International Journal of Engineering & Technology, 7 (3.28) (2018) 252-257

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Waste Polymer Blended with Copolymer Polypropylene to Enhance Mechanical Properties Using Injection Moulding

N. Afiqah S., Anika Zafiah M. Rus*, A. Shahrizan Syah, Farhana Hazwanee M. J., Noraini M., S. Aida I.

Sustainable Polymer Engineering, Advanced Manufacturing and Material Center (SPEN-AMMC), Faculty of Mechanical and Manufacturing Engineering (FKMP), Universiti Tun Hussein Onn Malaysia, (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia
**Corresponding author E-mail: zafiah@uthm.edu.my*

Abstract

This study was constructed to examine the tensile properties and the microstructure of wood-plastic composites (WPCs) before and after being subjected to UV irradiation. The pellet of the wood polymer composites consists of waste polypropylene as the matrix and rice-husk flour as the reinforcing filler. They were mixed blended with virgin copolymer polypropylene through injection moulding and were UV irradiated from 1000 hours to 3000 hours to study the effect of weathering on the tensile properties of the WPCs. The microstructures of the fractured surface of the specimens were examined under Scanning Electron Microscope (SEM). The tensile properties of the composites decreased with the increase of UV irradiation due to photo degradation. Adding copolymer polypropylene by 10-30 wt% in the composition helps improve the tensile properties of the WPCs.

Keywords: *Copolymer polypropylene; tensile properties; rice husk flour; recycled polypropylene; weathering; wood-polymer composites.*

1. Introduction

Polymers can be defined as a substance which comprised of molecules consisting of extended structure of one or additional numbers of types of atoms or group of atoms connected to one another usually by means of covalent bonds. Naturally, polymers have long existed as DNA, RNA, proteins and polysaccharides in which they played major roles in the life of animals and plants. In the early times, men have exploited these natural polymers as materials for their daily needs. Regardless of that, the origin of today's polymer industry is highly due to the discoveries of modification of certain natural polymers in the nineteenth century.

Nowadays, polymers are produced in massive quantity and range. Film packaging, insulator for registration, body parts for cars and TV cabinets are some of the many functions of polymer. Our modern world is conceived by the presence of polymeric materials. Polymers are considered as a necessity as they serve various and sophisticated functions which act as a catalyst for a better and much more comfortable life style [1].

However, due to widespread use, polymers are facing a huge hurdle which consists of material consumption and energy resources. Apart from that polymers are also one of the contributors to the increasing amount of solid waste [2]. One of the setbacks of polymers is that most of them are not biodegradable which means that once they are disposed in a landfill, they can remain there for quite a long period. Apart from that, additives used to improve the properties of polymers are capable of leaching from the landfill thus contaminating the soil and water table [3]. Burning of plastic waste spawns toxic substances which eventually lead to air pollution [4].

Apart from their strength and durability, polymers are widely used due to their versatile properties. Similar properties can be subjugated to be re-used in further applications [5]. Considered to be environmental friendly, composite materials consisting of plant fibre are currently receiving quite the attention. In general, wood plastic composites (WPCs) consist of natural lignocellulosic filler or fibers and thermoplastic materials (PE, PP, PVC and PS). Some of the typically used filler in WPCs are wood fiber and/or flour, kenaf fiber, hemp and rice husk. The manufacturing of composite materials from industrial and agricultural waste has caught a worldwide attention which is the result from the increasing demand for more environmental friendly materials [6].

Rice husk is considered as an agricultural by-product from rice processing. Problems with rice husk is its resistance against decomposition in the ground and it's low in nutrition and difficult for animals to digest. Due to lower con-tents of lignin and hemicellulose but similar cellulose content, rice husk can go through a higher temperature process than wood which is why it has been receiving attention [7]. With a weight composition of 35% cellulose, 25% hemicellulose, 20% lignin and 17% ash (94% silica), rice husk is known to be a major agro-waste product [8].

Even though it is common to use virgin plastics in WPCs, recycled plastics are highly suitable for a substitute. The presence of cellulose and hemicellulose in agro-fibers leads to certain setbacks such as degradation at relatively low temperature [9] restricting to only a few of thermoplastics that can be used together such as PE, PP, PVC and PS [24]. The application of waste plastics alongside lignocellulosic fibers might be able to overcome the setbacks and at the same time reduce the environmental impact.

There are few studies conducted to investigate the effects of weathering on certain aspects of wood polymer composites such as appearance and mechanical properties. In [10] investigated the effect of accelerated UV weathering on color changes of polypropylene-aspen fiber composites. The color turned from brown to chalky with the degradation depth being approximately 0.5mm. In [11] noticed that when the wood content increased, the degradation of PP-based WPC also increased. In [12] studied the influence of plastic grades (virgin and recycled polypropylene), loading of wood flour and addition of UV stabilizers on the discoloration of

WPC after natural weathering. It was observed that despite the addition of stabilizers reduced the rate of discoloration, fading of color on the composites was still inevitable and it increased alongside wood content. This study was conducted to study the effect of mixed blending virgin copolymer with recycled polypropylene wood polymer composites through injection moulding and the effects of UV irradiation.

2. Methodology

2.1. Materials

Materials used in this experiment were WPC pellets. These pellets were mixed blended with virgin copolymer polypropylene through injection moulding and turned into tensile specimens. The compositions were as follow.

Table 1: WPC pellets composition

Sample	Composition (% Total Weight)	
	WP + RH	CO-PP
A1	100_{WP}	-
A2	90_{WP}	10
A3	80_{WP}	20
A4	70_{WP}	30
B1	$80_{WP} + 20_{RH}$	-
B2		10
B3		20
B4		30
C1	$60_{WP} + 40_{RH}$	-
C2		10
C3		20
C4		30
WP - Waste polypropylene RH- Rice Husk CO-PP – Virgin copolymer polypropylene		

2.2. Injection Moulding

Materials specimens for tensile testing were prepared by means of injection moulding according to ISO 527(5A) standard. The injection moulding was done using the Nissei NP7 real mini machine, which was equipped with horizontal type screw. The parameters for the injection moulding process were as shown in Table 2.

Table 2: Parameters for injection moulding

Parameter	Nozzle	Front	Middle	Rear 1	Rear 2	Feed
Temperature	220℃	205℃	215℃	200℃	175℃	50℃
Pressure	56.35 MPa					
Velocity	35 cm^3/s					

The injection time, cool time and cycle time for the injection process were 5.0s, 10.0s, and 2.0s respectively. The standard dimension of the dumbbell samples is shown in Figure 1.

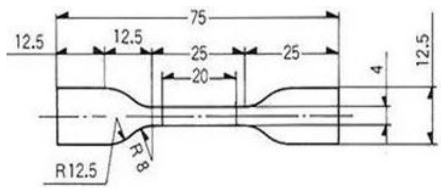

Fig. 1: Dimension of dumbbell samples according to ISO 527 (5A): R = radius

2.3. Accelerated Weathering Tests of WPC

The UV light irradiation on the tensile specimens was conducted by using the UV Accelerated Weatherometer Haida International Equipment Ltd. The UV accelerated weathering test was carried out according to the ASTM D 4587, which is a standard practice for light/water exposure of paint. The UV Weatherometer consists of UV fluorescent lamps that emit light ranging from 280 to 320 nm with a tail extending to 400 nm. The WPC samples were placed on a rack holder and were UV irradiated at 50℃. Each composition of the dumbbell samples were analysed after 1000, 2000 and 3000 hours of UV exposure to determine the effect of weathering on the mechanical properties of the WPCs. Figure 2 shows the illustration of the UV Accelerated Weatherometer.

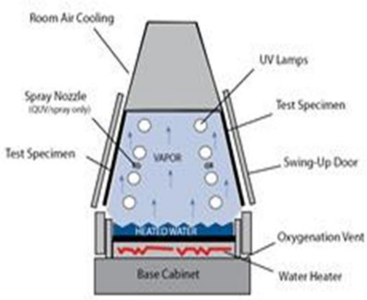

Fig. 2: UV accelerated weatherometer

2.4. Tensile Test

After being subjected to UV irradiation from 0 to 3000 hours, the WPC samples underwent tensile testing in accordance with ISO 527-2. The parameters of the tensile test were load frame with 5kN load cell and a crosshead speed of 5mm/min. The strain was measure over a 20 mm gage length by means of an extensometer. A minimum of five samples for each composition were analysed to obtain an average result.

2.4. Scanning Electron Microscope (SEM)

The morphological analysis on fracture surface of WPC is conducted using Scanning Electron Microscope Hitachi. The image of WPCs fracture surfaces before and after UV irradiation were magnified to correlate the weathering effects on the tensile properties of WPC. The fractured surface samples of WPC were coated first using Auto Fine Coater Machine where thin layer of gold is coated on the surfaces of samples at 25 mA current plasma and 2 Pa of chamber pressure. Cellular structure images were examined by using SEM of Hitachi operates at 10 kV at 100 µm magnifier under high vacuum.

3. Results and Discussion

3.1. Tensile Properties

The tensile strength of the WPCs is within the range of 12 MPa and 20 MPa as shown in Table 3. The specimen which comprised of 100% waste polymer shows higher tensile strength (19.52 MPa) compared to the specimens consisting of waste polymer and rice husk. This is likely due to stiffer polymer grades present in the waste polymer. As the percentage of rice husk increases, the tensile strength of the WPC decreases. The tensile strength of WPC with 20% of rice husk is 16.39 MPa, whereas the tensile strength of WPC with 40% of rice husk is 12.17 MPa. Every composition of the WPC samples was mixed blended with 10%, 20% and 30% of virgin polypropylene (PP) by injection moulding. As the percentage of virgin PP increases, the tensile strength of the WPCs also increases.

Figure 3 shows tensile strength of all the wood polymer composites before and after being exposed to UV irradiation. The polymer composite made from 100% waste poly-propylene exhibits better yield stress compared to the polymer with rice husk, which might be due to the presence of mixed type of polymer and chemical impurities present in the waste PP.

From Figure 3 and Figure 5, it can be observed that as the percentage of rice husk increased, the tensile strength and elongation at break decreased. This is due to the strong influence of wood content towards WPC properties. Increase in the wood fraction increases the elastic modulus, and at the same time decreases the

tensile strength and elongation at break [13]. Specimen C1 which consists of 40% weight of rice husk exhibits lower tensile strength and elongation at break compared to specimen B1, which only consists of 20% rice husk. Specimen A1 on the other hand exhibits a higher value of tensile strength and elongation at break when compared to specimen B1 and C1, since there is no presence of rice husk in its composition.
One of the ways to optimize the properties of WPC samples is by enhancing the ductility of the matrix itself [14]. Each of the basic compositions was mixed with 10%, 20% and 30% of virgin polypropylene. With the addition of virgin PP to the composition, the yield stress of the polymer composites with rice husk increased.
Figure 4-6 show modulus of elasticity, maximum strain and yield stress of the specimens after being subjected to UV irradiation for 1000 hours, 2000 hours and 3000 hours respectively. Each figures shows the decline of tensile properties of the specimen after being subjected to UV irradiation due to photo degradation of both polymer and wood filler. Specimens with higher content of rice husk experienced greater declination of tensile performance after UV irradiation due to the presence of lignocellulosic. Specimens with 100% of waste polypropylene content decreased less in terms of tensile properties compared to specimens incorporated with rice husk.
As the percentage of wood filler increased, the tensile strength decrease tremendously. It is reported that cellulose and stress transfer efficiency are co-dependent, where the addition of cellulose will increase crystallinity hence creating a rigid composites [15]. As such, the crystallinity of the composites decreased alongside increasing lignin loading levels which explains the low value of tensile strength in specimen C1. In [16] stated that when exposed to UV-irradiation, PP underwent chain scissions apart from being capable of rearranging into a crystalline phase through chemicrystallization. Apart from that, the micro cracks on the weathered surfaces of cellulose fiber limit the stress transfer efficiency from PP matrix to fibers, which result in poor tensile strength. Composites which contained higher content of lignin (Specimen C1) exhibits relatively high modulus of rigidity (MOR) retention ratios after weathering which might be contributed by the recrystallization and cross-linking in PP matrix and antioxidation effect of lignin [17].

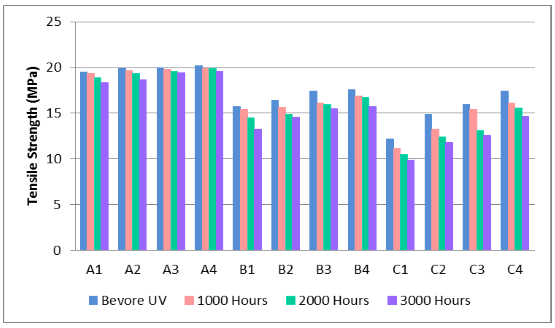

Fig. 3: Tensile strength of WPC samples before and after UV

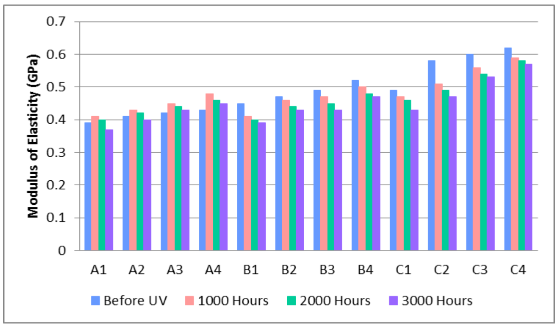

Fig. 4: Modulus of elasticity of WPC samples before and after UV

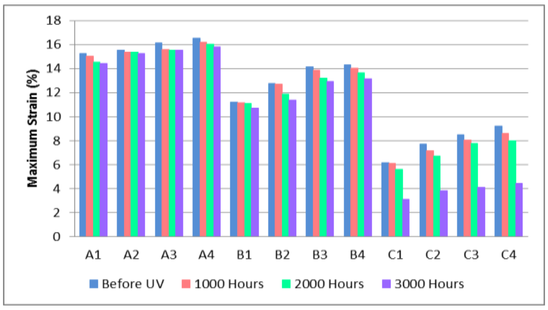

Fig. 5: Maximum strain of WPC samples before and after UV

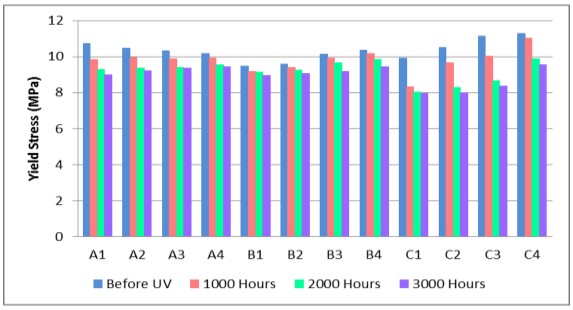

Fig. 6: Yield stress of WPC samples before and after UV

Table 3: Tensile properties of WPC samples

Sample	Ultimate Strength (MPa)				Maximum Strain (%)				Modulus of Elasticity (MPa)				Yield Stress (MPa)			
	0 hr	1000 hr	2000 hr	3000 hr	0 hr	1000 hr	2000 hr	3000 hr	0 hr	1000 hr	2000 hr	3000 hr	0 hr	1000 hr	2000 hr	3000 hr
A1	19.52	19.34	18.92	18.37	15.24	15.02	14.52	14.45	0.39	0.41	0.4	0.37	10.72	9.85	9.29	9
A2	19.87	19.66	19.37	18.67	15.54	15.4	15.39	15.27	0.41	0.43	0.42	0.4	10.47	9.95	9.37	9.21
A3	19.93	19.82	19.61	19.39	16.13	15.58	15.55	15.52	0.42	0.45	0.44	0.43	10.33	9.87	9.4	9.35
A4	20.18	19.9	19.87	19.58	16.56	16.22	16.02	15.81	0.43	0.48	0.46	0.45	10.17	9.93	9.56	9.42
B1	15.7	15.45	14.51	13.26	11.2	11.18	11.08	10.71	0.45	0.41	0.4	0.39	9.46	9.16	9.13	8.94
B2	16.39	15.66	14.85	14.56	12.78	12.7	11.9	11.4	0.47	0.46	0.44	0.43	9.6	9.39	9.26	9.07
B3	17.41	16.12	15.97	15.49	14.14	13.9	13.21	12.95	0.49	0.47	0.45	0.43	10.12	9.91	9.67	9.17
B4	17.57	16.91	16.69	15.69	14.33	14.04	13.65	13.13	0.52	0.5	0.48	0.47	10.37	10.16	9.84	9.43
C1	12.17	11.15	10.46	9.88	6.18	6.09	5.63	3.12	0.49	0.47	0.46	0.43	9.9	8.32	8.03	7.96
C2	14.87	13.26	12.44	11.78	7.74	7.19	6.7	3.81	0.58	0.51	0.49	0.47	10.5	9.64	8.27	7.99
C3	15.98	15.44	13.09	12.58	8.47	8.04	7.75	4.12	0.6	0.56	0.54	0.53	11.14	10.02	8.65	8.35
C4	17.44	16.15	15.57	14.61	9.24	8.63	8.01	4.45	0.62	0.59	0.58	0.57	11.27	11.03	9.88	9.55

3.2. Characterization of Fracture Surface

Figure 7 shows the microstructure of fracture surface of the specimens after being subjected to tensile test before and after UV irradiation.

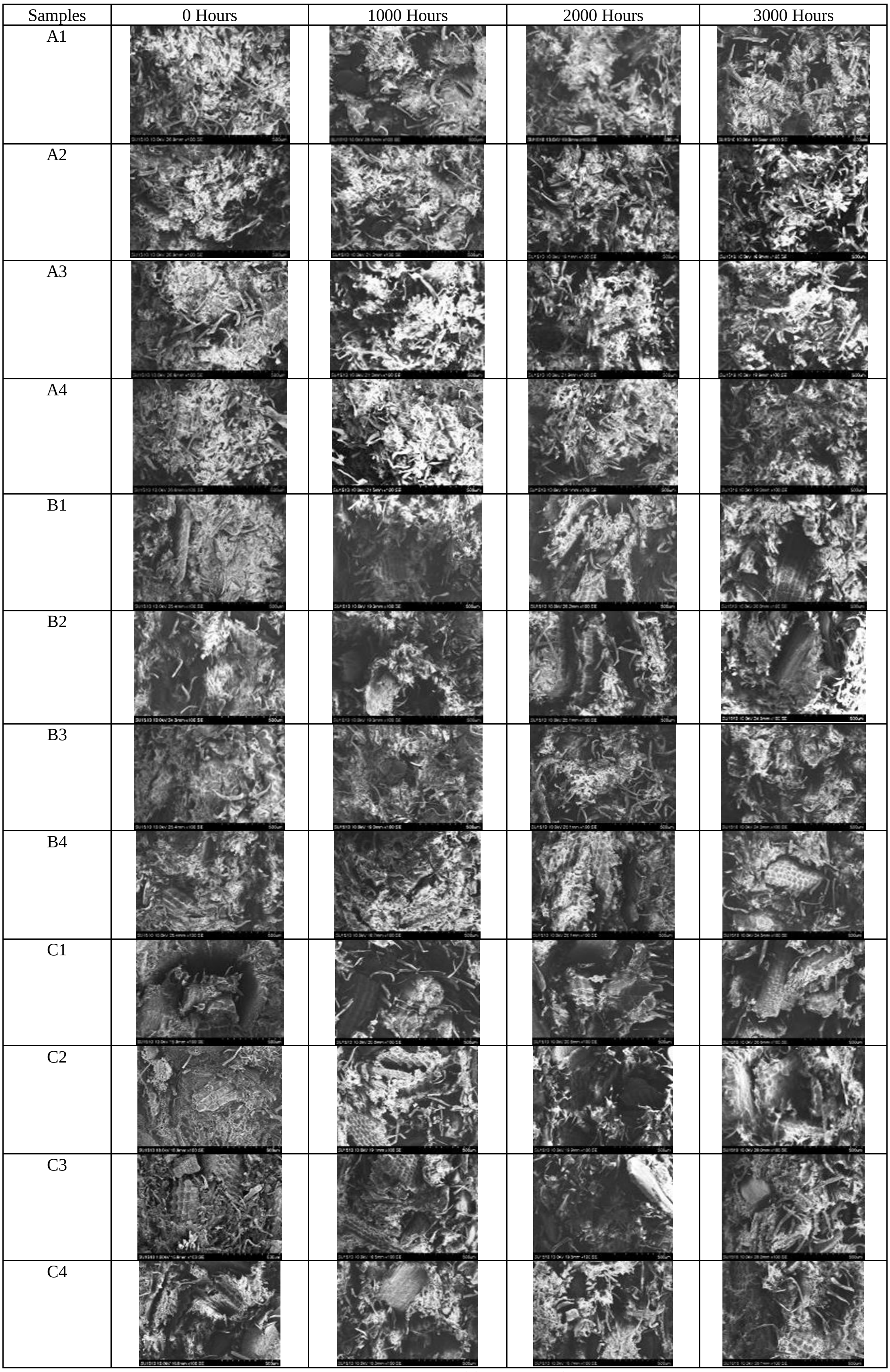

Fig. 7: Microstructure of fractured surfaces

For specimens with 100% waste PP (A1), the nature of the fracture surface is somewhat homogenous with matrix pulled-out. The tensile fracture surface of the specimen with 20% rice husk (specimen B1) exhibits several cavities and fibers breakage compared to specimen A1. As the percentage of rice husk increased to 40%, the presence of cavities and fibers breakage is more apparent. As the percentage of rice husk increased, the interfacial bonding between the filler and the matrix polymer becomes poor and weak [18]. The distinct cavities between the matrix and the fibers indicate poor adhesion [19]. For specimen C1, the crack running through the wood fiber is an indication of stress-transfer from the weaker matrix to the stronger wood fiber. The interfacial bonding between the filler and the waste PP matrix is improved due to the esterification mechanism hence the occurrence of fracture at the

filler itself [20]. In other words, stress is well propagated between the filler and the matrix polymer which improves the modulus when subjected to stress. The fracture surface of specimen C1 shows a very limited amount of torn matrix. This proves that the specimen with higher content of rice husk percentage is much more brittle.
Virgin PP was added to each of the composition (A1, B1 and C1). Each composition was mixed blended with 10%, 20% and 30% of virgin PP through injection moulding. As the percentage of virgin PP increased, the bonding between rice husk and plastic matrix were improved reasonably for specimens with rice husk. The SEM images show that as the percentage of virgin PP in the wood polymer composites increase, the gaps between the wood flour and polymer matrix become less apparent hence indicating a better interface bonding.
Similar condition can be observed for specimen with 100% waste PP composition. As the percentage of virgin PP in-creased, the fracture surface indicates limited amount of torn matrix which suggests that the composite becomes more brittle. Each of the specimens was subjected to 1000, 2000 and 3000 hours of UV irradiation to study the effect of weathering on the mechanical properties and morphology of the fracture surface. After weathering, all the composites were degraded.
After being subjected to 3000 hours of UV irradiation, the cavities on the fracture surface of specimen A1 become slightly apparent alongside several matrixes pulled-out. There is not much fibers pull-out on the fracture surface of specimen B1, since the content of rice husk is only 20%. However, compared to specimen A1, the effects of pull-out were seen on large fibers as the percentage of rice husk increased to 40% (specimen C1). Protruding wood particles were likely caused by the swelling and shrinking of the wood particles after moisture absorption and desorption [21]. The occurrence of surface cracking on the fractured surface of the specimens was probably due to the photo degradation of both the polymers and wood particle [22]. The amount of cellulose exposed on the surface of fiber is the result of better mechanical interlocking. Even though natural fibers are applied to produce composites with several advantages, they are normally polar fibers which mean that they have inherently low compatibility with non-polar polymer matrices, specifically hydrocarbon matrices such as polypropylene and polyethylene. This incompatibility can cause problems to composites processing and material properties. Hydrogen bonds may formed between the hydrophilic fibers, which can lead to agglomeration of fibers into bundles and uneven distribution throughout the non-polar polymer matrix during compound process. Apart from that, insufficient wetting of fibers caused by non-polar polymer matrices may result in weak interfacial adhesion.

4. Conclusion

In this work, WPCs consist of both recycled and virgin polypropylene alongside rice husk flour. For the purpose of product utilization, aspects such as mechanical properties and the microstructure of the fracture surface with regards to the wood flour content and types of plastic were examined. The following conclusions are drawn from the current study.
The mechanical properties of the composites made fully from recycled polypropylene are much better than the composites incorporated with rice husk flour. Increase in wood content reduces the ultimate strength and strain of the composites. However, the modulus of elasticity and the yield stress are improved as the wood content increased. The addition of virgin PP helps enhanced the mechanical properties of the WPCs.
However, these properties are affected due to weathering. Weathering of WPCs resulted in the decrease of the mechanical properties. The SEM images of the fracture surface confirmed the degradation in mechanical properties of the WPCs, especially those incorporated with rice husk flour. Increase in the gaps size between wood fibers and plastic matrix and the increase of pulled-out fibers were observed from the WPCs after being subjected to 3000 hours of UV irradiation. Photo degradation of the WPCs are slightly improved with the addition of virgin PP to the composition.
The results of the present study clearly indicate that recycled polypropylene and rice husk wood flour can be successfully used to create strong and stable WPCs. Increasing the polymer content of the composites can help achieve the mechanical properties suitable for product utilization of the composites. This study has shown that the composites with higher content of virgin PP will be more suitable to be used as building materials due to improvements in mechanical stability.

Acknowledgement

The authors would like to acknowledge the Sustainable Polymer Engineering, Advanced Manufacturing and Material Center (SPEN-AMMC), Faculty of Mechanical and Manufacturing Engineering (FKMP) Universiti Tun Hussein Onn Malaysia (UTHM) Malaysia and Universiti Teknologi Petronas (UTP) for supporting this research under URIF Vot A136.

References

[1] Narinder Singh, David Hui, Rupinder Singh, I. P. S. Ahuja, Luciano Feo, Fernando Fraternali. Recycling of plastic solid waste. Journal of Composites Part B: Engineering 115 (2017): 409-422.
[2] Mwanza, Bupe G. and Mbohwa, Charles. Drivers to Sustainable Plastic Solid Waste Recycling. Procedia Manufacturing 8 (2017): 649-656.
[3] F. Pacheco-Torgal, Yining Ding and Said Jalali. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles). Journal of Construction and Building Materials 30 (2012): 714-724.
[4] Butu A. W. and Mshelia S. S. Municipal Solid Waste Disposal and Environmental Issues in Kano Metropolis, Nigeria. British Journal of Environmental Sciences 2 (2014): 10-26.
[5] Adhikary Kamal B., Shusheng Pang, Mark P. Staiger. Dimensional Stability and Mechanical Behaviour of Wood-Plastic Composites Based on Recycled and Virgin High-Density Polyethylene (HDPE). Journal of Composites Part B 39 (2008): 807-815.
[6] Han-Seung Yang, Hyun-Joong Kim, Son Jungil, Park Hee-Jun, Lee Bum-Jae, Hwang Taek-Sung. Rice-Husk Flour Filled Polypropylene Composites: Mechanical and Morphological Study. Journal of Composite Structures 63 (2004): 305-312.
[7] Mohammad Ghofrani, Pishan Sakineh, Mohammadi Reza Mohammad and Hossein Omidi.A Study on Rice-Husk/Recycled High Density Polyethylene Composites – Their Physical and Mechanical Properties. Journal of Environmental Sciences 9 (2012): 99-112.
[8] Helal G. A. Bioconversion of Straw into Improved Fodder. Journal of Microbiology 34 (2006): 14-21.
[9] Nurain Johar, Ishak Ahmad, Alain Dufresne. Extraction, Preparation and Characterization of Cellulose Fibers and Nanocrystals from Rice Husk. Journal of Industrial Crops and Products 37 (2012): 93-99.
[10] Rowell RM, Lange SE, Jacobson RE. Weathering performance of plant-fiber/ thermoplastic composites. Mol Cryst Liq Cryst 353 (2000): 85–94.
[11] Falk RH, Lundin T, Felton C. Durability and disaster mitigation in wood-frame housing. In Proceedings, 2000, pp. 175–179.
[12] C. Homkhiew, T. Ratanawilai, W. Thongruang, Effects of natural weathering on the properties of recycled polypropylene composites reinforced with rubberwood flour. Ind. Crops Prod. 56 (2014): 52-59.
[13] L. Soccalingame, D.Perrin, J.-C. Benezet, A.Bergeret. Reprocessing of UV-weathered Wood Flour Reinforced Polypropylene Composites: Study on Natural Outdoor Exposure. Polymer Degradation and Stability 133 (2016): 389 – 398.
[14] Irina Turku, Anna Keskisaari, Timo Kärki, Ari Puurtinen, Pasi Marttila. Characterization of Wood Plastic Composites Manufactured From Recycled Plastic Blends. Composite Structures 161 (2017): 469-476.
[15] R. Ou, Y. Xie, W.P. Wolcott, E. Yuan, Q. Wang, Effect of wood cell wall composition on the rheological properties of wood particle/high density polyethylene composites. Compos. Sci. Technol. 93 (2014): 68–75.

[16] N.M. Stark, L.M. Matuana, Ultraviolet weathering of photostabilized woodflour-filled high-density polyethylene composites. J. Appl. Polym. Sci. 90 (2003): 2609–2617.
[17] C. Homkhiew, T. Ratanawilai, W. Thongruang, Effects of natural weathering on the properties of recycled polypropylene composites reinforced with rubberwood flour. Ind. Crop. Prod. 56 (2014): 52–59.
[18] A.A. Morandim-Giannetti, J.A.M. Agnelli, B.Z. Lanc¸ as, R. Magnabosco, S.A. Casarin, S.H.P. Bettini, Lignin as additive in polypropylene/coir composites: Thermal, mechanical and morphological properties. Carbohyd. Polym. 87 (2012) 2563–2568.
[19] Célia Badji, Lata Soccalingame, Hélène Garay, Anne Bergeret, Jean-Charles Bénézet. Influence of Weathering on Visual and Surface Aspect of Wood Plastic Composites: Correlation Approach with Mechanical Properties and Microstructure. Polymer Degradation and Stability 37 (2017): 162 – 172.
[20] Hattotuwa G. B. Premalal, H. Ismail, A. Baharin. Comparison of the Mechanical Properties of Rice Husk Powder Filled Polypropylene Composites with Talc Filled Polypropylene Composites. Polymer Testing 21 (2002): 833 – 839.
[21] M. García, J. Hidalgo, I. Garmendia, J. García-Jaca. Wood-Plastics Composites with Better Fire Retardancy and Durability Performance. Composites: Part A 40 (2009): 1772 – 1776.
[22] Yao Peng, Ru Liu, Jinzhen Cao. Characterization of Surface Chemistry and Crystallization Behaviour of Polypropylene Composites Reinforced With Wood Flour, Cellulose and Lignin During Accelerated Weathering. Applied Surface Science (2015): 253 – 259.
[23] Te-Hsin Yang, Tsu-Hsien Yang, Wei-Cheng Chao, Shao-Yuan Leu. Characterization of the Property Changes of Extruded Wood-Plastic Composites during Year Round Subtropical Weathering. Construction and Building Materials 88 (2015): 159 – 168.
[24] Silva RV, Aquino EM. Curaua fiber: A new alternative to polymeric composites. Journal of Reinforced Plastics and Composites 27 (2008): 103-112.