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Palm leave and plastic waste wood composite for out-door structures

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HIGHLIGHTS

- Wood plastic composite (WPC) materials produced from palm leave and plastic wastes.
- The mechanical and physical properties proved an acceptable final and promising WPC product.
- The rate of linear burning was highest for natural wood and MDF, than WPC.

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ABSTRACT

The objective of this paper is to produce an environmentally friendly artificial wood for structural application, by recycling mixed plastic waste and date palm leaves waste. Several pretreated wood plastic composites mixtures, using a 1:1 ratio of palm leaves and plastic waste, were designed and developed—namely, polycarbonate (PC-mix), polystyrene (PS-mix), and polyvinyl chloride (PVC-mix). The batch mixture of each type was extruded at different temperature profiles.

The density, water absorption, hardness, modulus of elasticity (tensile and flexure), impact strength, and linear burning rate of the WPC samples produced were determined, and the results were compared with the natural hard, soft wood, and medium density fiberboard (MDF) woods. The developed wood plastic composites exhibited less water absorption, linear burning and hardness, higher density than that of natural and MDF wood, and can be used in outdoor structures.

1. Introduction

Wood–plastic composite (WPC) products have emerged as a new class of materials used as an alternative having close similar mechanical and physical properties to solid wood in a variety of applications [1–6]. WPC commercial products are increasingly replacing many products in many applications, especially in outdoor applications and construction-related materials [7,8]. In contrast, commodity plastic filled with wood fibers differs in brittleness and has lower impact resistance (or toughness) than unfilled polymers [3,4]. Several factors, such as the nature of matrix resin and fiber volume fraction influence the toughness of filled polymers [5]. The use of additives such as impact modifiers, plasticizers, or lubricants as well as blending them with another polymer allow for controlling the ductility of the polymer. Consequently, the use of ductile polymers in WPCs would increase the toughness of the composites [5,9].

Wood–plastic composites (WPC) are a new group of materials generating interest in different parts of the world because they can divert recyclable wood and plastics from the landfill into durable building applications; additional environmental benefits could be obtained if the composites themselves are recycled at the end of their useful life [10].

Thus, the development and production of fiber composites using agricultural and plastic wastes are promising solutions for recycling the waste and utilization of such waste as renewable sources for beneficial use. Therefore, from both environmental and economic point of view, the simultaneous utilization of plastic and fiber from date palm leaf wastes for producing fiber reinforced WPCs as an alternative to natural wood. The major objective of this paper is to produce environmentally friendly artificial wood (e.g. WPC) by recycling mixed plastic from municipal solid waste and date palm leaf waste from agricultural farms.

2. Research methodology

2.1. Materials

Three combinations of WPCs were developed: PC-mix, PS-mix, and PVC-mix. The raw materials used were plastic waste and date palm leaves. Polycarbonate, polyvinyl chloride, and polystyrene solutions were used in the pretreatment of the raw materials.

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Table 1
Processing conditions applied for final product formation of artificial wood.

Artificial wood composite mix	Palm leaves waste (%)	Mixed plastic waste (%)	Pre-treatment coupling agent	Mixture speed (RPM)	Coloring agent
PC-mix	50	50	Saturated solution of polycarbonate in methylene chloride	40–50	Red
PVC-mix	50	50	Pre-treatment with mixture of acetone + carbon disulfide + PVC polymer	40–50	Yellow
PS-mix	50	50	Saturated solution of polystyrene in chloroform	40–50	Blue

The palm leaves used in the production of WPC have unidirectional loading with thin and thick fibers that exist in the frond. The fibers extend from the fronds to the leaves and form the main loading fibers. The swelling ratio and the tensile strength of the three portions of the palm leaves namely; nodal, middle and rear portion along with their average are calculated and plotted in Fig. 2. The swelling is due to absorption of water which varies in the three portions of leaflet with 69.8% in near nodal portion followed by 60–64% in middle and rear portions of the leaflet. The tensile strength of the leaf is between 41.8 and 50.7, with an average of 45.3 MPa. Tensile strength near the nodal portion is slightly greater than middle and rear portions, with an average of 45.33 MPa (see Fig. 2), which accounts for the shrinkage of leaves as water content is lost and the increased ratio of fiber. Furthermore, this variation may be due to more aggregation and distribution of fiber content per unit area at nodal region.

2.1.1. Preparation of palm leave waste and fiber

Date palm leaf waste was collected from agricultural farm areas and dried in sunlight in an open place so as to lower the moisture level to 10–15%, which is measured by dielectric meter. The leaves were chopped into smaller length segments, and further cut into pieces ranging in size from approximately 0.63–4.0 mm in a shredder machine. The pieces were stored in suitable polyethylene bags in a dry place.

2.1.2. Preparation of shredded plastic waste

A randomly collected mix of domestic plastic waste was procured. The material was immersed in diluted Clorox disinfectant solution (5%) for 60 min, followed by washing with a liquid detergent solution and two rinses in water. The water was then drained, and the waste was allowed to dry completely in the open air. All plastics were compacted and shredded into 1–4 mm particles by passing them through size-selective meshes and stored in containers.

2.2. Mix design

Shredded mixed plastic and leaf materials were used at a 1:1 ratio. The raw materials were pretreated with saturated polycarbonate, PVC, and polystyrene solutions in three separate batches of mixes (PC-mix, PVC-mix, and PS-mix) and thoroughly mixed in a mixer (Model: Phase1 with 2HP motor and 60 cycles, Mgf: Tsung Nsing Machinery Co. Ltd., Taiwan) at a speed of 40–50 rpm. The resultant mixture of each batch was allowed to air dry. Each batch of mixture was re-run for 3–4 min in order to dislodge any lumps and separate particles from one another. The components of each mixture, its compatible encapsulating/coupling agent, and coloring agent are shown in Table 1.

2.2.1. Extrusion and compression molding

The batch mixture was extruded in different temperature profiles using single screw 25 mm, 30L/D floor model vented extruder (Lab Tech Engineering Co. Ltd., Thailand). The mixture was then pressed with hydraulic compression under a hot molten condition of extruded mixture using a hydraulic press machine (Model 4P150F 2416, Beckwood Press Co., USA). The process conditions are summarized in Table 2.

2.3. Testing of physical and mechanical properties

2.3.1. Density

The density and specific gravity of samples of palm leaves and WPC samples were measured using displacement method as per ASTM-D-792.

2.3.2. Water absorption and swelling ration

Water absorption of palm leaves and WPC samples was determined as per ASTM-D-570-95. The prepared samples in addition to natural wood and MDF are immersed in water for exactly 24 h. After surface drying, all samples are re-weighted and the change of mass due to swelling is determined as percentage of the dry sample mass following the ASTM method-D 570-95.

The swelling ration of the palm leave is calculated by the following method:

- Three pieces from a dry date palm leave of about 5 cm long were cut and mark them as N (Nodal), M (Middle) and R (Rear) portions each
- The masses of the dry samples was measures and record as m_N, m_M and m_R.

Table 2
Processing conditions applied for the formation of WPC.

Processing conditions	Mix formulation		
	PC-Mix	PVC-Mix	PS-Mix
Extruder heating profile (°C)	120–240	100–220	120–180
Die-head temperature (°C)	225	220	180
Screw speed (RPM)	25–55	25–50	70
Motor speed (%)	52	51	52
Mold temperature settings (°C)	185	185	160
Hydraulic compression applied (Tons)	118	119	119

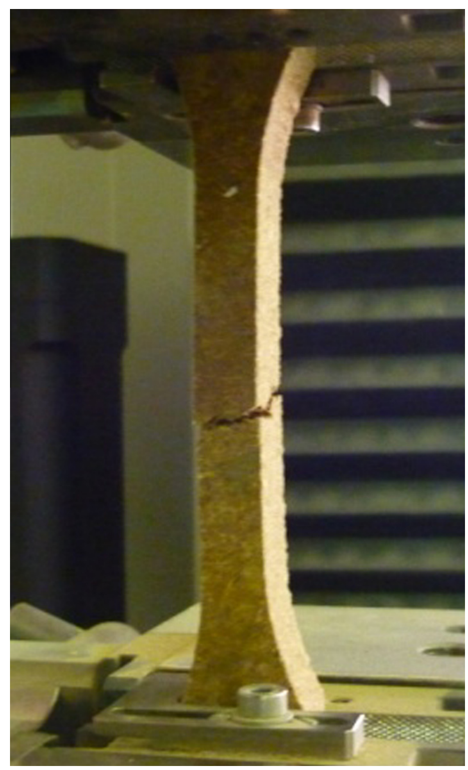

Fig. 1. Cracked WPC specimen under tensile strength test.

- The samples soaked in a beaker filled with distilled water and keep them for 24 h.
- After 24 h the samples were surface dried and weighed. Record M_N, M_M and M_R masses of the swelled samples.
- The swelling ratio (SR) was calculated in percentage of weight difference. The average of the three specimens was calculated.

2.3.3. Hardness

The hardness test was conducted as per ASTM standard ASTM-D-2240-05 using the Digital TWIN Rockwell Hardness tester (Model: QualiRock-RS, USA).

2.3.4. Tensile strength

Tensile strength, modulus of elasticity, maximum load, and percentage of breaking strain of palm leaves and WPC samples were measured using the Zwick/Roell universal testing machine as per ASTM-D-638M-93 standard testing procedure. Fig. 1 shows the tensile strength test of WPC specimen.

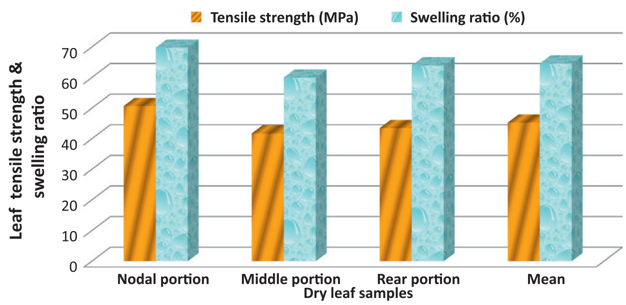

Fig. 2. Tensile strength and swelling ratio of dry leaf samples.

2.3.5. Impact test

The Charpy impact test was conducted on WPC samples according to ASTM-D-6110 standard procedure.

2.3.6. Flexural modulus

A three-point loading test method was applied on WPC samples in according with ASTM-D-790M-93.

2.3.7. Linear burning test

This fire-test was conducted according to ASTM Standard ASTM-D-635-06. The WPC specimens were prepared at a size of 125 ± 5 mm long by 14 ± 0.5 mm wide, with a minimum thickness of 10 ± 0.5 mm with smooth edges. The specimens were conditioned at 23 ± 2 °C and 50 ± 5% RH for a minimum 48 h; after conditioning, the specimen was tested within 1 h.

2.3.8. TGA/DSC

The thermogravimetric analysis (TGA) of the palm leave, PVC, PS plastic waste and WPC was carried out in Shmadzu TGA-51 analyzer. Sample weighing 1.1–1.2 mg in mass was heated up to 600 °C at a rate of 10 °C/min under a continuous air. The Differential Scanning Calorimetry (DSC) analysis was conducted in Shmadzu DSC-60A up to 250 °C.

3. Results and discussion

3.1. Density and water absorption

The measured densities of the PC-mix, PVC-mix, and PS-mix composites were 1.0, 1.03, and 0.87 g/cm^3, respectively. The corresponding values of natural hard wood, soft wood, and MDF were 0.66, 0.47, and 0.71 g/cm^3 (see Table 3). The differences ranged from 45% to 80%. This primarily depends on the specific gravities of its ingredients' interaction and their proportional formulation. During the extrusion process, the moisture in the natural cellulose fibers creates steam and vapor while plastic decomposition produces a volatile organic compound at high melting temperatures, leading to the development of internal air voids and porosity (see Fig. 3). Similar observations were made by Kazayawoko et al. [11]. The density of the developed artificial wood was expected as the input components of the mix are of high density, in addition to the fact that the molding process was under high pressure, which eventually produced a compact structure. The high density of the wood composites restricts their applications. However, their physical and mechanical properties may be of use and are recommended for specific applications, like doors and floors.

Table 3
Physical characteristics of natural and wood plastic composites (WPCs).

Sample wood	Density (g/cm^3)	Water absorption (%)	Hardness (Rockwell scale)
Natural hard wood	0.66	29.2	85.46
Natural soft wood	0.47	42.4	56.1
MDF	0.71	31.9	64.2
PC-mix	1.00	8.7	54.82
PVC-mix	1.03	9.01	57.05
PS-mix	0.87	9.9	52.65

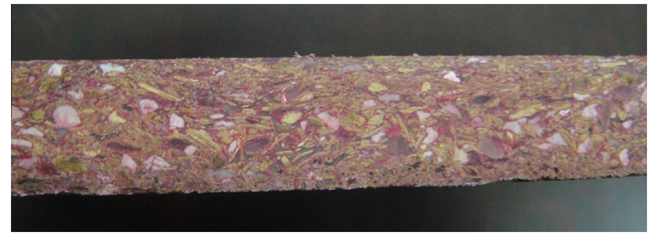

Fig. 3. Cross-section view of wood plastic.

Table 3 shows the water absorption (swelling ratio). The swelling ratios of different samples were inversely proportional to the density. All WPC samples measured less swelling than natural woods and MDF due to the nature of the input components (i.e., waste plastics), which encapsulate the palm fiber component as a barrier to resist the absorption of water by the fiber content. The application of high compaction pressure (110–120 tons) is another factor for producing less porosity with higher density. Both the hard and soft woods and MDF recorded the highest water uptake because most components in natural wood and MDF are lingo-cellulosic and hydrophilic in nature.

3.2. Hardness

The mean hardness results recorded for PC-mix, PVC-mix, and PS-mix were 54.82, 57.05, and 52.65, on the Rockwell scale. For natural hard wood, soft wood, and MDF, the hardness was measured at 85.46, 56.1, and 64.2. PVC-mix acquired greater hardness (57.05) than PC-mix or PS-mix. In comparison to natural wood samples, all the three mixed versions are within the range of natural soft wood (see Table 3). Well-polished surfaces show values that are more reliable. In the case of MDF and natural hard wood, which have well-finished surfaces, they showed better surface hardness.

3.3. Strength and modulus of elasticity

This study assessed the feasibility of using palm leaves for WPC. Since no reports exist in the literature on the use of palm leaves in WPCs, particular emphasis focused on assessing their effect on the mechanical properties of WPCs. Tensile strength and modulus, flexural modulus, and impact strength are presented in Table 4. The PVC- and PS-mix exhibited higher strength and modulus (in both flexural and tensile) and lower breaking strain (elongation) than PC-mix due to the inherent high strength, stiffness, and lower elongation at the break of the PVC and PS matrix. Most matrix specimens failed in a brittle mode. A material property such as elongation at break can indicate the ductility of a material, with toughness associated with necking before fracture [4]. High ductility or flexibility may have caused high elongation at the break of PC-mix composites in comparison to PVC- and PS-mix composites. Low values of breaking strain may be due to the phase separation of the different plastic types. Afrifah et al. [12] showed a similar trend in the energy at break or toughness. The higher degree of brittleness introduced by the incorporation of wood flour into the PB matrix may have caused the decreased elongation at break and energy to break [4,9,13]. Rigid leaves may restrict elongation, limiting almost all the stretching that occurs to the polymeric matrix [4,9]. Nevertheless, composites with 50% wood flour showed no yield point before the fracture and failed in a brittle mode [3,4,9,13].

Table 4
Elastic modulus and tensile strength of wood–plastic composites.

Sample	Tensile strength (MPa)	Tensile modulus (GPa)	Breaking strain (%)	Flexural modulus (GPa)	Impact strength (kJ/m^2)
PC-mix	2.88	1.13	5.8	1.68	1.95
PVC-mix	4.44	1.31	4.3	1.89	1.56
PS-mix	4.82	1.22	4.0	1.91	1.61

Table 5
Linear burning rate of natural wood and WPC samples in horizontal position.

Sample	Length (mm)	Width (mm)	Thickness (mm)	Length of burning (mm)	Time of burning (s)	Rate of linear burning $V = 60$ L/t (mm/min)
Hard wood	125.34	13.71	10.41	11.0	81.6	8.09
Soft wood	124.98	13.51	10.71	24.4	68.6	21.34
MDF	125.16	13.51	11.03	60.0	423.6	8.5
PC-mix	124.49	13.4	11.76	72.0	485.8	8.9
PVC-mix	124.85	14.08	10.12	68.6	626.4	6.5
PS-mix	124.2	14.0	10.4	75.0	471.8	9.5

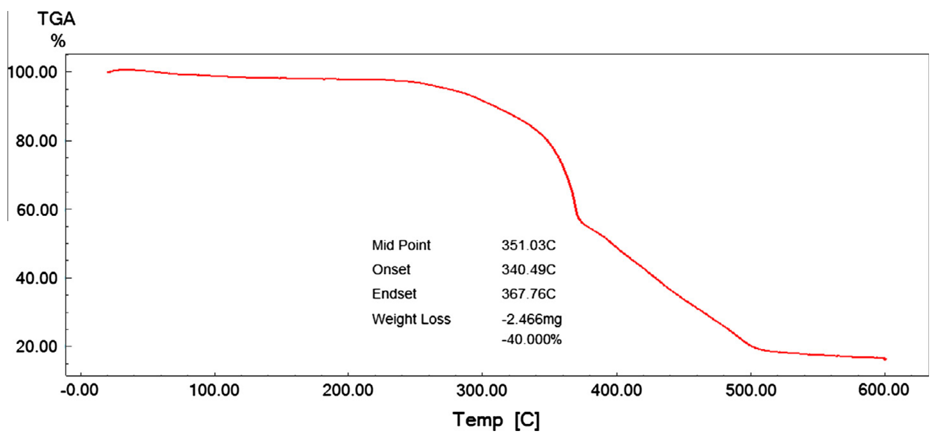

Fig. 4. TGA of PS-mix composite specimen showing the weight loss.

A comparison of impact strength indicated the importance of using a ductile matrix such as PVC- and PS-mix in enhancing the toughness of WPCs compared to the PC-based counterparts (see Table 4). The high ductility (high elongation at break) of the PC-mix, compared to that of the PVC- and PS-mix, may have influenced this high impact resistance. The palm leaf fibers also act as a discontinuity capable of initiating cracks in the composite.

Importance remains in the significantly high impact resistance and toughness (regardless of other relatively low strength properties) as it positions these composites for use in areas with such properties as the prime requirement, where they would be subjected to recurrent vibrations and impact stresses.

3.4. Linear burning rate

WPCs are highly flammable. As organic materials, the polymers and wood fibers are very sensitive to flame; improvement of the composite materials' flame retardancy has become increasingly important in order to comply with safety requirements of the wood fiber-composite products [14]. Little research exists on the flammability of nature fiber and wood fiber composites in the literature.

Table 5 shows the linear burning rates of different wood samples. WPC samples possess reasonable burning rate compared with other natural wood samples. The rate of linear burning was highest (21.34 mm/min) for natural soft wood while for hard wood and MDF the rate was 8.09 and 8.5 mm/min, respectively. However, for PC-mix, PVC-mix and PS-mix, the value of the linear burning was an average of 8.3 mm/min. This shows that, with palm leaves and plastic materials used, the burning rate was similar and was not influenced by changing the polymer type (i.e., PC, PVC, PS). This may be attributed to variations in the chemical composition, density, nature of the plastics, plastic content, and amount of fillers. Further research may be needed using fire retard agents for fire resistance and safety.

3.5. TGA/DSC

Fig. 4 shows the results of TGA of the PS-mix composite sample. The onset temperature is about 340.49 °C with total 40% weight loss. This loss is due the decomposition of the palm leaves. It shows that the temperature ranges for palm leaves fiber drying, slow up to 220 °C, followed by slow decomposition of the celluloses and lignin up to the onset temperature. Two stages of rapid decomposition of the celluloses and lignin was observed at 367 °C to about 500 °C. The DSC chart shows peak temperature at 131 °C with close onset and endset temperature as presented in Fig. 5. This sharp peak indicates the influence of the palm leave content in the composite.

4. Conclusions

Date palm leaves and plastic waste were recycled to produce WPCs with characteristics similar or close to commercial wood that were innovative, clean, cheap, and effective. The mechanical and physical properties proved an acceptable final and promising WPC product. The composite samples prepared and tested in this paper have the following properties:

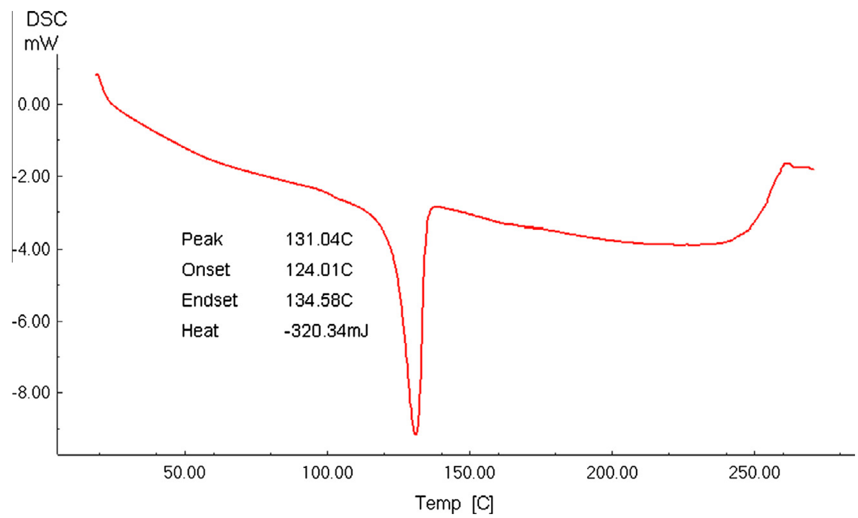

Fig. 5. DSC of PS-mix composite specimen showing the peak, onset and endset temperatures.

1- It was found that PS-mix composites was less dense compared to PC and PVC mix composites. The swelling ratios of different samples were inversely proportional to the density.
2- The mean hardness of PC-mix, PVC-mix, and PS-mix were less than natural wood, and MDF.
3- The PVC- and PS-mix exhibited a higher strength and modulus (in both flexural and tensile) and lower breaking strain (elongation) than the PC-mix.
4- The rate of linear burning was highest for natural wood and MDF, than PC-mix, PVC-mix, and PS-mix.
5- The onset temperature of the TGA was about 340.49 °C with total 40% weight loss. The DSC peak temperature was at 131 °C.
6- Further study using biodegradable polymers is suggested for future work.

As a global environmental view, the recycling of plastic will save much energy, power, and pollution. On the other hand, using palm leaf waste will save trees and forest resources and promote a greener environment. As a cost benefit, these wastes are priceless raw materials that could be assets for the outdoor structures and construction industry, generating economical outcomes.

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References

[1] Matuana LM. Recent research developments in wood plastic composites, guest editorial. J Vinyl Addit Technol; 2009.
[2] Faruk O, Matuana LM. Nanoclay reinforced HDPE as a matrix for wood–plastic composites. Compos Sci Technol 2008;68(9):2073–7.
[3] Mengeloglu F, Matuana LM, King JA. Effects of impact modifiers on the properties of rigid PVC/wood–fiber composites. J Vinyl Addit Technol 2000;6:153–7.
[4] Matuana LM, Park CB, Balatinecz JJ. The effect of low levels of plasticizer on the rheological and mechanical properties of polyvinyl chloride/newsprint–fiber composites. J Vinyl Addit Technol 1997;3:265–73.
[5] Park BD, Balatinecz JJ. Mechanical properties of wood–fiber/toughened isotactic polypropylene composites. Polym Compos 1997;18:79–89.
[6] Faruk O, Matuana LM. Reinforcement of rigid PVC/wood–flour composites with multi-walled carbon nanotubes. J Vinyl Addit Technol 2008;14:60–4.
[7] Yeh Shu-Kai, Agarwal Sushant, Gupta RakeshK. Wood–plastic composites formulated with virgin and recycled ABS. Compos Sci Technol 2009;69:2225–30.
[8] Adebola AB, Dawson-Andoh B, George BP, Nkansah K, Medley C. Adsorption and desorption behavior of some commercial wood plastic composites. Forest Prod J 2008;58:32–6.
[9] Oksman K, Clemons C. Mechanical properties and morphology of impact modified polypropylene–wood flour composites. J Appl Polym Sci 1998;67:1503–13.
[10] Winandy JE, Stark NM, Clemons CM. In: 5th Global Wood and Natural fiber Composites Symposium. Kassel (Germany); 2004.
[11] Kazayawoko M, Balatinecz JJ, Matuana LM. Surface modification and adhesion mechanisms in woodfiber–polypropylene composites. J Mater Sci 1999;34(24):6189–99.
[12] Afrifah KA, Hickok RA, Matuana LM. Polybutene as a matrix for wood plastic composites. Compos Sci Technol 2010;70:167–72.
[13] Matuana LM, Woodhams RT, Balatinecz JJ, Park CB. Influence of interfacial interactions on the properties of PVC/cellulosic–fiber composites. Polym Compos 1998;19:446–55.
[14] Sain M, Park SH, Suhara F, Law S. Flame retardant and mechanical properties of nature fiber–PP composites containing magnesium hydroxide. Polym Degrad Stab 2004;83:362–7.