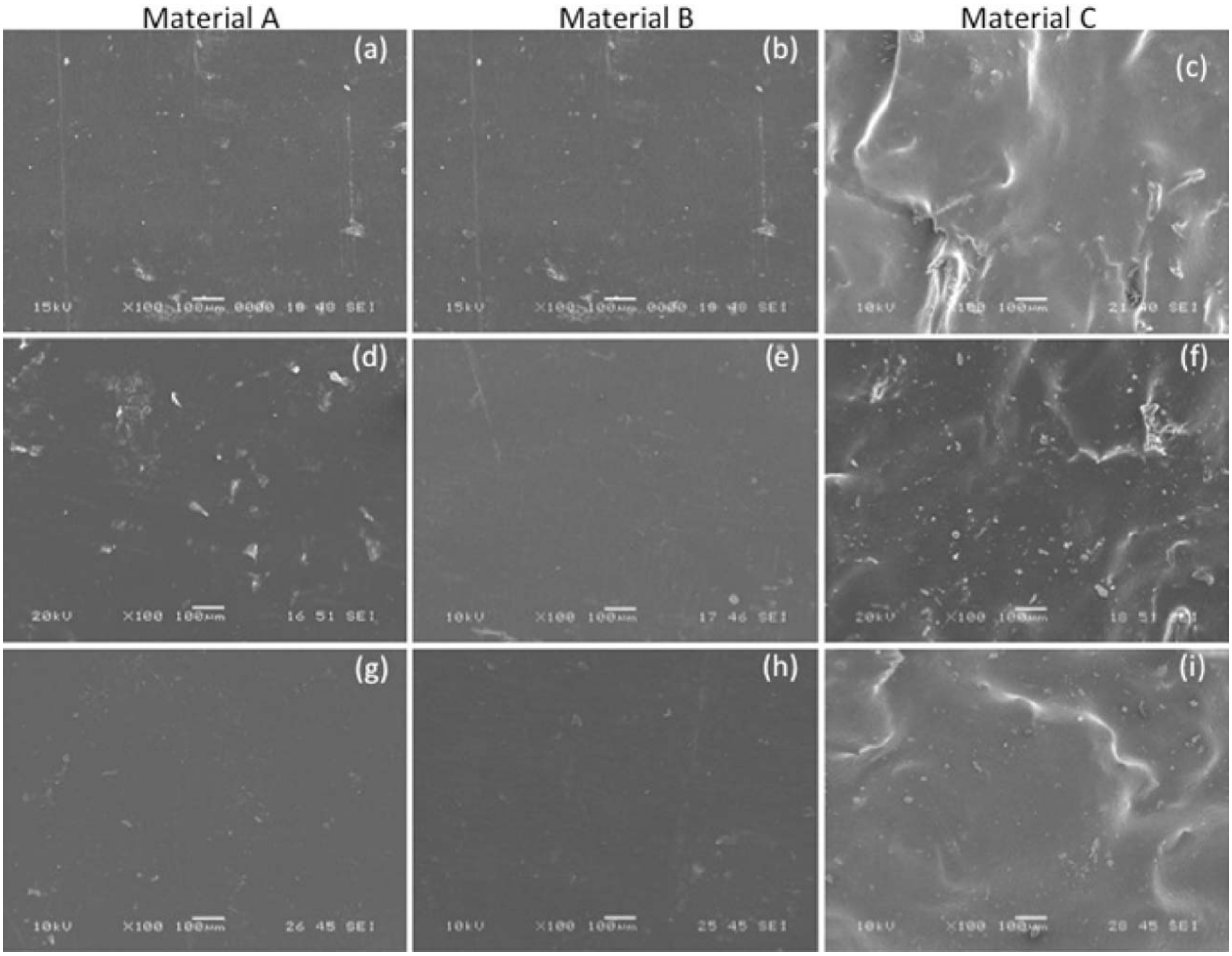


**Figure 4.** SEM micrographs of the nonweathered samples of materials A, B, and C exposed to termite attack. Exposure to termite attack = 0 days (a–c), 15 days (d–f), and 30 days (g–i).

**Mechanical Characterization**

The flexural properties are presented in Table II. With regard only to the effect of accelerated weathering, the flexural strength and modulus [modulus of elasticity (MOE)] of material A decreased slightly after 1000 h of exposure. After 2000 h, the flexural strength remained constant, whereas MOE dropped 11% from its initial value. For material B, a slight drop in its properties was observed after 1000 h; it experienced a very small additional decrement after 2000 h of accelerated weathering. In a similar trend, the flexural properties of material C slightly diminished after 1000 and 2000 h of exposure. Although the flexural properties for all of the composites decreased after weathering, those of material C, which was believed to have more HDPE on its surface, decreased the least. Composites A and B showed significant drops ($p < 0.05$), in contrast to what occurred with composite C.

With respect to the effect of termite attack, the properties of composite A previously aged for 1000 and 2000 h decreased significantly after 15 and 30 days of exposure, as shown in the results presented in Table II. Only in the case of the samples subjected to 2000 h of weathering and 15 days of biotic treatment, the change in strength was not significant, perhaps because the termites degraded the specimens randomly. Thus, in this particular case, it was possible that the attack was not homogeneous in the specimen's testing section. For material B, a significant decrement in the strength and module occurred only when the samples were previously exposed to 2000 h of accelerated weathering. In this case, the presence of a CA in its formulation could have retarded the degradation process. For material C, only drops in MOE were significant. It should be mentioned that the termites did not damage the nonweathered samples; therefore, their properties did not change, and hence, these results are not included in Table II.

The effects of other biotic agents on the mechanical properties of WPCs have been reported before. For instance, Schirp[22] studied the influence of fungal decay on the performance of extruded composites and concluded that decay fungi did not significantly affect the flexural strength of their samples. On the other hand, the stiffness (MOE) increased unexpectedly in soil block tests and registered nonsignificant decrements in agar-block tests. Once again, according to the results of this investigation, termites seemed to have caused more aggressive changes than fungi did to the mechanical properties of the extruded samples because MOE was significantly affected in all cases.

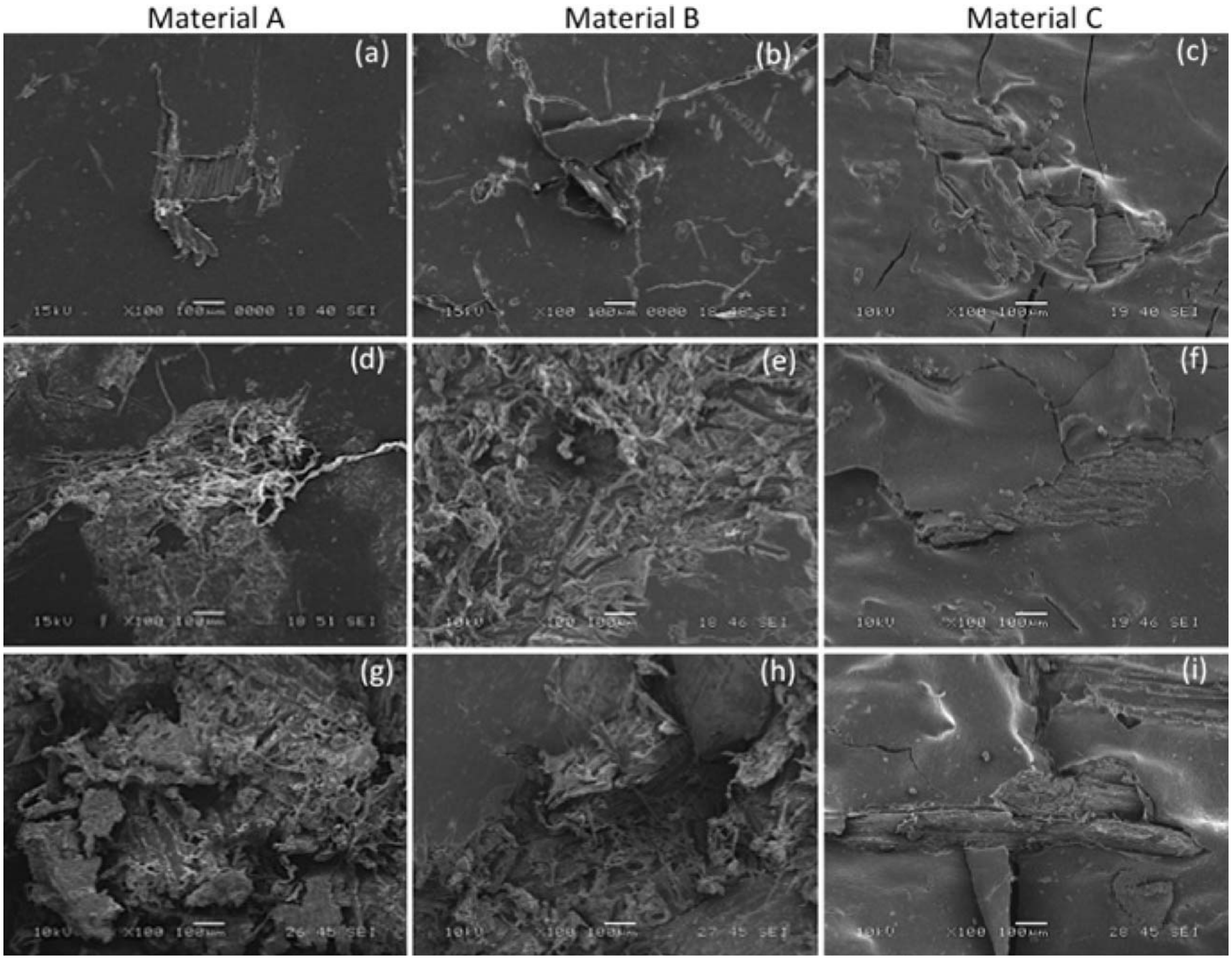


**Figure 5.** SEM micrographs of materials A, B, and C exposed to termite attack and 1000 h of accelerated weathering. Exposure to termite attack: 0 days (a–c), 15 days (d–f), and 30 days (g–i).

The results presented in this article, therefore, indicate that both accelerated weathering and termite attack caused a loss of mechanical properties in every tested material. In agreement with previous works, we observed that accelerated weathering was responsible for the appearance of cracks caused by chain scissions in the polyethylene, and the depolymerization of lignin and cellulose resulted in wood fragments that were leached by the action of water.[17,18,23] All of this led to the loss of mechanical properties. Additionally, in agreement with related literature, the results of this study demonstrate that termites were able to mechanically deteriorate wood and plastics by the action of their mandibles[24] and that while searching for food, they penetrated and damaged both cellulolytic and noncellulolytic materials, breaking them apart.[9] As a result, their mechanical properties were affected.

As it has been discussed, the diminishment of the flexural properties occurred to a different extent, depending on the formulation of the material and the processing method; these affected the surface appearance, the state of the interphase, and the density of the material. However, there may have been other factors that should have been taken into account. For instance, it is known that the vibratory characteristics of a material are intimately related to the processing method used to obtain it. As termites assess a material as a possible food source with its vibratory response, the processing method plays an important role in determining whether or not a material will be attacked by these insects; thus, this affects its mechanical performance. Inta et al.[25] gave an account of termites' ability to search for food with a material's vibratory response. It seems to be that the mechanism that they use to select their food is really sophisticated and includes more than simple cues such as mass or density and that vibrations produced by the termites themselves are also used to evaluate potential food sources.

## Termite Mortality

An assessment in terms of termite mortality based on a visual inspection of the containers was done according to ASTM D 3345.[12] The results show that after 1 week, virtually 100% of the organisms were alive. At the end of the second week, the mortality was around 40%, and this increased up to 70% by the end of the third week. Finally, after a month, the mortality was above 90% (nearly 100%) in most cases. Containers used as controls showed virtually complete survival after 1 week; this indicated that vigorous termites were used.

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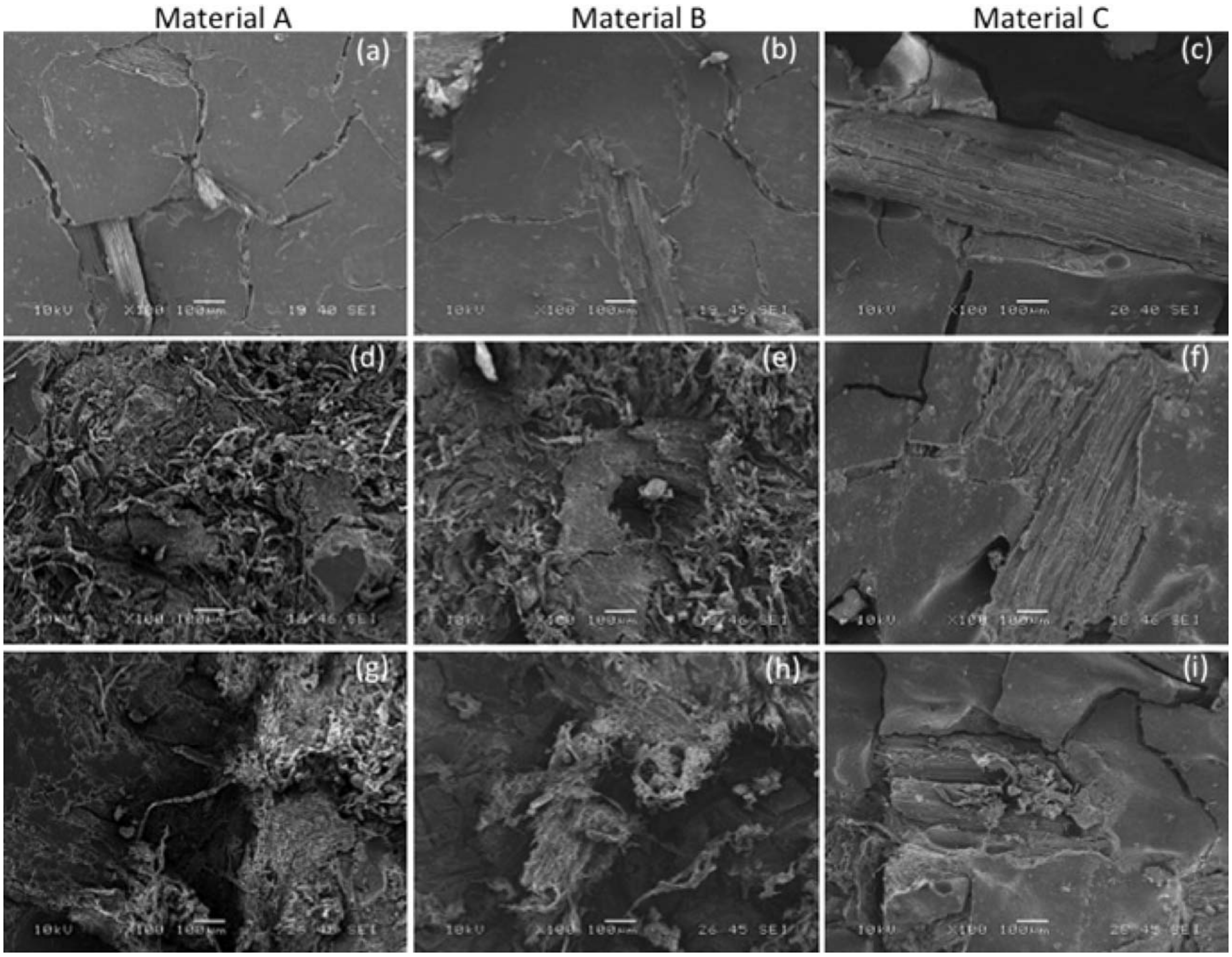


**Figure 6.** SEM micrographs of materials A, B, and C exposed to termite attack and 2000 h of accelerated weathering. Exposure to termite attack: 0 days (a–c), 15 days (d–f), and 30 days (g–i).

## CONCLUSIONS

Accelerated weathering produced cracks over the surfaces of all of the composites, leaving wood exposed to the environment and creating access routes to termites' mandibles; this caused significant changes in the mechanical properties. The number of cracks affecting the surfaces of all of the composites and the decreases in the flexural properties increased with increasing exposure time.

Termites constitute a serious threat to WPCs used for outdoor applications because they are able to produce significant changes

**Table II.** Flexural Properties of 40% Wood-Filled HDPE Composites after 0, 1000, and 2000 h of Accelerated Weathering

| | Strength (MPa) | | | Module (GPa) | | |
|---|---|---|---|---|---|---|
| Degradation process | Material A | Material B | Material C | Material A | Material B | Material C |
| 0AW | 13.7 (0.53) | 14.1 (0.20) | 9.8 (0.40) | 0.52 (0.06) | 0.58 (0.03) | 0.33 (0.04) |
| 1000AW | 12.2 (0.37) | 13.2 (0.50) | 9.1 (0.63) | 0.50 (0.02) | 0.52 (0.03) | 0.31 (0.04) |
| 2000AW | 12.2 (0.38) | 12.2 (0.40) | 9.1 (0.50) | 0.46 (0.02) | 0.47 (0.02) | 0.29 (0.04) |
| 1000AW + 15TA | 10.6 (0.69)[c] | 12.9 (0.34) | 8.4 (0.98) | 0.38 (0.02)[c] | 0.49 (0.02) | 0.23 (0.03)[b] |
| 2000AW + 15TA | 11.7 (0.68) | 10.5 (0.58)[c] | 8.6 (0.80) | 0.42 (0.02)[a] | 0.37 (0.03)[c] | 0.23 (0.02)[b] |
| 1000AW + 30TA | 10.7 (0.33)[c] | 13.2 (0.30) | 8.5 (0.93) | 0.48 (0.01)[a] | 0.48 (0.04) | 0.23 (0.03)[b] |
| 2000AW + 30TA | 10.4 (0.22)[c] | 10.6 (0.59)[b] | 8.6 (0.30) | 0.42 (0.01)[a] | 0.42 (0.04)[a] | 0.26 (0.02)[a] |

Test specimens were obtained by compression molding and extrusion. The values listed are the means plus or minus the standard deviation (in parentheses) values of five probes per group. The superindices indicate values significantly different from the 0 days TA matched group, [a]$p < 0.05$, [b]$p < 0.01$, [c]$p < 0.001$.

in their flexural properties and in their aesthetic appeal. Insects were able to remove plastic from the materials' surface to reach the wood, which was clearly degraded as it was identified as a food source. Evidently, once the HDPE and wood were removed from the composites, their mechanical properties decreased.

The presence of a CA on the composite formulation did not prevent the loss of its flexural properties; however, it seemed to delay it. Although the flexural properties of the weathered samples of materials A and B decreased after termite attack, the decrease for composite B was significant only after 2000 h of aging. Thus, it seemed that the presence of a CA helped to retard the effects of termite attack on such material.

The processing method seemed to interfere with the severity of termite attack, even in the case of materials previously exposed to accelerated weathering. The flexural properties characterization and SEM results demonstrated that the profile-extruded samples were more resistant to termite attack. This could have been due to a higher amount of HPDE on their surface as a result of the processing method used to obtain them.

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