Characterization of the property changes of extruded wood–plastic composites during year round subtropical weathering

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Highlights

- Increased degradation rates were characterized in subtropical outdoor WPCs.
- Color shaded at the first 90 days and cracking occurred after 90 or 180 days.
- Carbonyl indexes increased continuously to 50–100% in 1 year.
- Morphology of fracture areas confirmed with the experiment results.

Abstract

Wood–plastic composites (WPCs) are an emerging material which has been widely applied in outdoor application, but their long-term decomposition behaviors under subtropical weather have not been completely characterized. In this study, WPCs manufactured using recycled wood flour and polypropylene resin were tested for the changes in surface characteristics, physical properties, and mechanical strengths after different time of weathering exposure for one year. Color differential tests showed that significant increase in lightness occurred at the first 90 days of weathering exposure, while notable cracking and mass loss of the components occurred after 90 or 180 days. Carbonyl indexes increased continuously during the testing period for all the tested WPCs. Moisture contents increased most significantly at the initial 90 days of the weathering tests and reached steady states afterward. Increases of water absorption and thickness swelling, and decreases in mechanical properties, were not dramatic except for the samples with excessive-dosed wood contents (i.e. 60% wood flour). The degradation rates of all the parameters were higher than the literature values, which is most likely due to higher sunlight intensity and heavier rainfall in the tested subtropical regions. Changes in morphology of the WPCs surfaces and fracture areas confirmed with the experiment results, and more “pulled-out” fibers were observed for the WPCs after 1 year weathering exposure.

1. Introduction

New generation wood–plastic composites (WPCs) are an environmental-friendly green material created from the “marriage” of the forestry and plastic industries [1,2]. This type of new materials differ from the conventional wood–plastic products, which were mainly composed of virgin thermosetting resins (i.e. phenol- or melamine-formaldehyde resin) and different types/shapes of woods (i.e. sheets, particles, or fibers), and can be manufactured by using recycled wood flour (WF) and recycled plastic resins [3]. Additional values can be created and the service life of wood products can be extended, resulting in significant reduction in environmental impacts and carbon footprint of the waste materials [4]. Furthermore, WPCs have many unique properties which differ significantly from the original materials: WFs can provide physical support to the plastic matrix and increase the mechanical strengths (i.e. stiffness) of the products [5]. Although the biological resistance of WPCs is not as superior as believed by the conventional wisdom [6], the plastic matrix do can provide protection to the wood fiber from moisture: if the wood fiber and plastic can be properly bounded through coupling agents and suitable wood/plastic combination, the resistances of WPCs to water.
absorption and thickness swelling can be significantly improved [7].

WPCs have found applications in many areas, i.e. automotive industries, windows, doors, and decking [8,9]; and have become very popular in Europe and the United States [1,10]. WPCs have also been widely used in outdoor applications, i.e. public facilities, and industrial or recreational purposes. When applied in the outdoor environment, however, different weathering conditions, i.e. sunlight exposure, rainfall, changes in humidity and/or temperature, could considerably affect the durability of WPCs. Wood is a biomaterial with which the physical and mechanical properties can be significantly affected by the ambient conditions, especially when the plastic matrix cannot completely cover the wood fibers.

Many studies have been carried out to investigate the changes in properties of WPCs under artificial and/or outdoor weathering conditions. Kiguchi, Kataoka, Matsunaga, Yamamoto and Evans [11] investigated the color changes of a WF/PP composites after nature and artificial weathering exposure and showed that color differentials and brightness of WPCs both increased and achieved the maximum value after 3 months weathering exposure. Stark, Matuana and Clemons [12] compared the changes in surface and weathering characteristics of WF/HDPE composites manufactured by different molding processes (i.e. injection, extruded, and planed samples), and showed that color changes were not a function of the manufacturing processes but the weathering resistance do reduce with the percent exposure of WF. Injection-molded WPC had higher flexural MOE and strength properties after weathering in comparing to WPCs produced after other types of molding processes; the differences were more significant in the first 1000 h, which is possibly due to higher moisture exposure at the period. In a following study the same research group showed that the densities of WPC decreased with the weathering, and observed the damaged surfaces which may cause the reduction of densities through weathering processes [10]. Furthermore, La Mantia and Morreale [13] investigated the photooxidation of the WF/PP WPCs under accelerated weathering conditions, through sophisticated FTIR analysis, and suggested that degradation of plastic is more severe than the degradation of WF in the composite materials.

Among all the previous studies, which many of them were conducted under accelerated weathering conditions [10,12,14–18], the long-term dynamic changes in physical and mechanical properties of the WPCs under outdoor environment were not investigated. Most of the outdoor weathering tests, furthermore, were conducted in the western countries with temperate weather with relatively lower sunlight intensity, humidity, and temperature [19]. The results of accelerated aging may not directly reflect to the outdoor degradation behavior of the WPCs at different testing regions, i.e. in subtropical regions discussed in this study. In addition, the influences and sensitivity of changing WF/PP ratios to weathering durability was not clear. This study, therefore, performed a set of year-round outdoor exposure tests on the recycled waste-derived WPCs manufactured after our previous works [7], which investigated the optimal composition of recycled WF/PP WPCs after extruded molding. During different periods of outdoor exposure various types of property analyses were carried out to investigate the effects of changing the WF/PP ratios to color changes, chemical characteristics (i.e. FTIR and carbonyl index analysis), physical and mechanical properties. It was expected by the authors that through the experiments a more clear understanding can be obtained for the long-term weathering behaviors of the WPCs in subtropical regions.

2. Materials and methods

2.1. Materials

Recycled WF, PP, coupling agent, and lubricant were similar to the authors’ previous work [7]. The recycled WF was wood processing sawdust provided by Bestwood Co., LTD, Taiwan. The recycled PP (Code ST868 M) pellets was prepared from recycled plastic containers by Shih-Jie Inc., Taiwan. The coupling agent, i.e. Maleic Anhydride Polypropylene (MAPP), and the lubricant, i.e. Zinc stearate (Zn(C18H35O2)2, ZnSt), were prepared by Plastics Industry Development Center (PIDC), Taiwan. The sawdust was composed of three species, i.e. spruce, pine, and fir (SPF). Before experiment the WF was oven dried at 105 °C until the moisture content decreased to 2% and then screened to remove the large particles by an automated mesh. Wood particles with size smaller than 125 μm (120 mesh screen) were used in this study.

2.2. WPC sample preparation

Extruded WPC samples with four WF/PP ratios were tested, and the compositions of the WPCs were shown in Table 1. The percentages were the mass ratios of WF and PP before compounding. For the four tested samples (i.e., PP-70, -60, -50, and -40), the wood contents in the mixture were gradually increased from 30% to 60%, respectively. The chemical reagents, i.e. the MAPP and ZnSt, at mass contents of 3%, were mixed into the wood–plastic mixture. The actual mass contents of wood and plastics in the WPC were therefore slightly less than the values presented in Table 1. The dosages of the chemical reagents were optimized based the authors’ previous works [7] and will not be tested again in this study.

The WF–PP mixtures were mixed with the chemical reagents in a banburing machine for producing the wood–plastic pellets. The total mass of the mixed materials for each compounding series was 3 kg. The mixing rate, temperature, and mixing time were 5.23 rad s⁻¹ (50 rpm), 180 °C, and 15 min, respectively. The wood–plastic pellets were oven-dried at 105 °C for 24 h. Extruded molding was performed by a single-screw extruder with 7 mm screw diameter and 28:1 length to diameter ratio. The extruding temperature was between 150 and 170 °C, and the extruding speed was 0.7–0.8 m min⁻¹, respectively. The cross-section dimensions of the extruded samples were 95 mm wide and 4.5 mm thick, and the length of the samples can vary depending on the requirement.

2.3. Year-round weathering exposure tests

Weathering tests were performed after the Chinese National Standards (CNS) method (CNS 8909). The WPC samples were placed on the rooftop (5th floor) of the main building of the Forestry Department in the National Chung Hsing University, Taiwan (24.7°N, 120.40°E). The mean temperature at the location was 23.8 ± 4.9 °C during the testing period. The maximum observed temperature was 35.7 °C and the highest monthly average was 29.1 °C, and the minimum monthly average temperature was 16.5 °C with the lowest observed temperature 10.1 °C. The average monthly relative humidity (R.H.) was 73.0 ± 2.3%. The maximum monthly average R.H. was 77% and the minimum R.H was 70%. The average solar ultraviolet index (UVI) was 5.7 ± 1.4, with a maximum of 8.2 at July and a minimum of 3.7 at December, respectively. The maximum observed UVI was 11. The monthly rainfall of the testing location was approximately 126.1 ± 94.0 mm, and the rainfall days in a month ranged between 5 and 17 days. The average sunlight exposure time in a month was approximately 149.3 ± 33.8 h.

The samples were mounted on a testing stand with 45° angle to the horizon and facing toward the south for maximizing the sunlight exposure. The samples were harvested for property tests after 3, 6, 9, and 12 months of weathering exposure. The evaluated properties included the surface characteristics, carbonyl index, and the physical/mechanical properties after damages tests. The experiment procedures of the property tests were presented in the following sections in greater details.

Table 1

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Wood/plastic ratio (wt%)</th>
<th>Wood</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP-70</td>
<td>30</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>PP-60</td>
<td>40</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>PP-50</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>PP-40</td>
<td>60</td>
<td>40</td>
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</table>

* The ratios are for the wood/plastic mixture before mixing with the other chemical reagents (see text for more details).
2.4. Color coordinates

Color coordinates were measured by using a CM-3600 spectrophotometric colorimeter (Minolta Co., Japan). Illuminant D65 with 10° observer angle was used and the diameter of the observation window was 8 mm. The samples were placed on the observation windows for measuring CIEL*a*b* (lightness, a* (redness), and b* (yellowness)) based on the CIELab system developed by the International Commission on Illumination (CIE, 1976). The changes in the various color parameters over time were evaluated by comparing the results with the initial measurements using the following equations:

\[ \Delta L' = L'_1 - L'_0 \]  
\[ \Delta a' = a'_1 - a'_0 \]  
\[ \Delta b' = b'_1 - b'_0 \]  
\[ \Delta E' = \sqrt{(\Delta L')^2 + (\Delta a')^2 + (\Delta b')^2} \]

where \( \Delta L' \), \( \Delta a' \), and \( \Delta b' \) represent the overall color differential of the samples.

2.5. Carbonyl index

Carbonyl indexes were measured by a PerkinElmer Fourier Transform Infrared spectroscopy (FTIR, Spectrum 100, USA) after attenuated total reflectance (ATR) mode, or ATR-FTIR. The ATR-FTIR can analyze the WPC samples without pulverization. For each sample, 32 scans were conducted and the spectra between 4000 and 600 cm\(^{-1}\) absorption units were recorded. The carbonyl index was determined by comparing the peak intensity of the carbonyl group measured at 1735 cm\(^{-1}\) with that of the methyl group at 2916 cm\(^{-1}\), by using the relationship developed by Stark and Matuana [14] as follows:

\[ \text{Carbonyl index} (%) = \frac{I_{1735}}{I_{2916}} \times 100 \]

where \( I_{2916} \) is the peak intensity of \(-\text{CH}_3 \) at 2916 cm\(^{-1}\); and \( I_{1735} \) is the peak intensity of C=O measured at 1735 cm\(^{-1}\).

2.6. SEM images

SEM images were taken to visualize the morphology of the WPCs surfaces before and after the weathering tests, and the surfaces of sample breakages after mechanical property tests. The degrees of magnification of the images were 50–500, and the model of the SEM was Hitachi S-4800 (Hitachi High-Tech. Corp., Japan).

2.7. Physical and mechanical property tests

The physical and mechanical properties of the WPCs were determined based on similar approaches presented in the authors’ previous works [7]; and the measured parameters were summarized as follow: (a) physical properties – density, moisture content, water absorption, and the thickness swelling were measured after the standard procedures. The changes of sample weights and thickness were measured after 2, 4, 6, 12, and 24 h water dipping; and (b) mechanical properties – static bending tests and tensile strength tests were carried out based on the standard methods of ASTM D638-08 [20] and ASTM D790-10 [21], respectively.

The mechanical property tests evaluated the static modulus of elasticity (MOE) and modulus of rupture (MOR) after the bending tests; and the tensile modulus of elasticity (MOE) and the tensile strength (or the tensile modulus of rupture, MOR) were evaluated after the tensile tests. The results presented in this study are averages of twenty replicates for each testing condition. To quantify the changes in mechanical properties of the WPCs after weathering tests, the retained MOR and MOE ratios (i.e. \( R_{\text{MOR}} \) and \( R_{\text{MOE}} \), respectively) were calculated by using the following equations:

\[ R_{\text{MOR}} = \frac{\text{MOR}}{\text{MOR}_0} \times 100 \]  
\[ R_{\text{MOE}} = \frac{\text{MOE}}{\text{MOE}_0} \times 100 \]

where the indexes with subscript “0” were the initial data and ones with subscript “T” were measured after weathering tests at the selected time points, i.e. \( \text{MOR}_0 \) is the MOR measured after 0 days of weathering tests.

2.8. Statistical analysis

Statistical analysis was carried out using the Analysis of Variance (ANOVA) function provided by the Statistical Package for the Social Sciences (SPSS, IBM Corp., USA). The differences of experiment results collected from different testing groups were analyzed using the Turkey test with 95% confidence intervals.

3. Results and discussion

3.1. Changes in surface structure

The changes in surface morphology of the WPCs under SEM before and after outdoor weathering tests were shown in Fig. 1. Before weathering tests, the surfaces of the WPCs were all very smooth, while after weathering tests different severities of cracking were observed for the four WPCs. Severe cracking was observed on the sample surfaces of WPCs with the highest wood/plastic ratio (i.e. PP40, Fig. 1(a)), and the cracking was less severe at WPC surfaces with increasing PP contents. In PP40 and PP50, a part of the plastic matrix was removed from the WPC, and hence the inner layer of the WPC was exposed. While cracking was also observed on the surfaces of PP60 and PP70, the damages were not deep enough to penetrate the outer layer of the plastic matrix, so the majority of the plastic matrix was still remaining on the surfaces of the WPCs. Repeated sunlight exposure may accelerate the degradation of the materials; frequent changes in moisture contents and/or temperature may cause swelling of the WF and furthermore damage the bonding between WF and plastic matrix; and the damaged parts of the WPCs may be washed away by the rain. The data of color changes and FTIR analysis were investigated to provide detailed explanations to the observation.

3.2. Color changes

The results of four color indexes (i.e. \( L' \), \( a' \), \( b' \), and \( \Delta E' \)) were plotted over the exposure time in Fig. 2(a)–(d), respectively. The shaded bars shown in Fig. 2(a) were the daily rainfall of the testing site with a maximum of 98.9 mm. The lightness of all WPCs increased dramatically from approximately 52.3–56 to 67.2–77.2 after the first 90 days of exposure. After 90 days of weathering exposure, the lightness of sample PP40 (with lowest amount of PP content) started to decrease, and the decreasing continued until the end of the weathering tests; and the final lightness of PP40 was 66.5. The lightness of PP50, PP60, and PP70 increased only slightly after 90 days of exposure and then decreased gradually between 180 and 270 days of exposure. After 270 days of weathering, the lightness of the three samples increased slightly toward the end of the experiments, and the final lightness of the samples were 67.8–68.5. The lightness was very close for all WPCs before and after 360 days of weathering exposure, and the differences are mainly on the rates of changing.

The different changing rates in lightness of the WPCs could be due to two reactions as discussed in the previous studies of Kiguchi, Kataoka, Matsunaga, Yamamoto and Evans [11]. At the beginning phased of weathering exposure the WPCs became brighter, which was possibly due to sunlight degradation of the colorful compounds in the WF; and then in the second phase the damaged part of WPCs (due to cracking and/or chalking) at the sample surface may be opened or washed away with rainfall. The inner part of the WPC which was better covered by the plastic matrix was exposed, and then the changes became less significant afterward. The pattern of the changes in redness and yellowness after Day 90 were different:
except PP70 the redness of the WPCs decreased to nearly zero at Day 270, and the yellowness of the WPCs increased considerably at the same time except for sample PP40 (yellowness did not increase). The increases in yellowness were roughly related to the amount of PP in the samples. The reduction of the redness and yellowness of WPCs could be due to different mechanisms, i.e. sunlight exposure or rainfall intensities. The measurements conducted at Day 270 were at the dry season; therefore the WPCs were yellower than measurements conducted during other testing periods, whereas degradation of redness may be less reversible.

Amongst all the tested WPCs, sample PP70 showed the highest resistances on color changes to weathering, and WPCs with higher WF contents (PP40–PP60) had similar levels of resistances to color changes. Kiguchi, Kataoka, Matsunaga, Yamamoto and Evans [11] showed that the color changes of WPCs (with a 55:45 WF/PP ratio) was most dramatic at the first 90 days of nature exposure; then it decreased slightly and stabilized to reach a plateau after 180 days exposure. The significant changes in color differential was confirmed in our study at the beginning 90 days of exposure, with differences on maximum $\Delta E's$ (i.e. maximum values around 20–25). Rather than stabilizing after Day 180, furthermore, the $\Delta E's$ continuously decreased over time until Day 270, and then increased again until, especially in the samples with higher PP contents. The differences between our studies and the references could be due to the more stringent weather conditions in this study, i.e. higher sunlight intensities and rainfalls.

Photodegradation and yellowing of WPC have been observed in many studies and hence several hypotheses have been proposed to explain the mechanisms of the color changes. Muasher and Sain [22] suggested that color changes could be due to two reactions: (a) lignin oxidation to form the paraquinone chromophoric structures (causing decrease of $b^*$) in the beginning 250 h of exposure, and (b) reduction of the paraquinone structures to form

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![Fig. 1. SEM images of WPCs surface before and after 360 days outdoor weathering tests. Subfigures (a)–(d) show the WPCs with the lowest to highest plastic contents (i.e. 40%, 50%, 60%, and 70%, respectively). Cracking is more severe with increasing wood contents.](image-url)
hydroquinones (photobleaching). Photobleaching has been observed throughout this work, but significant increase in yellowing was not observed at the beginning stage of weathering exposure. It could be possibly due to the longer weathering period (90 days) than the previous study. Yellowing did occur, however, during the dry season at Day 270, and was found in the WPCs with higher plastic contents. The delay in yellowing could be due to different levels of exposure of the WF to the atmosphere, but the mechanism relied on more sophisticated experimental works and further investigation.

3.3. ATR-FTIR and carbonyl index

ATR-FTIR analysis was conducted to evaluate the changes in chemical properties of the WPC samples at the surfaces of the samples, and an example FTIR spectrum of sample PP40 was shown in Fig. 3. FTIR scans were conducted in similar fashion to all other samples during different time of weathering exposure, and the patterns of property changes were all similar (spectrums of PP50–PP70 were not shown). The responses of lignin and polysaccharides both decreased over time of exposure. The band at 1510 cm\(^{-1}\) (mark (d) in Fig. 3) and 1595 cm\(^{-1}\), representing the ether groups in lignin [19], and the band at 1240 cm\(^{-1}\) for the C=O stretching of the aromatic compounds of lignin (mark (e) in Fig. 3), both decreased or disappeared after 90 days of outdoor exposure. The broad peak between 3050 and 3600 cm\(^{-1}\) (mark (a)) for the hydroxyl groups of polysaccharides [19] also decreased over time after weathering exposure.

Photodegradation of polymers were carried out through two reactions, i.e. Norrish Types I and II reactions [23]. Stark and Matuana [14] provided detailed explanation of the photodegradation processes in WPCs: in Norrish Type I reactions, UV radiation stimulates the cleavage of the carbonyl groups and forms free radical. The free radicals then attack the polymer, causing chain scission or crosslinking. In Norrish Type II reactions, carbonyl and vinyl groups are formed from the chain and the cleavage of the carbonyl group will continue. With the repeating of chain scission and crosslinking, short molecule polymers are formed, resulting in higher crystallinity and higher MOE of the materials.
Measuring the amount of vinyl groups formed in the compounds, therefore, can effectively characterize the conditions of photodegradation. Before Day 180, the band of the vinyl group at 1640 cm⁻¹ increased significantly over time of weathering exposure, implying the PP plastic resin was undergoing the Norrish II degradation [24]. The changes in carbonyl groups, i.e. the band at 1714 cm⁻¹ (mark (c), Fig. 3) for hydrogen bonded carboxylic acids and the band at 1735 cm⁻¹ for esters both increased, confirming the photo-oxidation of the WPC [24]. After 180 days of exposure, the band of vinyl group stopped to increase or even slightly decreased with the increasing exposure time, disregarding to further oxidation of PP. This is possibly due to the physical wash-off of the oxidized materials at the sample surface, which furthermore confirmed the hypothesis made from the observation from color changes (significantly brighter and then slightly darker).

Carbonyl indexes were calculated to quantify the degree of photo-oxidation of the WPCs, and the results of the four WPCs over different time of weathering exposure were presented in Fig. 4. The initial carbonyl index of PP70 was much lower than the other samples (15.5% versus 18.6–19.5%), suggesting a more complete coverage of the PP matrix on the WPC surface of the sample. Carbonyl indexes increased with the increasing time of exposure for all samples with minor variations among the WPCs. The differences in the changing patterns of the tested WPCs could be also caused by the different rates of wash-off of the PP over time. The steady increase in the carbonyl index for sample PP70, with the lowest degrees of material wash-off (Fig. 1(d)) through better formation of the plastic matrix, confirmed the hypothesis.

3.4. Changes in physical properties

Physical properties of the WPCs were measured to clarify the impacts of weathering exposure to the strengths of the composite materials. The physical properties, including densities, moisture
contents, water absorptions and thickness swellings were presented in Fig. 5(a)–(d), respectively (i.e. detailed data and statistics were provided in Table S1). Densities of the WPCs were not changed significantly throughout the weathering tests except PP40, for which its density decreased with the time of exposure (Fig. 5(a)). Stark and Matuana [10] suggested that high thickness swelling of certain WPCs could result in lower densities after weathering. Moisture contents (Fig. 5(b)) and water absorptions (Fig. 5(c)) increased considerably for all WPC samples after 360 days of weathering exposure. The patterns of changes in moisture contents over time were not very consistent for all WPCs during weathering exposure (especially at Day 360), but it was clear that PP40 had much higher moisture content than all the other WPCs. Water absorption was carried out on the WPCs after different time of weathering exposure, and PP40 absorbed much more water than the other WPCs. Water absorption of different WPCs after 360 days exposure was 10.2% for PP40; 3.1% for PP50 and PP60; and 1.5% for PP70. The damaged surfaces of WPCs after weathering may result in higher accessibility of water to the WF in the plastic matrix and reduce the resistances to water absorption. The patterns of the increases of thickness swellings (Fig. 5(d)) confirmed with increasing water absorptions. For example, PP40 with the highest WF content showed significantly higher thickness swelling than all the other WPCs.

3.5. Changes in mechanical properties

The changes of the tensile strength, MOR, MOET, and MOEB of the WPCs during weathering exposure were presented in Fig. 6(a)–(d) (i.e. the numerical data was presented in Table S2). The tensile strengths of the WPCs all decreased with increasing time of exposure, as expected. The tensile strength of PP40 was significantly lower than the other samples. The tensile strength of PP40 was only 0.60 MPa after 360 days of exposure, and the tensile strength of other WPCs were approximately similar to PP40 before...
exposure (8.3–9.8 MPa). The performances of MOR over time of exposure were similar to the pattern of tensile strength. The MORs of PP50, PP60, and PP70 were significantly higher than PP40, and all decreased with increasing time of weathering exposure. In line with the changes in physical properties of the products (i.e. water absorption and thickness swelling), changes in PP content do show significant impacts to the mechanical properties of the WPCs.

The patterns of changes in the modulus of elasticity (MOET in Fig. 6(c), and MOEB in Fig. 6(d), respectively) differed slightly than the ones for tensile strengths and MORs. Before weathering exposure, the elasticity of the WPCs increase with the amount of WF contents in the WPCs. At the beginning time of exposure the elasticity of all WPCs (especially PP40) all increased with exposure time, but then decreased after different time of weathering exposure. For PP40, PP50, and PP60 the MOET started to decrease after 90 days exposure, and the time of decrease of MOET initiated after 180 days of exposure. Degradation of MOEs was most significant for PP40 and less severe for the other WPCs with higher plastic contents.

Physical and mechanical properties of the WPCs were highly related to the wood/plastic ratios. Percent changes of several key physical and mechanical properties after 360 days weathering exposure were summarized in Fig. 7 (i.e. numerical data presented in Table S3). Five parameters were plotted against the increasing plastic contents in the WPCs, and the presented parameters include: (1) water absorbed, (2) thickness swelling (giving the unit in the Y-axis at the left side of Fig. 7), and percent strength retained of (3) MOET, (4) MOEB, and (5) MOR (unit presented at the right Y-axis of Fig. 7). The results implied that keeping wood/plastic ratio to be less than 50:50 can be crucial to the overall properties of the WPC. When increasing the plastic contents from 40% to 50%, water absorption and thickness swelling dropped dramatically from 10.2% to 3.1% and from 3.2% to 1.3%, respectively. When

![Fig. 8. SEM images of the fractures surface of tensile tested WPCs before and after 360 days outdoor weathering exposure.](image-url)
increasing the plastic contents from 50% to 60%, furthermore, the rates of reductions of water absorption and thickness swelling became less significant or even stopped to decrease. Increasing the WF content to 70% provided the highest water resistances, but the improvements were not very dramatic in comparing to the effects between 40% and 50%, or 50% and 60%.

The patterns of increases of strength retains were slightly different among the three parameters MOET, MOES, and MOR. After 360 days of weathering exposure, the strength retained of MOET for PP40 and PP50 increased significantly with increasing PP contents (from 15.48% to 78.69%), and then the improvement gradually decreased with the increasing PP contents. The final strength of retained MOET was 120.6% for PP70, which is better than before and MOR due to increasing PP products.

Morphology of the WF–plastic interaction was investigated through SEM images, and the fracture surfaces of the tensile tested WPCs before and after 360 days weathering exposure were shown in Fig. 8. The WPCs with increasing PP contents (i.e. from 40% to 70%) were shown in Fig. 8(a) through Fig. 8(d). Before weathering exposure, the bonding between the WF and plastic matrix were reasonably well for most of the WPCs: the fracture occurred on both the WF and plastic matrix and only small fraction of the “pull-out” effects were observed for the larger fibers. The plastic matrix still attached well with the fibers after the tensile tested. While after 360 days of weathering exposure, the pull-out effects for the large fibers were observed at the fracture surfaces of all tested WPCs. Weathering exposure could have caused chain scission of the PP plastic via photodegradation [22] and/or moisture intrusion through the cracks of the sample surfaces or swelled structures, resulting in the larger gapping between the WF and plastic matrix. Reduction in mechanical properties confirmed with the observation under SEM. Increasing the dosages of coupling agents to improve the bonding between the WF–plastic interaction, this observation confirmed with our hypothesis discussed in the previous study [7].

4. Conclusions

Surface and mechanical properties changes of extruded WF/PP WPCs manufactured at different wood/plastic ratios were monitored for 1 year to investigate the weathering performances of the materials. The property changes of the WPCs generally confirmed with previously stated hypotheses, although the rates and/or scales of degradations of certain parameters (i.e. color changes) were much severe than some references with similar testing conditions. These differences could be due to the more stringent weathering conditions in the location of the weathering tests, i.e. higher rainfall frequencies (5–17 days/month), overall precipitation (1200 mm/yr), temperature (9.6–37.5 °C), and sunlight exposure (88.7–188.6 h) in the subtropical zone, in comparing to other testing regions.

The results of color differentials, ATR-FTIR, and morphology provided useful information on the changes of the physiochemical properties at the WPC surfaces. The changes in chemical properties, i.e. photobleaching and photodegradation, initiated with highest rates at the very beginning of the weathering exposure, and slow down after 90 days of exposure. Physical damages, i.e. cracking, chalking and mass loss, occurred simultaneously and aggregated throughout the whole period of weathering exposure (i.e. identified from the reduction in lightness and significant increases of water absorption). Property changes and/or degradations of the physical properties were most significant for the WPCs with 40% plastic contents.

Increasing the plastic contents to more than 50% can significantly improve the resistances of the WPCs to weathering. The effects of improvements became less significant when the plastic contents were increased to more than 60%. SEM images confirmed the degradation in mechanical properties of the WPCs. Larger “gaps” between the wood fibers and the plastic matrix, and more pulled-out fibers were observed from the WPCs after 360 days weathering exposure.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.conbuildmat.2015.04.019.

References


