Research paper

Preparation and Characterization of Novel Indoor Usage of Wood-Plastic Composites from Polypropylene/Recycled Rice Straw

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【Summary】

Most wood-plastic composites (WPCs) are fabricated using thermoplastics and sawdust (or other natural fibers). In this study, we used polypropylene (PP) and recycled rice straw (RS) as raw materials to prepare 22 types of WPCs for indoor use. We also incorporated chemical agents to enhance resistance to UV light, coupling capability, and flame retardancy. We then assessed how the PP/RS ratio and the addition of chemical agents affected the density of the resulting WPCs and the water-absorption rate (WAR), length-swelling rate (LSR), and microstructure. We also performed a thermogravimetric analysis, evaluated the weathering performance and flame retardancy, and measured the release of organic volatile matter (formaldehyde) to determine whether the proposed WPCs meet established standards for indoor usage. Samples prepared without a coupling agent exhibited increased WAR and LSR values with an increase in the content of recycled RS powder (24-h soaking test). Samples prepared with a coupling agent presented increased WAR values with an increase in soaking time when the content of recycled RS powder exceeded 50 phr (indicates the percentage of additives in rubber (or resin)) (28-day soaking test). The best composites evaluated in this study were self-extinguishing (limited oxygen index (LOI) = 27) and flameproof (based on V-0 criteria), exhibited low formaldehyde release (0.07 mg/L), and presented no differences in appearance before and after weathering tests.

Key words: flameproof, polypropylene, recycled rice straw, wood-plastic composites, weathering test.

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研究報告

聚丙烯/回收稻草新型木塑複合材作為室內用途之製備與性質

林曉洪[1)] 周春禧[2,3)]

摘　要

多數木塑複合材(WPC)是使用熱塑性塑料和鋸屑(或其他天然纖維)製成。本研究之目的為以聚丙烯(PP)和回收稻稈(RS)為原料，製備22種適合室內使用之木塑複合材。加入功能性化學試劑以增進試材之抗紫外線能力、耦合能力和防焰性。其次，評估PP / RS比率和化學藥劑之添加對木塑複合材之密度及吸水率(WAR)、長度溶脹率(LSR)和微觀結構之影響。並進行熱重分析，評估耐候性和防焰性，及測定有機溶劑揮發物(甲醛)之釋放量，以確定木塑複合材是否滿足室內使用之規範標準。無添加偶合劑及回收稻稈粉含量增加之試樣顯示會提高其吸水率和長度溶脹率值(24小時浸泡測試)。當回收之稻稈粉含量超過50 phr (橡膠(或樹脂)中添加劑的百分比)時，使用偶合劑製備之樣品吸水率值會隨浸泡時間增加而增加(28天浸泡)。本研究評估最佳複合材具有自熄性(限氧指數(LOI) = 27)和防焰性(基於V-0標準)，甲醛釋放量低(0.07 mg / L)，及風化試驗後在外觀上無差異。

關鍵詞：防焰性、聚丙烯、 回收稻稈、木塑複合材、風化試驗。

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INTRODUCTION

The term wood-plastic composites (WPCs) refers to thermoplastics that are reinforced with wood or other natural fibers. Most of these materials are fabricated using commodity thermoplastics, such as polypropylene (PP), polyethylene (PE), or polyvinyl chloride (PVC) (Wolcott 2001, Kuo et al. 2009). As a result, WPCs possess properties of wood as well as those of plastic. WPCs improve the physical properties of wood by enhancing the durability and resistance to insects and fungal growth, and reducing moisture adsorption and swelling (Leu et al. 2012). This has led to the wide-scale adoption of WPCs for both indoor and outdoor applications, such as building and construction products, consumer goods, and automotive components. Overall, WPCs have proven themselves to be low-cost, biodegradable, eco-friendly alternatives to conventional building materials. The global WPC market was valued at US$2.64 billion in 2012 and was anticipated to reach US$5.39 billion by 2019 (FORDAQ.com 2019).

Lignocellulosic materials are becoming increasingly important as fillers or reinforcements in polymer and ceramic matrices, due in part to their cost advantage over inorganic or synthetic materials as well as the fact that they are recyclable and non-abrasive to machinery (Magalhães et al. 2013, Mattos et al. 2014). Lignocellulosic materials used to reinforce WPCs include pulp fibers, peanut hulls, bamboo, straw, digestate, cotton and guayule biomass residues (Bajwa et al. 2011), heart-of-palm sheaths (Magalhães et al. 2013), bagasse (Darabi et al. 2012), sunflower stalk flour (Kaymakci et al. 2013), and palm leaves (Binhussaina and El-Tonsy 2013).

Rice straw (RS) is a by-product of rice cultivation. Each kilogram of milled rice results in roughly 0.7~1.4 kg of rice straw, depending on the variety, cut height, and moisture content (MC). In Taiwan, approximately 1.5 million tons of rice straw is produced each year; however, much of it is burned or left in the field for the next plowing, or used as feed for livestock (Kadam et al. 2000). Chou et al. (2009a, b) proposed converting RS into a renewable energy resource (e.g., fuel briquettes). In this study, we sought to make use of waste RS as a filler or reinforcement in WPCs.

In a previous study (Lin 2018), we investigated the mechanical properties of WPCs prepared using recycled RS and PP. The materials produced in that study outperformed those of Mattos et al. (2014) (in terms of tensile strength), those of Sommerhuber et al. (2015) and Najafi and Habibollah (2011) (in terms of bending strength), and those of Ren et al. (2015) (in terms of impact strength).

Long-term stability is one of the most important considerations when assessing indoor applications of WPCs (Chan et al. 2018). Most WPCs intended for indoor use provide little resistance to ultraviolet (UV) light and fire. Photocatalytic oxidation is increasingly being used in heating, ventilation, air purification, and air conditioning (HVAC) systems. This method involves the use of short-wave UV light to energize a catalyst (e.g., titanium dioxide (TiO_2)) to degrade organic contaminants. Concerns regarding the effects of air pollution have prompted the installation of these systems in households as well as in medical, industrial, and commercial facilities. However, this has greatly increased exposure to UV, with the result that many indoor materials are susceptible to degradation. Furthermore, the flammability of wood limits its applicability, making exploration into the flame retardancy of wood-based materials an important issue. These factors were the main motivator behind this investigation.

The current study is an extension of our previous research (Lin 2018). We incorporated chemical agents to prepare 22 types of WPCs for indoor usage to enhance the resistance to UV light, the coupling capability, and flame retardancy. We then assessed the degree to which the PP/RS ratio and added chemical agents affected the density and microstructure of the WPCs as well as their water-absorption rate (WAR) and length-swelling rate (LSR). We performed thermogravimetric analyses and assessed the weathering performance and flame retardancy. Finally, we measured the release of formaldehyde to ensure that the proposed WPCs meet standards established for indoor usage.

MATERIALS AND METHODS

Preparation of WPC test specimens (WPC-TSs)

The first step involved the collection and crushing of RS using a proprietary device described in Chou et al. (2009a). The crushed RS was ground into a powder with a particle size of 60~120 mesh (250~120 μm). The resulting material was then subjected to characterization in terms of the MC (CNS 2013), ash content (CNS 2004), hot-water extractives (CNS 2005a), 1% NaOH extractives (CNS 2004), alcohol-toluene extractives (CNS 2005b), holocellulose (CNS 2002), and lignin (CNS 2005c). Characterization results are listed in Table 1.

WPC-TSs were prepared as follows: (1) In accordance with test conditions listed in Table 2, recycled RS, PP, and chemical agents (all in powdered form) were blended

Table 1. Characterization results of rice straw (RS)

	MC (%)	Ash (%)	Hot-water extractives (%)	1% NaOH extractives (%)	Alc.-toluene extractives (%)	Holocellulose (%)	Lignin (%)
RS	10.0	9.78	12.0	23.4	3.05	70.36	18.15
	(1.05)[1]	(1.11)	(0.40)	(0.51)	(0.09)	(0.12)	(1.25)

Note:[1], standard deviation. MC, moisture content; Alc. alcohol.

in a Banbury mixer at a rotation speed ranging 50~60 rpm for a duration of 15 min. (2) Granulation was conducted by breaking up the blended mixture into grains using a pelletizer at a temperature ranging 160~185℃. (3) An injection molding machine was then used to extrude the resulting granular mixture, to produce WPC-TSs meeting ASTM (2017a) criteria. Extrusion was conducted under the following conditions: a socket temperature of 180℃, an injection distance of 60 mm, a maximum injection pressure of 55 bar, a dwell pressure of 10 bar, a back pressure of 30 bar, a screw rotation speed of 135 rpm, a mold temperature of 60℃, and a cooling time of 20 s.

Chemical agents in the blend included two types of coupling agent of CA-I (maleic anhydride grafted polypropylene, MAPP) and CA-II (PP-grafted-maleic anhydride, PP-g-MA); two types of anti-UV agent of AUV-I (UV760, Xingxing, Taichung) and AUV-II (metal oxidative agent (Red102), Liang Chang Technology, Tainan); and two types of flame retardant of FR-I (ammonium polyphosphate, APP) and FR-II (DMOP-8037, Dear Man Industry, Kaohsiung).

Characterization of WPC-TSs

A scanning electron microscope (SEM) (Hitachi S-3000N, Japan) was used to obtain micrographs of WPC-TSs. Thermogravimetric analysis of WPC-TSs was conducted using a thermogravimetric analyzer (DuPont, TA Q50, where?). Flame-retardant tests were performed in accordance with UL94 (2013) test standard using three criteria: V-0, V-1, and V-2. Limiting oxygen index (LOI) values were determined in accordance with ASTM (1977), Fenimore and Martin (1966), and CNS (1995).

In accordance with the UV test methods for plastic ASTM (2017b), a QUV accelerated weathering tester (CSI, UV 2000,Q-LAB) was used in conjunction with a powerful light source (UVA-340) to perform accelerated weathering tests under the following conditions: an irradiation intensity of 0.77 W/m^2, a wavelength of 340 nm, an irradiation temperature of 60±3℃, an irradiation time of 8 h, a condensation temperature of 50±3 ℃, a condensation time of 4 h, and a total irradiation time of 720 h. We then registered changes in the color of the WPC-TSs.

We measured the release of organic volatile matter (formaldehyde) in accordance with CNS (2017a) specifications. We also assessed the physical properties of WPC-TSs in accordance with the relevant test standards: density (ASTM 2011a), WAR (CNS 2017b; ISO 2008), and LSR (CNS 2017b; ASTM 2011b).

RESULTS AND DISCUSSION

Physical properties of WPC-TSs

In a previous study, we investigated the mechanical properties of WPC-TSs prepared using recycled RS and PP (Lin 2018). In that study, we discovered that the tensile strength,

Table 2. Test conditions of preparing test specimens of wood-plastic composites (WPCs)

	RS/PP ratio (phr/phr)	Coupling agent	Anti-UV agent (phr)	Carbon black (phr)	Flame retardant (phr)	Lubricant (phr)
WPC-1		-			FR-I (30)	
WPC-2	30/70	-			FR-I (35)	
WPC-3		-			FR-I (40)	
WPC-4		-	AUV-I (0.3)		FR-I (30)	1
WPC-5		-			FR-I (35)	
WPC-6		-			FR-I (40)	
WPC-7	40/60	CA-I (2)				
WPC-8		CA-I (3)			FR-I (35)	
WPC-9		CA-I (4)				
WPC-10		CA-I (5)				
WPC-11		-			FR-I (30)	
WPC-12	50/50	-			FR-I (35)	
WPC-13		-			FR-I (40)	
WPC-14		-			FR-I (30)	
WPC-15	60/40	-			FR-I (35)	
WPC-16		-			FR-I (40)	
WPC-17	30/70	CA-II (5)				
WPC-18	40/60	CA-II (5)			FR-I (55)	
WPC-19	50/50	CA-II (5)				
WPC-20	60/40	CA-II (5)				
WPC-21	40/60	CA-II (5)	AUV-II (2)	1	FR-I (55)	
WPC-22	40/60	CA-II (5)			FR-II (55)	

RS, rice straw; PP, polypropylene; UV, ultraviolet.

Note: CA-I and CA-II refer to maleic anhydride grafted polypropylene (MAPP) and polypropylene-grafted-maleic anhydride (PP-g-MA), respectively; AUV-I and AUV-II refer to UV760 and Red102, respectively; and FR-I and FR-II refer to ammonium polyphosphate (APP) and DMOP-8037, respectively.

bending resistance, impact resistance, and resistance to elongation of the WPC-TSs decreased with an increase in the amount of recycled RS powder; however, the modulus of elasticity did not follow this trend. Table 3 lists the density, WAR, and LSR of WPC-TSs, in which the air-dried density of all WPC-TSs ranged 1.12~1.27 g cm^{-3} (i.e., in accordance with 0.8~1.5 g cm^{-3} specified by CNS (2014)). In this study, WPC samples were assigned numbers ranging from WPC-1 to WPC-22 for identification.

Overall, WAR values increased with an increase in the content of recycled RS powder. For example, in samples with 35 phr of flame retardant and no coupling agent, WAR values varied according to the RS/PP ratio as follows: WPC-2 (30/70: 0.47%), WPC-5 (40/60: 1.16%), WPC-12 (50/50: 1.25%), and WPC-15 (60/40: 6.61%). This can be attributed to the characteristics of the biomass materials. According to CNS 15730, WAR values must be < 10% CNS (2014). The maximum WAR value of WPC-TSs in this study was

7.13%, as shown in Table 3.

We also recorded variations in WAR values as a function of soaking time. Briefly, WPC-TSs were immersed in water for a given duration of up to 28 days. Figure 1A presents results for WPC-2, WPC-5, WPC-12, and WPC-15 (i.e., with 35 phr flame retardant and no coupling agent). We discovered the following. (1) For a fixed soaking time (such as 4 days), a higher proportion of recycled RS powder corresponded to a higher WAR value, as follows: WPC-2 (30/70: 0.46%), WPC-5 (40/60: 1.19%), WPC-12 (50/50: 1.22%), and WPC-15 (60/40: 5.65%). (2) When the content of recycled RS powder in the WPC-TSs was ≤ 50 phr, WAR values varied little with soaking time. (3) When the content of recycled RS powder exceeded RS/PP = 60/40, WAR decreased from 6.61% (1 day soaking) to 5.4% (28 days soaking). This was due to the fact that without a coupling agent, a higher proportion of recycled RS powder (> 50 phr) allowed a portion of the WPC-TSs to dissolve during the water absorption test, which reduced the mass of the WPC-TSs and led to a decrease in the WAR.

Figure 1B presents variations in WAR values associated with soaking time for WPC-17 (RS/PP = 30/70), WPC-18 (RS/PP = 40/60), WPC-19 (RS/PP = 50/50), and

Table 3. Density, water absorption rate, and length swelling rate of wood-plastic composites (WPCs)

	Density (g cm^{-3})	Water-absorption rate (%)[1]	Length-swelling rate (%)
WPC-1	$1.12^{b}\pm0.00$	$0.30^{k}\pm0.17$	$0.26^{e}\pm0.15$
WPC-2	$1.13^{b}\pm0.00$	$0.47^{j}\pm0.13$	$0.80^{d}\pm0.26$
WPC-3	$1.15^{a}\pm0.00$	$0.43^{j}\pm0.10$	$0.58^{d}\pm0.08$
WPC-4	$1.16^{a}\pm0.00$	$1.65^{g}\pm0.13$	$1.38^{c}\pm0.25$
WPC-5	$1.19^{a}\pm0.00$	$1.16^{h}\pm0.15$	$1.19^{c}\pm0.15$
WPC-6	$1.20^{a}\pm0.00$	$1.23^{g}\pm0.14$	$1.54^{c}\pm0.22$
WPC-7	$1.17^{a}\pm0.00$	$0.89^{i}\pm0.13$	$1.31^{c}\pm0.20$
WPC-8	$1.18^{a}\pm0.00$	$2.33^{e}\pm0.07$	$2.15^{b}\pm0.13$
WPC-9	$1.17^{a}\pm0.00$	$1.95^{f}\pm0.09$	$1.65^{c}\pm0.15$
WPC-10	$1.17^{a}\pm0.00$	$2.25^{e}\pm0.08$	$1.88^{b}\pm0.08$
WPC-11	$1.21^{a}\pm0.00$	$1.80^{f}\pm0.25$	$1.91^{b}\pm0.09$
WPC-12	$1.21^{a}\pm0.00$	$1.25^{g}\pm0.46$	$2.14^{b}\pm0.38$
WPC-13	$1.23^{a}\pm0.00$	$0.83^{i}\pm0.07$	$2.18^{b}\pm0.23$
WPC-14	$1.27^{a}\pm0.00$	$4.68^{c}\pm0.50$	$3.37^{a}\pm0.62$
WPC-15	$1.16^{a}\pm0.02$	$6.61^{b}\pm0.78$	$3.05^{a}\pm0.47$
WPC-16	$1.14^{b}\pm0.01$	$7.13^{a}\pm0.51$	$1.38^{c}\pm0.15$
WPC-17	$1.17^{a}\pm0.01$	$1.64^{f}\pm0.20$	$0.73^{d}\pm0.46$
WPC-18	$1.19^{a}\pm0.00$	$1.94^{f}\pm0.06$	$1.40^{c}\pm0.08$
WPC-19	$1.18^{a}\pm0.00$	$2.06^{e}\pm0.07$	$1.92^{b}\pm0.18$
WPC-20	$1.19^{a}\pm0.00$	$3.33^{d}\pm0.16$	$2.42^{b}\pm0.26$
WPC-21	$1.11^{b}\pm0.00$	$3.49^{d}\pm0.14$	$0.71^{d}\pm0.23$
WPC-22	$1.19^{a}\pm0.00$	$1.15^{h}\pm0.03$	$0.65^{d}\pm0.14$

Note: [1]Refers to the water absorption rate (%) in the 24-h soaking test.

Each experiment was performed 5 times, and the data were averaged (n = 5). Numbers followed by different letters (a~k) significantly differ at the level of $p < 0.05$ according to Scheffe's test.

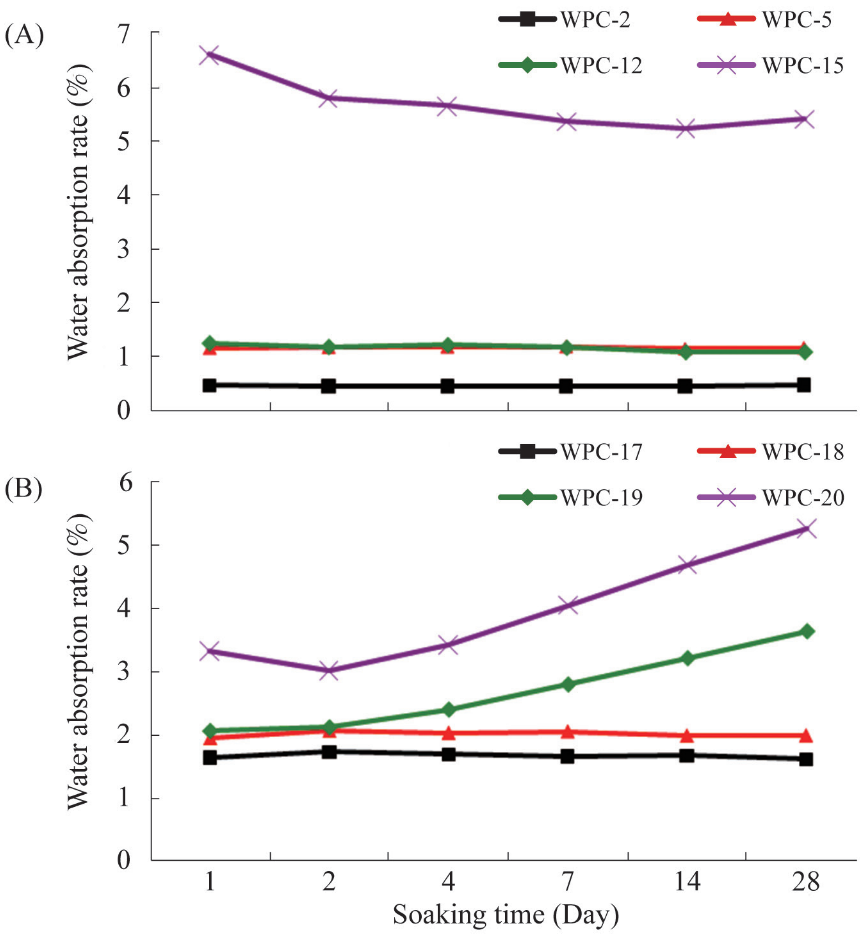

Fig. 1. A, B. Variations in the WAR of wood-plastic composite test specimens (WPC-TSs) with soaking time (28 days): (A) for WPC-2, WPC-5, WPC-12, and WPC-15; (B) for WPC-17, WPC-18, WPC-19, and WPC-20.

WPC-20 (RS/PP = 60/40), which included 5-phr CA-II (PP-g-MA). When the content of recycled RS powder was ≤ 40 phr, WAR values only slightly varied. However, when the content of recycled RS powder was ≥ 50 phr, the WAR values notably increased with an increase in soaking time. For example, when RS/PP = 60/40, WAR values increased from 3.33% (1 day of soaking) to 5.27% (28 days of soaking), due to the addition of 5-phr CA-II.

Variations in the LSR with the content of RS in WPC-TSs followed the trend described above for WAR values. For example, without a coupling agent and with 30-phr flame retardant, LSR values varied with the RS/PP ratio as follows: WPC-1 (RS/PP = 3 0/70; LSR = 0.26%), WPC-4 (RS/PP = 40/60; LSR = 1.38%), WPC-11 (RS/PP = 50/50; LSR = 1.91%), and WPC-14 (RS/PP = 60/40; LSR = 3.37%). According to CNS (2014) requirements, the maximum LSR of WPC-TSs should be < 3%. The LSR values of the 22 WPC-TSs in this study ranged 0.26%~2.42%, as shown in Table 3. However, samples prepared using 60-phr RS without a coupling agent were exceptions: WPC-14 (3.37%) and WPC-15 (3.05%).

WPC-TSs before and after the weathering test

Figure 2 presents photographs of WPC-TSs before and after the weathering tests. As shown in Fig. 2, we observed three characteristic test results: 1) whitening, powdery precipitation, and warping in the first group of WPC-1~16 (top image); 2) whitening in the second group of WPC-17~20 (central image); and 3) no change in appearance in the third group of WPC-21~22 (bottom image). Only the third group (WPC-21~22) met weathering requirements listed in CNS (2014).

These differences can be explained as follows. (1) WPC-TSs in the first group were prepared with or without the MAPP (CA-I) coupling agent and with the UV760 anti-UV agent (AUV-I), which resulted in low UV resistance. (2) WPC-TSs in the second group were prepared using the coupling agent PP-g-MA (CA-II) with AUV-I. (3) WPC-TSs in the third group were prepared using CA-II with the Red102 anti-UV agent (AUV-II). These results indicated that CA-II and AUV-II provided the best anti-UV performance.

Figure 3 presents SEM micrographs (×500) of WPC-TSs prior to (left column) and after (right column) weathering tests of the following samples: WPC-1 (RS/PP = 30/70; AUV-I), WPC-5 (RS/PP = 40/60; AUV-I), and WPC-22 (RS/PP = 40/60; AUV-II). When the RS/PP changed from 30/70 to 40/60, a larger proportion of RS powder appeared in the WPC-TSs (as indicated by the red arrow in the left-central image of Fig. 3). As indicated by the orange arrow in the top- and central-right SEM micrographs in Fig. 3, a number of cracks,

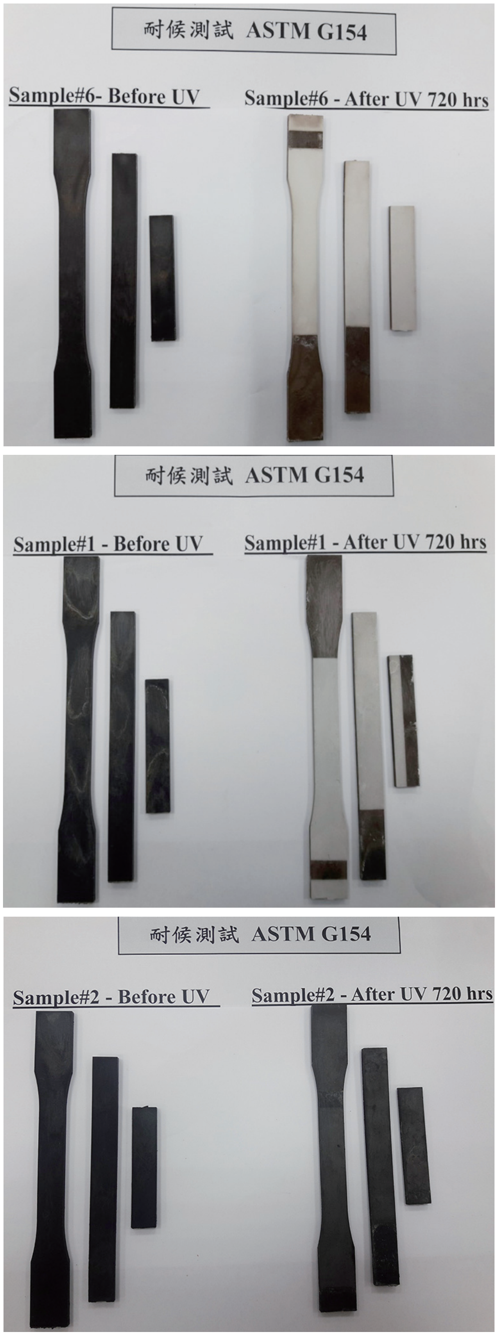

Fig. 2. Photographs of wood-plastic composite test specimens (WPC-TSs) prior to and after the weathering test. Top image (WPCs-1~16); central image (WPCs-17~20); bottom image (WPCs-21, -22).

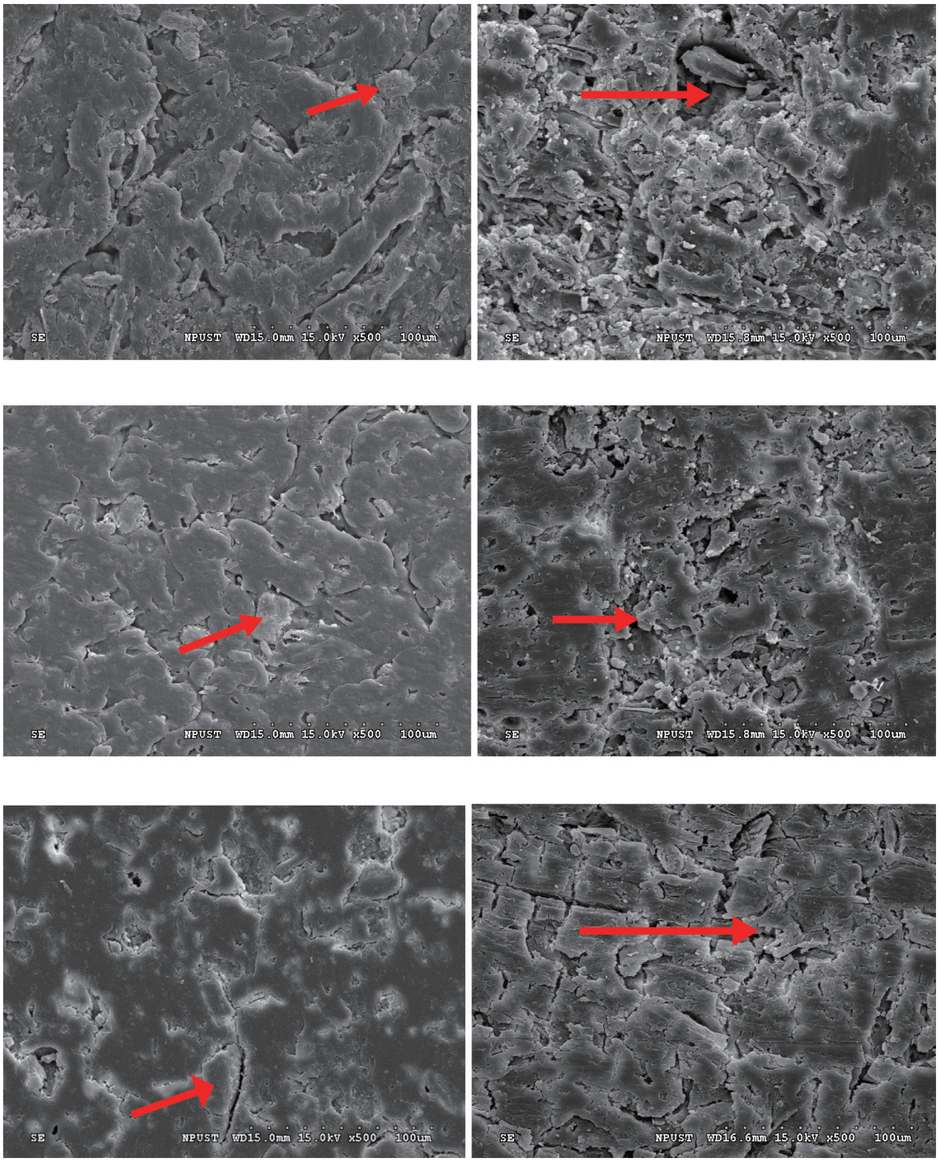

Fig. 3. SEM micrographs (×500) of wood-plastic composite test specimens (WPC-TS) prior to (left column) and after (right column) ultraviolet irradiation for WPC-1 (rice straw (RS)/ polypropylene (PP) = 30/70; AUV-I), WPC-5 (RS/PP = 40/60; AUV-I), and WPC-22 (RS/PP = 40/60; AUV-II).

gaps, and/or holes appeared in WPC-1 and WPC-5 after UV irradiation for 720 h. This is a clear indication of the importance of adding an appropriate anti-UV agent or antioxidant when preparing WPCs intended for indoor usage.

Flame retardancy and thermal degradation of WPC-TSs

In this study, we conducted thermogravimetric analyses, flame-retardancy tests, and LOI experiments to characterize the properties of WPC-TSs. Table 4 lists the results obtained from thermogravimetric analyses of WPC-18 (RS/PP = 40/60; FR-I), WPC-19 (RS/PP = 50/50; FR-I), WPC-20 (RS/PPm = 60/40; FR-I), WPC-21 (RS/PP = 40/60; FR-I), WPC-22 (RS/PP = 40/60; FR-II), and the control group (RS/PP = 0/100; without FR). These samples were prepared using 55 phr of FR. The initial thermal decomposition temperature (ITDT) and the carbon residue (CR) at 800℃ were as follows: control group (347.02℃ and 0.1575%), WPC-18 (216.98℃ and 30.97%), WPC-19 (266.00℃ and 24.64%), WPC-20 (255.34℃ and 25.06%), WPC-21 (257.48℃ and 28.79%), and WPC-22 (207.75℃ and 28.27%), respectively. WPC-22 presented the lowest ITDT values due to the addition of FR-II (DMOP-80), which improved the flame-retardant characteristics. WPC-22 also presented a higher CR (28.27%), indicating high performance in flame suppression. Jeska et al. (2012) used the thermogravimetric analysis to obtain the ratio of wood flour (WF) to PP in WPCs to derive a systematic method for determining the WF/PP ratio.

The LOI can be used to categorize the flame-retardant capability of materials, as follows: slow burning (20 ≤ LOI ≤ 26) and self-extinguishing (LOI ≥ 27) (Fenimore 1975). WPC-TSs could be categorized according to the LOI as follows: (1) LOI ≤ 22 (WPC-1~WPC-16); (2) LOI = 26 (WPC-17~WPC-21); (3) LOI = 27 (WPC-22). These results show that WPCs with an FR of at least 55 phr were nearly self-extinguishing.

Tests were conducted to assess the flame-retardant and flameproof characteristics of the WPC-TSs in accordance with UL94 (2013) test standards. The testing results coincided with the LOI values as follows: (1) the first group (WPC-1~WPCs16) did not meet the V-2 criterion; (2) the second group (WPC-17) met the V-1 criterion; and (3) the third group (WPC-18~WPC-22) met the V-0 criterion. These results can be attributed to the fact that a suitable quantity of an appropriate FR (such as APP) led to the formation of a carbonized layer during combustion, which in turn suppressed the spread of flames. Umemura et al. (2014) investigated the synergistic effects of wood flour and fire retardants on the flammability of WPCs, which included PP and WF. They observed that WPCs with (36.7% PP, 50% WF, 10% APP, and 3% MAPP) met the V-0 criteria.

Organic volatile matter release (formaldehyde) of WPC-TSs

CNS (2014) stipulates that indoor WPCs must meet the following requirements: (1) average formaldehyde release of ≤ 0.3 mg/L and (2) maximum formaldehyde release of ≤ 0.4 mg/L. Our test results revealed that the formaldehyde released from the 22 types of

Table 4 Thermogravimetric analysis of wood-plastic composite test specimens (WPC-TSs)

	RS/PP (phr)	FR (phr)	Thermal decomposition temp. (℃)	Residue in N_2 at 800℃(%)
PP	0/100	-	347.02	0.1575
WPC-18	40/60	FR-I (55)	216.98	30.97
WPC-19	50/50		266.00	24.64
WPC-20	60/40		255.34	25.06
WPC-21	40/60		257.48	28.79
WPC-22	40/60		207.75	28.27

Note: Flame retardant (FR)-I and FR-II refer to ammonium polypropylene and DMOP-8037, respectively.
RS, rice straw; PP, polypropylene.

WPC-TS in this study ranged 0.01~0.09 mg/L. Thus, all of the WPCs in this study (including RS and PP) qualified for indoor usage. Furthermore, two of the samples (WPC-21 and WPC-22) also passed the weathering test and were flameproof (V-0 criterion).

CONCLUSIONS

In this study, we sought to make use of waste RS produced by rice milling. Rather than converting RS into refuse-derived fuel (such as RDF5), we combined RS with PP and functional agents to create 22 types of WPCs. We then investigated the means by which the RS/PP ratio and the addition of various chemical agents affected the physical properties (WAR and LSR), flame retardancy (TG, LOI, and UL-94 flameproof), and resistance to UV light. We also measured the release of formaldehyde to determine whether the materials met requirements for indoor WPCs. The novel WPCs in this study proved highly resistant to weathering with low formaldehyde release. They were also shown to be self-extinguishing and fully compliant with V-0 criteria for flameproofness. We believe that the proposed strategy could help reduce pollution associated with waste RS and provide a robust indoor design material to increase the overall economic value of WPCs.

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